

# WORLD CLIMATE RESEARCH PROGRAMME



## CLIVAR Initial Implementation Plan

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# CLIVAR INITIAL IMPLEMENTATION PLAN

## TABLE OF CONTENTS

	<b>Page no.</b>
<b>PREFACE</b>	<b>1</b>
<b>I OVERVIEW</b>	<b>3</b>
<b>1. INTRODUCTION AND PURPOSE</b>	<b>3</b>
<b>2. CLIVAR SCOPE AND APPROACH</b>	<b>4</b>
<b>3. THE CLIVAR PRINCIPAL RESEARCH AREAS</b>	<b>5</b>
<b>4. CONSIDERATIONS IN DEVELOPING PRIORITIES</b>	<b>7</b>
<b>5. CLIVAR IMPLEMENTATION</b>	<b>9</b>
<b>II UNIFYING THEMES AND APPROACHES</b>	<b>11</b>
<b>1. GLOBAL FRAMEWORK FOR CLIVAR</b>	<b>11</b>
<b>2. GLOBAL MODELLING AND PREDICTION</b>	<b>13</b>
2.1 Organisation of Modelling within CLIVAR and the WCRP	13
2.2 Climate Modelling on Seasonal to Interannual Time Scales	14
2.2.1 Current projects of NEG-1	14
2.3 Global Modelling on Seasonal to Century Time Scales	15
2.3.1 Current projects of WGCM	16
2.4 Paleoclimate Modelling	18
2.5 Downscaling	20
2.6 Computational requirements for the CLIVAR Numerical Experimentation Programme	20
<b>3. GLOBAL-SCALE EMPIRICAL, ANALYTICAL AND DIAGNOSTIC STUDIES</b>	<b>23</b>
<b>4. GLOBAL SUSTAINED OBSERVATIONS</b>	<b>25</b>
4.1 General Considerations	25
4.2 Requirements and Potential Contributions	26
4.2.1 Ocean observing systems	26
4.2.2 Elements of the ocean observing system for CLIVAR	30
4.2.3 Atmosphere and land surface observing system	48
4.3 Implementation and Oversight Mechanisms	50
4.4 Concluding Remarks	51
<b>5. DATA SET DEVELOPMENT, POLICY AND MANAGEMENT</b>	<b>53</b>
5.1 Historical Data	53
5.2 Reanalyses	54
5.3 Paleoclimatic Data Sets	55
5.4 Data Management Policy	57
5.5 The Global Ocean Data Assimilation Experiment (GODAE)	58
<b>6. LINKAGES</b>	<b>61</b>
<b>7. REFERENCES (Part I and II)</b>	<b>62</b>

	<b>Page no.</b>
<b>III THE CLIVAR PRINCIPAL RESEARCH AREAS</b>	<b>65</b>
<b>III (i) CLIVAR GOALS</b>	<b>65</b>
<b>1. ENSO: EXTENDING AND IMPROVING PREDICTIONS (G1)</b>	<b>69</b>
1.1 Scientific Rationale	69
1.2 Analyses, Modelling and Prediction	72
1.2.1 Analyses and model initialisation	72
1.2.2 Modelling and prediction in the tropics	73
1.2.3 Prediction of the extra-tropical atmospheric circulation	74
1.2.4 Prediction and assessment	75
1.2.5 Current projects	76
1.3 Observing Needs	76
1.4 Focused Research Projects	77
1.4.1 Observing system evaluation	77
1.4.2 The 1997-98 ENSO event	78
1.5 Data Set Development, Diagnostics and Empirical Studies	78
1.6 Linkages with other Elements and Programmes	79
1.7 References	81
<b>2. VARIABILITY OF THE ASIAN-AUSTRALIAN MONSOON SYSTEM (G2)</b>	<b>83</b>
2.1 Introduction	83
2.2 Scientific Rationale	83
2.2.1 The annual cycle	85
2.2.2 Intraseasonal oscillations (ISO)	86
2.2.3 ENSO-monsoon coupling	88
2.2.4 The tropospheric biennial oscillation (TBO)	88
2.2.5 Oceanic processes	88
2.2.6 Land surface processes	89
2.2.7 Tropical-extratropical interaction	89
2.3 Programme Objectives	90
2.4 Modelling and Prediction	91
2.4.1 Experiments with AGCMs	92
2.4.1.1 Atmospheric model intercomparison projects	92
2.4.1.2 Monsoon predictability	92
2.4.1.3 Intraseasonal variability	94
2.4.1.4 Role of SST anomalies in influencing the monsoon	94
2.4.2 Experiments with OGCMs	95
2.4.2.1 Ocean process modelling and intercomparison	95
2.4.2.2 Evaluation of observed surface fluxes	96
2.4.3 Experiments with CGCMs	97
2.5 Process Studies Including Field Campaigns	97
2.5.1 Diagnostic studies	97
2.5.1.1 Seasonal variations	97
2.5.1.2 Intraseasonal variations	98
2.5.1.3 Monsoon-ENSO coupling	98
2.5.1.4 Tropospheric biennial oscillation	99
2.5.1.5 Heat balance of the Indian ocean	99
2.5.2 Parameterisation of physical processes	100

	<b>Page no.</b>
2.5.3 Special observations and enhanced monitoring	100
2.6 Observation System Requirements	101
2.6.1 Meteorological variables	101
2.6.2 Oceanic Variables	102
2.6.2.1 The TRITON array	102
2.6.3 Land variables	103
2.7 Data Set and Prediction System Development	104
2.7.1 Data set development and related studies	104
2.7.2 Monsoon prediction system	105
2.8 Programme Linkages	105
2.9 References	106
<b>3. VARIABILITY OF AMERICAN MONSOON SYSTEMS (VAMOS) (G3)</b>	<b>109</b>
3.1 Scientific Rationale	109
3.1.1 The American monsoon systems	109
3.1.1.1 The monsoon system in the Northern Hemisphere	110
3.1.1.2 The monsoon system in the Southern Hemisphere	113
3.1.2 The importance of ocean processes	116
3.1.3 The importance of orography and land surface processes	118
3.2 VAMOS: Programme Definition	118
3.3 Modelling and Prediction	119
3.3.1 Atmospheric General Circulation Models (AGCMs)	119
3.3.2 Oceanic General Circulation Models (OGCMs)	121
3.3.3 Coupled Atmosphere Ocean-Land GCMs (coupled GCMs)	122
3.3.4 Mesoscale atmospheric models	123
3.3.5 Predictability	124
3.3.6 Prediction	124
3.4 Special Observing Needs	125
3.4.1 Enhanced monitoring in the eastern tropical Pacific region	125
3.4.2 Surface fluxes over the oceans	126
3.4.3 Atmosphere-ocean interaction in the stratus deck region	126
3.4.4 High resolution sea surface temperature	127
3.4.5 Soil moisture	127
3.4.6 Precipitation	127
3.4.7 Vertical structure of the atmosphere	128
3.5 Field Studies	129
3.5.1 Atmospheric PBL structure above the cold tongue	129
3.5.2 Structure and intensity of ITCZ rainfall	129
3.5.3 Air-sea fluxes in the cold tongue-ITCZ-complex	129
3.5.4 Vertical current profiles in the equatorial cold tongue	129
3.5.5 Tropical Rainfall Measuring Mission (TRMM)	130
3.6 Diagnostics and Empirical Studies	130
3.6.1 Diagnostic studies	130
3.6.2 Empirical studies	130
3.7 Data Set Development	131
3.7.1 Existing sources of data	131
3.7.2 Historic data sets / data archaeology	131
3.7.3 The VAMOS data base	132

	<b>Page no.</b>
3.8 Linkages	132
3.8.1 Within CLIVAR	132
3.8.2 Within WCRP	132
3.8.2.1 Global Energy and Water Cycle Experiment (GEWEX)	132
3.8.3 With other programmes	133
3.8.3.1 The Pan American Climate Studies (PACS)	133
3.8.3.2 The Pilot moored Research Array in the Tropical Atlantic (PIRATA)	134
3.8.3.3 The Inter American Institute for Global Change Research (IAI)	134
3.8.3.4 International Research Institute (IRI)	135
3.9 References	136
3.10 Table 1: Preliminary list of data available for VAMOS research	142
<b>4. AFRICAN CLIMATE VARIABILITY (G4)</b>	<b>145</b>
4.1 Introduction	145
4.2 Scientific Rationale	145
4.2.1 Past studies	145
4.2.2 ENSO influence	145
4.2.3 Influence of Indian monsoon and Indian Ocean SSTs	147
4.2.4 Numerical modelling studies	147
4.2.5 Extra-tropical influences	148
4.2.6 Atlantic influences	148
4.2.7 Influence of land-surface processes	148
4.2.8 Role of CLIVAR-Africa	149
4.3 Programme Objectives	150
4.4 Observational Requirements	151
4.4.1 Atmospheric needs	151
4.4.2 Oceanographic measurements	151
4.4.3 Land-based observations	152
4.5 Data Bases, Analysis and Prediction	152
4.6 Diagnostic and Process Studies	153
4.6.1 Atmospheric circulation and convection	153
4.6.2 Ocean forcing and monsoons	153
4.6.3 Oceanographic measurements	154
4.6.4 A terrestrial focus	155
4.7 Numerical Modelling	155
4.8 Training Efforts and Programme Linkages	155
4.9 References	156
<b>III (ii) CLIVAR DecCen</b>	<b>161</b>
<b>5. THE NORTH ATLANTIC OSCILLATION (D1)</b>	<b>163</b>
5.1 Scientific Rationale	163
5.1.1 Introduction: Characteristics of the NAO	163
5.1.2 The NAO and global change	164
5.1.3 Decadal changes in the NAO index	166

	<b>Page no.</b>
5.2 Modelling and Prediction	166
5.2.1 Uncoupled variability	169
5.2.2 Coupled variability	169
5.2.3 The role of transients	170
5.3 Diagnostics and Empirical Studies	171
5.3.1 Optimizing the NAO index	171
5.3.2 Detailed study of storm-surface interactions	171
5.3.3 Data archaeology	172
5.4 Special Observing Needs	173
5.4.2 Variability of North Atlantic heat fluxes and storage	173
5.4.2 A DecCen ‘NAO Array’	176
5.4.3 Water mass conversion processes in the subpolar North Atlantic: A Lagrangian process study	180
5.4.4 Repeat CTD-tracer sections	181
5.4.5 Inventories of deep and intermediate watermass changes	182
5.4.6 The Greenland Sea and its overflows	182
5.4.7 The Arctic response to NAO forcing	183
5.5 Linkages with other Elements and Programmes	184
5.5.1 Other elements of CLIVAR	184
5.5.2 Other WCRP programmes	185
5.5.3 European Union (EU) projects	185
5.5.4 Other ongoing or planned national programmes	185
5.6 References	187
<b>6. TROPICAL ATLANTIC VARIABILITY (D2)</b>	<b>193</b>
6.1 Scientific Rationale	193
6.2 Modelling and Prediction	199
6.3 Special Observing Needs	201
6.4 Focused Research Projects	203
6.5 Data Set Development, Diagnostics and Empirical Studies	204
6.6 Linkages with other Elements and Programmes	206
6.7 References	207
<b>7. ATLANTIC THERMOHALINE CIRCULATION (D3)</b>	<b>213</b>
7.1 Scientific Rationale	213
7.1.1 Sudden changes	213
7.1.2 Internal oceanic variability	215
7.1.3 Coupled modes	215
7.1.4 Atmospheric forcing	216
7.1.5 Links to other oceans	216
7.1.6 Overarching objectives	217
7.2 Modelling and Prediction	217
7.2.1 Sudden transitions	219
7.2.2 Multiple equilibrium states	219
7.2.3 Sensitivity to atmospheric fluxes	219
7.2.4 Resolution and parameterisation of climate-relevant processes	220
7.2.5 Predictability	220

	<b>Page no.</b>
7.3 Observing Needs	221
7.3.1 Watermass and current sections at crucial latitudes	221
7.3.2 Northern ice and freshwater import	222
7.3.3 NADW export array	222
7.3.4 Inventories of deep and intermediate water changes	222
7.3.5 Inventories of intermediate and subtropical mode water changes	223
7.3.6 Flux fields	223
7.3.7 Documentation of climate change response	223
7.4 Focused Research Projects	224
7.4.1 Water mass transformation and relation to thermohaline circulation variability	224
7.4.2 Role of equatorial zone in interhemispheric communication of thermohaline circulation variability	224
7.4.3 Deep to surface layer water mass modifications	225
7.4.4 Subgrid-scale processes for improved parameterisation	225
7.4.5 Interbasin exchange	226
7.5 Data Set Development, Diagnostics and Empirical Studies	226
7.5.1 Data sets on water mass and thermohaline circulation variability	226
7.5.2 Reanalysis of the instrumental record	226
7.5.3 Model analysis	227
7.5.4 The paleoclimatic record	227
7.6 Linkages with other Elements and Programmes	227
7.6.1 Other elements of CLIVAR	227
7.6.2 Other WCRP programmes	227
7.6.3 IGBP programmes	228
7.6.4 Other ongoing or planned programmes	228
7.6.5 The Global Ocean Observing System (GOOS)	228
7.7 References	229
<b>8. PACIFIC AND INDIAN OCEAN DECADEAL VARIABILITY (D4)</b>	<b>231</b>
8.1 Scientific Rationale	231
8.1.1 The Pacific and Indian Ocean: general considerations	231
8.1.2 Observed variability in the Pacific and Indian Oceans	233
8.1.2.1 Large-scale variability	233
8.1.2.2 Pacific Ocean variability	234
8.1.2.3 Indian Ocean variability	235
8.1.2.4 Western boundary currents	235
8.1.2.5 Indonesian throughflow	236
8.1.3 Possible mechanisms	236
8.1.4 Science questions	240
8.1.5 Approach	241
8.2 Modelling and Prediction Studies Required	241
8.3 Observing Needs	243
8.3.1 Broad-scale and ongoing routine observations	243
8.3.2 Proxy records of decadal and centennial variability	245
8.4 Focused Research Projects	246
8.4.1 Introduction	246

	<b>Page no.</b>
8.4.1.1 A Pacific basin-wide extended climate study	247
8.4.1.2 Mixing in the mixed layer and upper thermocline	248
8.4.1.3 Interaction of the upper thermocline with the surface layer: subduction	249
8.4.1.4 Direct observations of circulation	250
8.4.1.5 Enhanced surface meteorology	250
8.4.1.6 Enhanced salinity measurements	251
8.4.1.7 Subpolar North Pacific study	251
8.4.2 Southern Hemisphere subduction	251
8.4.3 Monsoon variability	252
8.4.4 Effects of western boundary currents on regional climate	252
8.4.5 Indonesian throughflow	253
8.5 Data Set Development, Diagnostics and Model-Assimilated Data	254
8.5.1 Data set development and studies based on existing data	254
8.5.2 Diagnostics	254
8.5.3 Model-assimilated data	254
8.6 Linkages with other Elements and Programmes	255
8.7 References	256
<b>9. SOUTHERN OCEAN CLIMATE VARIABILITY (D5)</b>	<b>259</b>
9.1 Scientific Rationale	259
9.1.1 Antarctic Circumpolar Current	259
9.1.2 Meridional fluxes and intermediate water ventilation	259
9.1.3 Deep and bottom water ventilation	260
9.1.4 Sensitivity of climate models to Southern Ocean sea ice	260
9.1.5 Sensitivity of climate models to heat storage and overturning in Southern Ocean	263
9.1.6 Coherent climate patterns and variability in the Southern Hemisphere	263
9.1.7 Unique Southern Ocean paleoclimate information	264
9.1.8 Scientific rationale summary	264
9.2 Scientific Foci of Southern Ocean CLIVAR	265
9.2.1 Variability in the Antarctic Circumpolar Current	265
9.2.2 Variability of Subantarctic Mode Water and Antarctic Intermediate Water	267
9.2.3 Coupled variability of deep water formation, sea ice and the atmosphere	267
9.2.4 Formation mechanism of Antarctic bottom water	270
9.3 Modelling and Prediction	270
9.3.1 Global circulation model studies	270
9.3.2 Regional model studies	271
9.3.3 Local process models	271
9.3.4 Modelling strategy	272
9.4 Observational Strategy	272
9.4.1 Chokepoints: Flux monitoring associated with the Antarctic Circumpolar Current between the three ocean basins	272
9.4.2 Mid-latitude zonal sections	273
9.4.3 Periodic (~5-year) repeats of selected additional deep hydrographic lines	273
9.4.4 Additional VOS sampling where practical	274



	<b>Page no.</b>
9.4.5 Salinity sampling; PALACE floats to monitor T(z), S(z) and the circulation	274
9.4.6 Surface drifters (including drifters in the sea ice zone)	274
9.4.7 Deep boundary current measurements	275
9.4.8 Satellite monitoring of SST, sea level, winds and sea ice	275
9.4.9 Ice and snow thickness	276
9.4.10 Monitoring of fast ice thickness at key sites	276
9.4.11 Combination of moored measurements and ‘rapid response’ cruises	276
9.5 Linkages with other CLIVAR Components and Programmes	276
9.5.1 Other elements of CLIVAR	276
9.5.2 Other WCRP programmes	277
9.5.3 Programmes outside of WCRP	277
9.6 References	278
<b>III (iii) CLIVAR ACC</b>	<b>281</b>
Reference	282
<b>10. CLIMATE CHANGE PREDICTION (A1)</b>	<b>283</b>
10.1 Scientific Rationale	283
10.1.1 What is known now	283
10.1.2 What is being done now	284
10.1.3 Among the questions remaining are	285
10.1.4 Where CLIVAR can help	287
10.2 Input Required	288
10.2.1 Improvements in the representation of physical, chemical and biological processes in models	288
10.3 Modelling and Prediction	289
10.3.1 Model improvement	290
10.3.2 Model evaluation	290
10.3.3 Idealised studies	290
10.3.4 Predictions	290
10.3.5 Multi-century simulations	290
10.3.6 Regional modelling	291
10.4 Computing Requirements	291
10.5 Special Focused Research Projects	292
10.5.1 Idealised sensitivity studies	292
10.5.2 Calibration of simple models	292
10.5.3 Standardised forcing scenarios	292
10.5.4 Coupled Model Intercomparison (CMIP)	293
10.6 Linkages	293
10.7 References	295
<b>11. CLIMATE CHANGE DETECTION AND ATTRIBUTION (A2)</b>	<b>297</b>
11.1 Scientific Rationale	297
11.2 Modelling and Prediction	303
11.3 Observing Needs	304
11.4 Focused Research Projects	305

	<b>Page no.</b>
11.4.1 Developing indicators and indices for climate extremes	305
11.4.2 Development of historical global temperature series from paleoclimatic data	305
11.4.3 Development of standard set of historical climate forcings (natural and human-induced)	306
11.4.4 Improved statistical methods for climate change detection and attribution	307
11.5 Data Set Development, Diagnostics and Empirical Studies	307
11.6 Linkages	308
11.7 References	309
<b>12. ASSESSMENT OF CURRENT STATUS OF PRINCIPAL RESEARCH AREAS</b>	<b>311</b>
<b>IV APPENDIX</b>	<b>A-1</b>
<b>A.1 ACKNOWLEDGEMENTS</b>	<b>A-1</b>
<b>A.2 LIST OF MEETINGS</b>	<b>A-5</b>
<b>A.3 PROGRAMMATIC INFRASTRUCTURE AND ORGANISATION</b>	<b>A-7</b>
3.1 Implementation and Oversight Structures	A-7
3.2 Resource Planning and Co-ordination	A-9
3.3 References	A-9
<b>A.4 IMPLEMENTING A CLIVAR DATA RESOURCE MANAGEMENT</b>	<b>A-11</b>
4.1 Preface	A-11
4.1.1 Purpose	A-11
4.1.2 "CLIVAR data"	A-11
4.1.3 "CLIVAR data" resources	A-11
4.2 Existing Structures	A-12
4.2.1 TOGA data management concept	A-12
4.2.2 WOCE data management concept	A-14
4.2.3 The GCOS programme	A-19
4.2.4 World Data Center system	A-20
4.3 General Data Management Requirements	A-21
4.4 References	A-23
<b>A.5 LINKAGES</b>	<b>A-25</b>
5.1 Linkages within the World Climate Research Programme (WCRP)	A-25
5.1.1 Global Energy and Water Cycle Experiment (GEWEX)	A-25
5.1.2 World Ocean Circulation Experiment (WOCE)	A-27
5.1.3 Arctic Climate System Study (ACSYS)	A-28
5.1.4 Stratospheric Processes and their Role in Climate (SPARC)	A-28
5.2 The International Geosphere Biosphere Programme (IGBP)	A-28
5.3 Intergovernmental Panel on Climate Change (IPCC)	A-30

	<b>Page no.</b>
5.4 “Climate” Observations Programmes	A-31
5.4.1 The Global Climate Observing System (GCOS)	A-31
5.4.2 The Global Ocean Observing System (GOOS)	A-32
5.5 International Human Dimensions of Global Environmental Change Programme (IHDP)	A-32
<b>A.6 ACRONYMS</b>	<b>A-33</b>

## PREFACE

1997 was marked with an unprecedented level of interest in issues relating to the Earth's climate, its variability and climate change. The Third meeting of the Parties to the UN Framework Convention on Climate Change in Kyoto in December 1997 focused the world's attention on how human activities may influence global climate. While the meeting established emission targets, it also asked nations to continue their efforts in climate research in areas on which this CLIVAR<sup>1</sup> Initial Implementation Plan focuses. The behaviour of the climate system itself has been a major news event as the 1997-98 El Niño has emerged as the biggest on record by some measures. Moreover, CLIVAR scientists forecast the event. The full TOGA/CLIVAR Pacific observing system has documented its development, providing a wonderful natural experiment for CLIVAR scientists to watch unfold. Many of the effects felt around the world were foreseen, but some were not, and the experience will provide valuable lessons for CLIVAR.

Throughout 1997 scientists around the world have focused on the formulation of an Initial Implementation Plan for CLIVAR. The plan was developed in a series of international workshops, regional and national meetings and then refined through the work of the CLIVAR Scientific Steering Group, its panels and working groups and through the efforts of writing teams.

The Initial Implementation Plan is the work of many. We are grateful to, and thank the scientists who have stepped forward and participated in this process, especially the chairpersons and organisers of the working groups, workshops and writing groups. On behalf of the SSG, we express our appreciation to all those who have contributed. A complete listing of authors and contributors is given in Appendix 1; special recognition is also due to the staff at the International CLIVAR Project Office. We now need the ideas and support of the scientists and agencies to move from plan to programme and let the implementation plan evolve to reflect changing scientific insight and emerging interests and priorities among participating national agencies.

CLIVAR focuses on the role of the coupled ocean and atmosphere within the overall climate system, with emphasis on variability, especially within the oceans, on seasonal to centennial time scales. CLIVAR intends to explore predictability and how to improve predictions of climate variability and climate change using existing, re-analysed, and new global observations, enhanced coupled ocean-atmosphere-land-ice models, and paleoclimate records. CLIVAR will promote the development of skilful regional and global predictive models that will enable a more accurate detection of anthropogenic modification of natural climate. CLIVAR strongly supports the design and implementation of global ocean and atmosphere observing systems for long-term climate research and will specifically address the variability of regional coupled ocean-atmosphere systems such as monsoons in relation to global patterns such as ENSO.

Accordingly, the plan describes CLIVAR's requirements for global observations, dataset development, empirical studies, model development and numerical experimentation, and process studies. The challenge has been to find the critical areas in which co-ordination and international infrastructure can make the research endeavours more effective and focused. The broad scope of the programme is focused initially on eleven principal research areas.

The Initial Implementation Plan is detailed where programmes are currently well defined and it identifies the directions that the development of focused programmes are expected to take over the next 5-10 years. In many respects it is more a strategic plan of action because implementation will depend on the interests of countries, their own needs and priorities, as well as the assessments of scientists as to how ready certain scientific questions are for substantive progress to occur. Updates to this plan will be issued at irregular intervals as focused programmes are developed and as the global programmes evolve. The name "Initial" Implementation Plan recognises the iterative nature of the process we are engaged in. A key step is the CLIVAR Science Conference in Paris at UNESCO 1-4 December 1998. This Conference will seek expressions of interest and commitments from nations. It will also identify national priorities and prospects for international collaboration and co-ordination and will guide the CLIVAR Scientific Steering Group on

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1. Climate Variability and Predictability

where emphases should be placed.

CLIVAR is undoubtedly the biggest and most diverse project yet undertaken by the World Climate Research Programme. The intellectual and material resources required are enormous, as can be seen from this volume. CLIVAR will bring together communities of meteorologists, atmospheric scientists, oceanographers and paleoclimatologists who may not have worked closely together in the past. It is exciting that there is a large community of researchers working on the analysis and modelling of climate variability ready to go forward and meet the challenges posed in the plan. We hope you will join us.

Kevin Trenberth, Allyn Clarke

(Co-chairs of the CLIVAR SSG)

## **I. OVERVIEW**

### **1. INTRODUCTION AND PURPOSE**

This document, the CLIVAR Initial Implementation Plan, continues the development of CLIVAR and provides a necessary step towards its implementation. It is based on the foundation provided by the CLIVAR Science Plan (WCRP, 1995) and the subsequent organisation of the programme by the CLIVAR Scientific Steering Group, including many scientific workshops and meetings which have been held in the interim (see Appendix 2). The vision of the programme presented here represents the current state of knowledge and planning. It is most detailed where programmes are currently well defined and identifies the directions that its sub-elements are expected to take over the next 5-10 years. Updates to the Implementation Plan will be issued at irregular intervals as the various parts of the programme are developed and as the global components evolve in response to new insights, scientific advances and technological developments.

The CLIVAR Science Plan was published in August 1995 and builds upon the heritage of the Tropical Ocean Global Atmosphere programme (TOGA), progress in the World Ocean Circulation Experiment (WOCE), and needs expressed by the Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment Reports. CLIVAR's scientific goals are directed towards the description, analysis, modelling and prediction of climate variability with time scales from seasonal to a century. The primary focus of CLIVAR is on the atmosphere and the ocean and their interactions, which recognises the complementary role with regards to other parts of the World Climate Research Programme (WCRP) such as GEWEX, and the International Geosphere Biosphere Programme (IGBP).

The overall scientific objectives of CLIVAR, as stated in the Science Plan, are to:

- Describe and understand the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal, and centennial time scales, through the collection and analysis of observations and the development and application of models of the coupled climate system, in co-operation with other relevant climate research and observing programmes;
- Extend the record of climate variability over the time scales of interest through the assembly of quality-controlled paleoclimatic and instrumental data sets;
- Extend the range and accuracy of seasonal to interannual climate prediction through the development of global coupled predictive models;
- Understand and predict the response of the climate system to increases of radiatively active gases and aerosols and to compare these predictions to the observed climate record in order to detect the anthropogenic modification of the natural climate signal.

Since the publication of the Science Plan, the international scientific community has been engaged by CLIVAR in exploring how best to proceed in addressing the scientific questions and in developing a strategy for implementing observations, data set development, empirical studies, model development and numerical experimentation, and process studies. The challenge has been to find the critical areas in which co-ordination and international infrastructure could make the research endeavours more effective and focused.

The proposals and plans presented in this document reflect the scientific communities' assessment of the major outstanding scientific questions, the state of knowledge, the prospects for advances, the technical feasibility and costs of proposed projects, probabilities for multiple pay-offs, possible collaboration with other programmes, an effective balance of activities, and importance of the projects' success for society.

This document synthesises the results of the many international workshops sponsored by CLIVAR, as well as through more regional and national workshops and meetings. The CLIVAR Scientific Steering Group (SSG) has also established a number of panels and working groups to provide continued direction in particular areas. These panels, working groups and ad hoc writing teams, along with the CLIVAR SSG, developed the material for the Implementation Plan. A list of meetings that has led to the publication of this CLIVAR Initial Implementation Plan is given in Appendix 2. It is important to realise the depth of involvement of the scientific community in pursuing the CLIVAR implementation plan development, and this will continue as nations respond to this initial plan.

## **2. CLIVAR SCOPE AND APPROACH**

CLIVAR is a big programme by any standards. It not only deals with variability and predictability on the global domain and covers all timescales from seasonal to centennial but also includes anthropogenic climate change detection and prediction. In contrast, TOGA, which has been a very successful WCRP programme and therefore perhaps one worth emulating, ended up focusing on the variability and predictability in just the tropical Pacific Ocean associated with ENSO. CLIVAR encompasses the domain of TOGA and extends to the other tropical oceans as well as to the extra-tropics of both hemispheres. In addition it extends the time domain from seasonal-to-interannual up to centennial. It has been stated that CLIVAR is maybe ten TOGAs in terms of its scope, implementation and planning needs. The initial TOGA plan was to deal with all the tropical oceans. This did not happen in part because of the dominance and importance of the ENSO phenomenon in tropical variability, but also because of funding, resource and personnel limitations. These limitations still exist and must be recognised, so that a phased approach is essential for focused projects within CLIVAR, called the Principal Research Areas (PRAs).

In August 1997, CLIVAR published a summary of this Initial Implementation Plan “CLIVAR: A Research Programme on Climate Variability and Predictability for the 21st Century” (WCRP, 1997). It provides some elaboration of the objectives and requirements of the three streams of CLIVAR, the Global Ocean Atmosphere Land System (GOALS), Decadal to Centennial Climate Variability (DecCen) and Anthropogenic Climate Change (ACC), all closely linked across geographical regions and with overlapping time scales. It also identifies and discusses common themes and approaches of global analysis and modelling activities that provide the unifying framework through which CLIVAR will be implemented.

These include

- Predictability and prediction
- Global modelling
- Downscaling
- Global sustained observations
- Improved historical data
- Paleoclimate data and modelling
- Reanalysis
- Empirical studies.

These are schematically illustrated in Figure 1 and described more fully in Section II. The summary further introduces the principal research areas which are individual regional focus programmes.

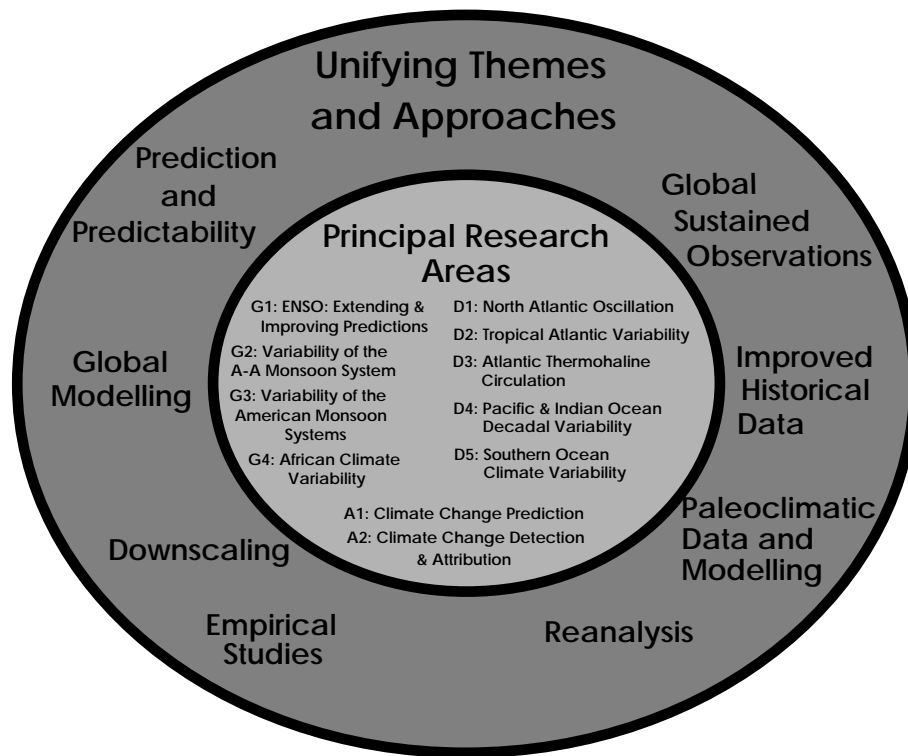


Fig. 1: Elements of the CLIVAR programme.

### 3. THE CLIVAR PRINCIPAL RESEARCH AREAS

The SSG has approved the choice of nine principal research areas with “natural” phenomena at their respective cores and two directed anthropogenic climate change that have been identified to facilitate the implementation of CLIVAR. Each principal research area is distinct, in its aims, phenomenological base, geographical region of interest, and even scientific approach required. The advantages of considering phenomena as the primary foci of CLIVAR research are considerable, including providing a high potential for strong interaction among the components of CLIVAR and a clear route to removing the distinction between the time scales that was introduced at the beginning of CLIVAR to facilitate its early growth from its foundation programmes. As stated in the Science Plan, the ultimate goal of CLIVAR is to develop a comprehensive and cohesive programme which spans all the scales of interest.

Much of this Implementation Plan addresses these principal research areas, their scientific rationale, analysis and modelling needs, observational requirements and focused areas of research as well as their linkages to each other, CLIVAR in general and the rest of the WCRP.

#### GOALS

The four principal research areas that have been identified in the GOALS component of CLIVAR are:

- ENSO: Extending and Improving Predictions (G1):  
Advancing understanding and observations of climate variability associated with El Niño - Southern Oscillation (ENSO) and global teleconnections to improve prediction and applications.
- Variability of the Asian - Australian Monsoon (G2):  
Developing better understanding of the mechanisms of interannual and interseasonal variations



## *I. Overview*

of the Asian-Australian monsoon and to improve their prediction.

- **Variability of the American Monsoon Systems (G3):**  
Developing better understanding of the Pan American monsoon, its interannual variations, and its origin and links to the Pacific and Atlantic.
- **African Climate Variability (G4):**  
Initiating studies of the interannual variability and predictability of the African climate and the dependence on SST changes to improve predictions of African climate.

## *DecCen*

The five principal research areas identified for the DecCen component of CLIVAR are:

- **The North Atlantic Oscillation (D1):**  
Improving the description and understanding of decadal ocean and atmosphere variability in the North Atlantic region involving the North Atlantic Oscillation.
- **Tropical Atlantic Variability (D2):**  
Improving the description and understanding of the patterns of decadal variability originating in the tropical Atlantic.
- **Atlantic Thermohaline Circulation (D3):**  
Improving the description and understanding of decadal to centennial variability and the possibilities of rapid climate change associated with the Atlantic thermohaline circulation.
- **Pacific and Indian Ocean Decadal Variability (D4):**  
Improving the description and understanding of the decadal variability and its predictability in the Pacific and Indian Ocean basins, and its relationship with ENSO and teleconnections.
- **Southern Ocean Climate Variability (D5):**  
Improving the description and understanding of the variability of the Antarctic Circumpolar Current, ocean overturning and water mass transformations in the Southern Oceans.

## *ACC*

The two principal research areas identified for the ACC component of CLIVAR are:

- **Climate Change Prediction (A1):**  
Improving prediction through the use of coupled climate models of the likely climate change in response to scenarios of effects of future human activities.
- **Climate Change Detection and Attribution (A2):**  
Detecting and attributing anthropogenic climate change in the presence of the natural variability of the climate system.

Figure 2 shows the overlap that exists between the three streams of CLIVAR through common modes of variability and across broad time-scale bands. Clearly then, close relationships will exist, for example, between projects aimed at improving ENSO-related predictions (G1), predicting the interannual variability of the Asian-Australian Monsoon (G2), and understanding of the causes of decadal variability in the Indo-Pacific region (D4). The modes of variability associated with G2 and D4 also affect ENSO, therefore a bet-

ter characterisation of their influence will help ENSO prediction. All three, in turn, must be taken into consideration in the detection and attribution of climate change (A2). A better characterisation and understanding of variability is essential in order to detect the anthropogenic signal over the “noise” of natural climatic variability. The Principal Research Areas are discussed more fully in Section III.

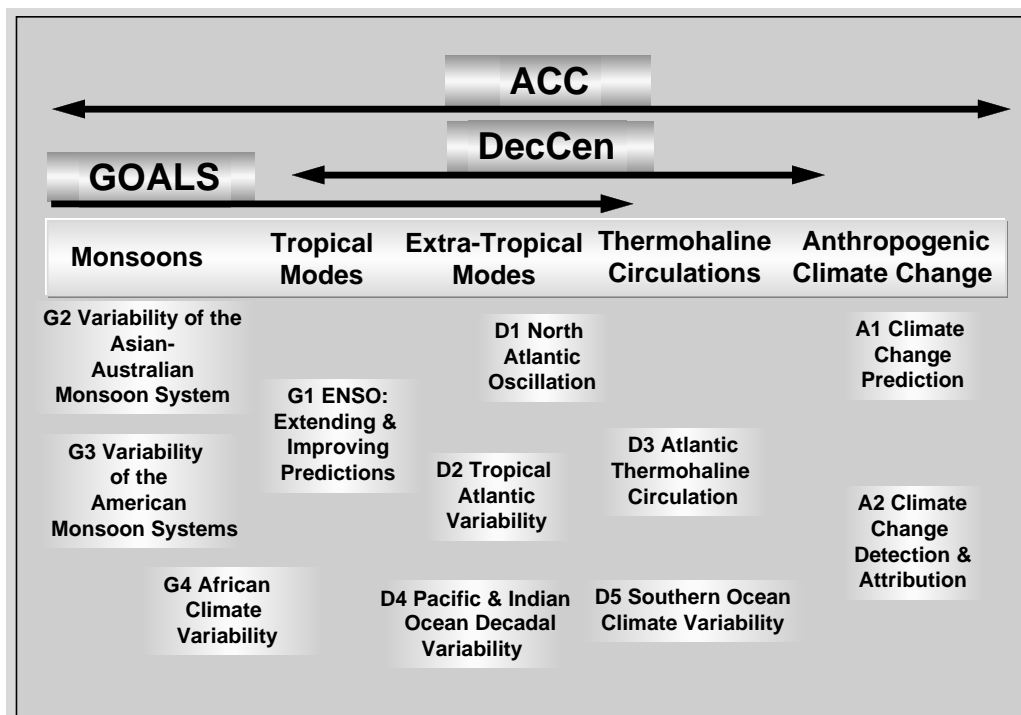


Fig.2: The CLIVAR Principal Research Areas

To integrate these focused activities, CLIVAR will maintain healthy cross-cutting programmes of global modelling, empirical, analytical and diagnostic studies and will develop project-oriented data sets (Section II). The ability to work within the larger framework will be critical to an effective implementation of the principal research areas.

#### 4. CONSIDERATIONS IN DEVELOPING PRIORITIES

The CLIVAR Scientific and CLIVAR Initial Implementation Plans have been written by scientists. They have used their understanding of both the science of climate variability and predictability and the technical feasibility of various proposed approaches to make choices and to arrive at the existing plan. CLIVAR is proposing tasks that require international co-operation to achieve objectives that would be difficult for an individual nation to accomplish through its own resources. Now it is the opportunity for nations to decide where they are prepared to invest their resources in support of CLIVAR activities. The International CLIVAR Conference at UNESCO, Paris, 1-4 December 1998, will collect expressions of interest from nations. On the basis of these national contributions, the CLIVAR SSG and its subsidiary panels will begin to implement CLIVAR. This section outlines the factors that have been and will be considered in developing priorities for CLIVAR implementation.

Priorities mean different things to different people, a point which must be recognised. Often priorities are expressed in terms of needs, such as the societal need to have information on climate change at local and regional scales. But whether this is feasible or not must also be a key consideration. Realistic priorities

## *I. Overview*

must take into account the readiness and feasibility of the possibilities. Even then, priorities may differ depending upon whether they refer to the most important topic, the area where there is most activity, or the area where there is the greatest need for international co-ordination and collaboration.

In setting priorities, assumptions are always involved and should be stated as explicitly as possible. A change in these underlying assumptions can completely change priorities. The assumptions include broad statements about funds available, people and ships available, remoteness and logistical aspects, whether satellites will be launched and succeed, collaboration among countries, whether one can rely and on the availability of basic observations under a GCOS or from the World Weather Watch network for weather prediction and build from there, access to and use of data archive facilities, and so on.

The SSG adopted guidelines to assist CLIVAR implementation workshops and panels to contribute to the development of the CLIVAR Initial Implementation Plan:

- (i) The aim is to go beyond the Science Plan by making concrete proposals for observations, process studies and modelling.
- (ii) A “wish list” of possible projects is not sufficient. Workshop recommendations must aim to contribute towards formulation of a realistic overall programme by:
  - defining project foci
  - setting priorities
  - recommending appropriate timetables and sequence of requirements.
- (iii) In setting priorities, the workshops should take into account:
  - scientific justification and rationale which must related to the CLIVAR objectives as stated in the Science Plan
  - readiness
  - feasibility - including technical and cost aspects
  - probabilities for multiple “pay-offs”, i.e. formulate hypotheses to provide focus, but design programmes so that even if these are not supported, there are substantial gains, for instance, in advancement in understanding, improved models, etc.
  - collaboration with other programmes
  - balance of activities (field programmes, background observations, modelling, empirical studies)
  - contributions to more than one CLIVAR sub-programme (GOALS, DecCen and ACC).

The SSG also agreed that, wherever possible, CLIVAR would use existing mechanisms to co-ordinate its observational and data collection, distribution and archiving programmes. The CLIVAR SSG wants GCOS/GOOS to play a major role in the implementation and operation of these components of the CLIVAR programme.

In drafting each section of the Implementation Plan, the authors were asked to consider:

1. What is now being done (that can be built upon)?
2. What would be a modest enhancement of that (and thus doable)?

## 3. What is really quite new?

- What kind of resources would be needed to bring this about?
- Consider specifically people, ship time, and funding resources.
- And thus give some sense of feasibility.
- If priorities can be set among various options within a project area, then that should be done.

These questions, if addressed, would help to bring certain things to the fore. They provide a basis for setting priorities. A key thing to recognise is that each Principal Research Area is at a somewhat different stage, some play off of activities such as TOGA and WOCE that exist, others are starting almost from scratch. We must recognise this up front and not make expectations unrealistic for all sections. Also, it is not clear that agencies and countries will want a frontal attack on all problems at once.

The following principles, as agreed to by the SSG, are put forward:

- For CLIVAR a phased or staged approach is the only practical way to proceed.
- Some level of activity is desirable in all areas, so that they can mature and become a fully active subsequently.
- Certain projects should receive more attention for focused activity at various times.

It is important to realise that the Principal Research Areas are focused projects and they are not intended to be exclusionary. Moreover, they take place in the context of the global modelling, empirical and diagnostic studies, observations, and dataset development (Section II). Consideration of the points raised above should make the priorities more apparent. Assigning priorities is not yet done, although it comes partly out of readiness. An assessment of the status of the CLIVAR Principal Research Areas as of mid-1998 is given in subsection 12 of Section III.

## 5. CLIVAR IMPLEMENTATION

This full CLIVAR Initial Implementation Plan lays out aspects related to implementation. However, in many respects it is more a strategic plan of action rather than a detailed implementation plan, in part because the WCRP and CLIVAR do not have funds to implement anything. That has to be done by participating countries, as noted above.

The name "Initial" Implementation Plan recognises the iterative nature of the process we are engaged in. A key step is the International CLIVAR Conference in Paris at UNESCO 1-4 December 1998. Many scientists have been involved in developing the plan but it is only as the CLIVAR Initial Implementation Plan is circulated that the plan as a whole is available for review and comment by the entire community. The Implementation Plan will be updated as required, as nations undertake to carry out parts of the plan and as scientific advances and new knowledge and understanding lead to modifications. It is anticipated that throughout the next few years, separate implementation plans will be produced for many of the principal research areas. Where these involve field studies, further detailed action plans will be required.

It is expected that major CLIVAR scientific conferences will be held at approximately five year intervals to review progress to date and to set new directions and fresh priorities.

The development of CLIVAR is the responsibility of the CLIVAR Scientific Steering Group (SSG) which is appointed by the WMO/ICSU/IOC Joint Scientific Committee of the World Climate Research Programme and to which it reports. The SSG is supported by a permanent International Project Office. To fur-

## *I. Overview*

ther its work the SSG has a number of subcommittees and panels addressing various aspects of the programme. A more detailed description of the organisational structure of CLIVAR is given in Appendix 3.

The following section (Section II) of this document addresses a number of the common integrating themes and approaches, the sustained observations required for CLIVAR research, and the infrastructure needed for CLIVAR implementation and management. This is followed in Section III by descriptions of the principal research areas with their implementation requirements. That some are presented in more detail than others is an indication of their current state of development within CLIVAR. The final subsection provides a brief assessment of the current (mid-1998) status of the CLIVAR Principal Research Areas in terms of their feasibility and readiness as a basis for helping to set priorities.

CLIVAR will ultimately be judged on how effective it is in mounting a coherent programme of enhanced observations, modelling, analysis and prediction, since that is the only road to success. This document proposes a number of possible approaches for constructing such a programme. Its actual implementation depends on the will and resources brought to bear by the scientists, institutions, agencies and governments of the world.

## **II. UNIFYING THEMES AND APPROACHES**

### **1. GLOBAL FRAMEWORK FOR CLIVAR**

The World Climate Research Programme (WCRP) at the 14th session (March 1993) of the Joint Scientific Committee established the 15 year CLIVAR programme to focus on the variability of the “slow” climate system. Accordingly, it is the primary WCRP programme for the study of the role of the ocean in the coupled climate system. It builds on the successes of TOGA on interannual timescales and WOCE on longer timescales, and as the response by the WCRP to the scientific assessment for the study of Anthropogenic Climate Change (ACC) of the IPCC.

The understanding of seasonal and interannual variations in climate has made enormous strides over the past decade or so, largely because of the TOGA programme. TOGA led to the development of a new capability for observing the surface and upper ocean and atmosphere in real time, methods of analysis and diagnosis, publication of various kinds of ongoing assessments in bulletins and various media, and the development of models that can replicate El Niño-Southern Oscillation (ENSO) with varying degrees of verisimilitude and which can be used for prediction along with various statistical techniques. A new depth of understanding of the ENSO phenomenon has been achieved. One key result from TOGA has been the demonstration that the coupled tropical Pacific is predictable up to at least a year in advance. Thus TOGA initiated experimental predictions of ENSO fluctuations. The scientific challenge is to capitalise on our understanding of ENSO and make seasonal predictions of the mean and variability of temperature and rainfall and how the risk of extremes changes. The heritage of TOGA provides an incentive for building infrastructure to capitalise on these beginnings because of the great potential for socio-economic benefits in many countries.

The Earth's climate record is a convolution of both natural variability and anthropogenic change. In that sense the CLIVAR-DecCen and ACC components are opposite sides of the same coin. CLIVAR-DecCen will focus on understanding of the physics of decadal and longer variability of the coupled climate system. Because ocean processes are very important on these time-scales, and because so little is known about their role, DecCen will initially make a special effort to explore the role of the ocean in determining climate variability on the time-scales of interest and thereby build on the WOCE Programme. CLIVAR-ACC will co-ordinate data analysis and climate modelling studies directed at the detection, attribution, and prediction of climate change due to human activity, and thereby build upon the IPCC second assessment report, while providing a solid research framework for future assessments.

CLIVAR is a programme with a projected life of 15 years. Accordingly, after CLIVAR is over there will at most be a 15 year extension of the climate record and, in places where new observations have begun, this will be the maximum record length possible.

On seasonal-to-interannual timescales, each additional year builds the experience base for short-term climate forecasts. The 1997-98 El Niño event has clearly demonstrated the huge variety of nature and emphasised that every El Niño is different from every other one. The observational record is not as long as desirable, especially for empirical or statistical forecasts, but also as an experience base for improving and testing forecasts based on dynamical models. It emphasises the need to exploit all the data available on past events by building databases and reanalysing data into global fields.

For decadal variability, the task is even more daunting. It is not possible to rely on instrumental observations to provide an adequate base for describing the full range of decadal variability, although quality controlled paleoclimatic reconstructions show promise of being invaluable in this regard. Even then, understanding the inferred climate variations depends critically on also knowing the climate forcings. Nevertheless, the likelihood of climate change means that future climates are apt to be different than anything in the experience base which may confound the interpretation of the new observations.

## *II. Unifying Themes and Approaches*

Clearly, all CLIVAR components require strong efforts in data archaeology and paleoclimatic activities to extend the climate record to the past, support and extend climate data collection programmes to continue the records into the future, and data analysis and modelling studies to describe, simulate, and predict climate variability on decadal to century time scales.

Moreover, the only viable strategy for dealing with decadal and longer time-scale variations and climate change is to analyse observations to improve understanding of processes sufficiently that we can build global climate models in which there is enough confidence in their ability to replicate the physical climate system in all of its manifestations, including means, variability and extremes. These models can then be used to explore the full range of natural variability in the absence of external forcings as well as the response to perturbations from changes in solar output, volcanic eruptions, and human influences such as from changes in land use and atmospheric composition. Such models can potentially be used for predictions and planning purposes.

Embedded within the climate variability are natural modes of coupled climate system behaviour such as ENSO and patterns of behaviour, such as the North Atlantic Oscillation. The latter may be primarily an atmospheric mode or it may have aspects of behaviour that depend on interactions of the atmosphere with the ocean and/or land surface. Because there are reasons to suspect that the climate system response to external perturbations may occur through these natural modes, it is important to further our understanding and improve our ability to model them. Because variations in these modes often have associated with them major changes in surface temperature, precipitation and storms, they are also of importance to society in their own right.

CLIVAR necessarily has to deal with the global aspects of climate variability. Accordingly, a global framework of modelling and analytical studies of globally distributed observations are essential for CLIVAR and provide the context for more regional or focused studies.

## **2. GLOBAL MODELLING AND PREDICTION**

In addition to providing an integrating modelling framework within the programme, CLIVAR's global modelling programme will work together with other modelling efforts within the WCRP and IGBP towards the construction of more comprehensive and efficient climate models that will in time provide more accurate predictions, more realistic simulations of past climates and ultimately, more confident scenarios of future climates.

### **2.1 ORGANISATION OF MODELLING WITHIN CLIVAR AND THE WCRP**

The development of global climate models is the main unifying component in the WCRP, building on the scientific and technical advances in the discipline-oriented activities. The output from such models are the fundamental “deliverables” from the whole WCRP, providing the basis for the understanding and prediction of (natural) climate variations on time scales from a season or two to a century or more and for projections of climate change that could result from either natural or anthropogenic causes. Models also offer the essential means of exploiting and synthesizing in a synergistic manner all relevant atmospheric, oceanographic, cryospheric and land observations collected in the WCRP and other programmes.

Modelling activities in the WCRP as a whole are organised around two main groups, namely the joint JSC/CAS Working Group on Numerical Experimentation (WGNE) and the joint JSC/CLIVAR Working Group on Coupled Modelling (WGCM). WGNE has the central responsibility for the development of the atmospheric component of climate models and works in close conjunction with the modelling and prediction thrust of GEWEX in the development of atmospheric model parameterisations, and maintains an overview of the development of model stratospheric simulations in SPARC. WGCM plays a fundamental role in CLIVAR (and the WCRP) in overseeing the development of the fully coupled atmosphere/ocean/land/cryosphere models needed for long-term climate simulations, studying climate variation on time scales from several years to a century and in providing projections of anthropogenic climate change. WGCM also keeps a broad overview of and co-ordinates other modelling activities within WCRP, important in the development of the full global coupled models and ensures the essential interface with the IPCC Scientific Assessment Working Group and the International Geosphere-Biosphere Programme (IGBP) Global Analysis Interpretation and Modelling (GAIM) element in the quest to develop fully comprehensive climate models (i.e. including representations of bio-geochemical processes as well as the physical climate system). Modelling activities in CLIVAR are also supported by a specific CLIVAR Numerical Experimentation Group (CLIVAR NEG-1) for dealing with questions of prediction and predictability on seasonal to interannual time scales. Although the models used in studying climate variability at different time scales are becoming increasingly similar, there is still a fundamental difference in the work of CLIVAR NEG-1 and WGCM. Notwithstanding, the CLIVAR strategy is to develop a common approach to climate problems across all time scales, and the intention is to gradually eliminate the distinction between the Groups and to form a single coherent modelling effort.

As noted elsewhere, the success of CLIVAR will depend on the results of each of the other WCRP projects, and this is especially true for modelling. In particular, CLIVAR will look to WGNE for the development of atmospheric models for use in climate studies on all time scales; the GEWEX Modelling and Prediction Panel (GMPP) is working in parallel to improve the representation of land-surface processes and clouds in these models; the WOCE modelling community will take on the task of combining the multiplicity of WOCE observational data sets into a dynamically consistent view of the global ocean circulation and improving the representation of ocean processes in climate models; the Sea-Ice/Ocean Modelling Panel under ACSYS is concerned with development, improvement and optimisation of parameterisations of land-surface/atmosphere/ocean interactions specific to the polar regions, as well as sea-ice dynamics and thermodynamics.



## 2.2 CLIMATE MODELLING ON SEASONAL TO INTERANNUAL TIME SCALES

The primary objective of the activities in this area undertaken by CLIVAR NEG-1 is to formulate and promote a programme of numerical experimentation using coupled ocean-atmosphere models for seasonal to interannual prediction and predictability studies and model validation in support of all the CLIVAR GOALS sub-elements, including ENSO prediction and studies of the monsoon. The development of data assimilation procedures for the initialisation of coupled models and assessing the adequacy of the CLIVAR observing system in support of CLIVAR-GOALS will also be concern of the Group.

As yet, much of the work simulating and predicting the seasonal to interannual climate variations associated with ENSO has focused on regional models of the equatorial Pacific. Increasingly, however, the need for global models is being recognised. Thus the influence of the Indian Ocean and the Asian-Australian monsoon on ENSO needs to be included in comprehensive numerical models, and models capable of including these effects are being developed. Eventually, models for simulating and predicting ENSO and its global impacts will need to be global, and very similar to the models used for climate change experiments. At the end of the TOGA programme, despite the definite improvements in modelling and prediction of seasonal climate anomalies, many questions, whose answers impact on the skill of seasonal to interannual predictions, remained unanswered. For example:

- What are the limits of ENSO-predictability?
- What are the underlying dynamics of the ENSO system. Is it a stochastically driven linear system or a low order non-linear system?
- What are the reasons for the variations in predictive skill over the annual cycle and from one decade to the next?
- What is a suitable ensemble prediction strategy?
- How do we extract information on a regional scale from the global models to make best use of the predictions?

To address these and other related questions, and to provide the integrating framework for the modelling initiatives to be conducted within the principal research area initiatives, NEG-1 is initially undertaking the following projects:

### 2.2.1 Current projects of NEG-1

#### 1. *Intercomparison of ENSO simulations in coupled models (ENSIP)*

This project will dovetail with the WGCM Coupled Model Intercomparison Project (CMIP) (see below), and will investigate the realism of simulations of ENSO events in both global regional domain coupled models.

#### 2. *Dynamical seasonal prediction*

This will be a co-ordinated modelling study to assess the predictability of seasonal mean circulation and rainfall up to a season in advance given the observed initial state of the climate system, and the most accurately observed surface boundary conditions possible.

3. *An intercomparison of simulations of monsoon variability and predictability or Seasonal Monsoon Intercomparison Project (SMIP)*

based on firstly an analysis of the summer ensemble cases in the dynamical seasonal prediction project from the perspective of the prediction and treatment of monsoon circulations, secondly an AMIP diagnostic sub-project on the representation of monsoonal circulations and their variability in the AMIP integrations, and thirdly a study of monsoons in integrations in the WGCM Coupled Model Intercomparison Project (CMIP) (see below).

4. *Improvement of initialisations and analyses for climate predictions*

This project will lead to more skilful forecasts on multi-seasonal time scales using coupled models. The strategy is to improve the ocean initial conditions and, in turn, the ocean analyses as a basis for validating and refining the ocean models used in the forecast process.

5. *Intercomparisons of specific predictions and estimates of predictability*

Various sea surface temperature anomaly hindcasts and predictions produced in operational, and experimental modes will be intercompared in order to assess the current level of skill and to provide a benchmark for the assessments of future progress.

6. *Intercomparison of ocean model simulations forced by wind stress products from reanalyses*

This project will compare the performance of tropical ocean models using wind-stress products of the reanalyses, and evaluate their capabilities using a variety of data sets for verification.

7. *Study of tropical oceans in climate models (STOIC)*

Tropical ocean behaviour in coupled ocean-atmosphere models will be compared on seasonal and interannual time scales, focusing on the Atlantic and Indian regions and investigating relationships with the Pacific region. In addition, in view of the global-scale of monsoon interactions, considerable emphasis will be placed on the simulation of monsoon variability and predictability as part of the CLIVAR global modelling integration strategy and in conjunction with the specific modelling proposals embodied within the individual monsoon programmes outlined above.

## 2.3 GLOBAL MODELLING ON SEASONAL TO CENTURY TIME SCALES

Numerical modelling of the fully coupled climate system is still in its infancy. This is primarily due to the immense complexity of the task and insufficient empirical knowledge of many aspects of climate related processes. This is not only the case for the oceans where the knowledge of the time-dependent deep ocean circulation is particularly poor, but also for example in the hydrological cycle where precipitation, evaporation and the three-dimensional distribution of water vapour and clouds are insufficiently known. We probably only know the global annual averaged precipitation within an accuracy of some 5-10%. Practically no reliable observations of precipitation exist over the oceans. At the same time, because of limited computing resources, the resolution of climate models has been very poor, often restricting horizontal resolution in the atmosphere to scales larger than 500 km (T40) or even 1000 km (T21 or R15). Experience from numerical weather prediction suggests that it may be necessary to increase the horizontal resolution to about 100-200 km, in order to properly resolve major orographic obstacles, to handle non-linear atmospheric dynamics and to obtain realistic parameters for the parameterisation of physical processes in the atmosphere. Clever ideas could perhaps alleviate the requirement for higher resolution in climate models, but these may emerge more slowly than the opportunities stemming from the present rapid speed of computer development? For ocean modelling the situation is even more serious. Numerical experiments suggest that horizontal resolutions down to 0.5° or so may be required to handle the El Niño phenomenon. Ocean eddies and sharp boundaries of major ocean currents may need even higher resolution. It is at least necessary to under-

take specific investigations on how to express such features in terms of large-scale parameters.

WGCM has the responsibility for trying to resolve these outstanding questions and problems and is defining a long-term strategy for the development of the appropriate coupled models to be used for, firstly, prediction of climate variability and, secondly, simulation of climate change resulting from natural or anthropogenic forcing. The Group will work to identify model shortcomings and quantify their influence on model simulations. Co-ordinated experimentation and studies will be organised to evaluate the climate response to internal, external and anthropogenic forcing separately or in combination. WGCM will also examine what other steps should be taken to assist in improving or validating climate models and predictions/simulations using these. This would involve improving access to additional data, especially paleo-data and development of new data sets (including better information on forcing). Other fundamental questions to be tackled are coupled model data assimilation and the detection and attribution of climate change (based on appropriate joint observational/modelling studies). WGCM will liaise with IPCC Working Group I as necessary, and, as the complexity of coupled models grows and additional processes are included, to explore and consider suitable joint efforts/studies with the Global Analysis, Interpretation and Modelling (GAIM) element of IGBP.

### 2.3.1 Current projects of WGCM

#### 1. *Coupled Model Intercomparison Project (CMIP)*

The first phase of CMIP (CMIP1), which began in 1996, is an intercomparison of the simulations of present climate from the control runs of coupled models, and includes specifically:

- a systematic documentation of errors in the control simulations of global coupled climate models (atmospheric, oceanic and cryospheric components);
- quantifying to the extent possible the effects of flux adjustment on simulations of mean climate and climate variability;
- documentation of simulated features of climate variability on a variety of time and space scales.

The second phase of CMIP (CMIP2), an intercomparison of global coupled model experiments of 80 years in length with atmospheric CO<sub>2</sub> increasing at a compound rate of 1% per year (i.e. CO<sub>2</sub> doubling at around year 70) has just begun. The goals of CMIP2 are:

- documentation of the mean response of the dynamically coupled climate system to a transient increase of CO<sub>2</sub> as simulated in models near the time of CO<sub>2</sub> doubling;
- documentation of features of the time evolution of the model-simulated response to gradually increasing CO<sub>2</sub>.
- quantifying to the extent possible the effects of flux adjustment on the model-simulated climate sensitivity;

#### 2. *Idealised sensitivity experiments*

The objective of this work is to estimate uncertainty in climate sensitivity linked to atmospheric feedbacks by examining results from available equilibrium doubled CO<sub>2</sub> experiments in which the atmosphere is coupled to a simplified slab ocean. Cloud-climate feedbacks continue to appear to be a major contribution to this uncertainty. WGCM will work with WGENE and GEWEX to consider aspects of these parameterisations which have a substantial effect on climate sensitivity and the use of observations where appropriate to constrain the range of these parameterisations.

3. *Standardised forcing scenarios*

In order to compare the model dependence of different projections of anthropogenic climate change, standardised experiments are required. WGCM keeps under review data sets of forcing parameters (CO<sub>2</sub>, sulphate aerosols, ozone, solar variations, volcanic dust) as produced from various sources and agrees on the most realistic scenarios to be used in standardised experiments. Recommendations in this area are considered in consultation with IPCC to ensure their acceptability and appropriateness in this context.

4. *Initialisation of coupled models for use in climate studies*

WGCM keeps under review the initialisations of coupled models as used by various groups: the challenge is to provide appropriate initial conditions so that the climate drift is minimised, the initial atmospheric and oceanic conditions are as realistic as possible, and that the initialisation scheme is not prohibitively expensive in terms of computer resources. Research to provide a more satisfactory basis for consistent initialisation of coupled models is needed. Initialisation and running models without flux adjustments in order to assess climate drift in these circumstances is being encouraged. (The use of flux adjustments acts to conceal climate drift and thus may conceal model errors contributing to the problems).

5. *Ocean model development and intercomparisons*

The shortcomings in the ocean component of coupled climate models are being investigated. The lack of realism in the representation of various ocean processes in the current generation of coarse resolution ocean components may well affect the capability of simulating the dynamics of the coupled ocean-atmosphere system on interannual to interdecadal time scales.

Specific objectives are to:

- assess how well different aspects of ocean dynamics need to be represented in order to achieve realistic simulations of the ocean's role in climate variability on decadal time scales;
- to develop benchmark data sets for quantitative model tests.

Long-term integrations with high resolution coupled models are also needed and the results and detailed simulation of the ocean and its variability compared with results from a coarse resolution model to identify discrepancies in the main parameters (ocean transports, eddy activity, etc.). Additionally, observations of time-dependent penetration into the ocean of bomb carbon and of chloro-fluoro carbons will be used as a means of evaluating the representation of ocean-only and coupled model mixing processes in the ocean.

6. *Detection and attribution of climate change*

WGCM will promote the use of modelling results as a means of identifying potential signals of climate change. Long-term (multi-century) integrations of climate models are needed to provide estimates of natural variability (since length of the instrumental record is too short and contaminated by natural and human factors). However, simulations of decadal and longer time scale variability have to be improved if confidence is to be placed in model estimates of this variability as a basis for detecting and attributing variations in the observed record to climate change.

7. *Paleoclimatic modelling*

Model simulations of extreme periods such as the mid-Holocene (6000 years BP) and the last glacial maximum are a valuable independent test of model validity and check of model sensitivity and have been organised as part of the 'Paleoclimate Modelling Intercomparison Project' (PMIP). Other opportunities for using paleoclimatic data to quantify climate variability and to verify model

simulations need to be investigated. In particular, abrupt events such as the 8000 year BP and Younger-Dryas oscillations could throw significant light on mechanisms of decadal variability and the role of the thermohaline circulation. Paleoclimatic modelling also provides an important link between CLIVAR and the study of past climatic changes under PAGES, helping both improve our knowledge of the mechanisms of natural variability on the decadal to centennial time scale and to evaluate the capabilities of climate models to reproduce climate conditions different from today.

8. *Atmosphere-ocean predictability on decadal time scales*

Co-ordinated studies of predictability of the coupled atmosphere-ocean system on decadal time scales as may be apparent in model simulations will be undertaken using 'potential predictability' or classical 'perfect model' approaches (in conjunction with CLIVAR NEG-1).

9. *Development of comprehensive models of the full climate system*

Comprehensive models of the full climate system (including the biosphere and atmospheric chemistry) will certainly be needed to improve estimates of anthropogenic climate change, and several groups are already taking steps in this direction. In co-operation with IGBP/GAIM, attention will be given to the incorporation of appropriate biogeochemical processes into the constructs of the Earth's physical climate system. Simple aerosol models are already being used in a number of climate change assessment studies. A priority requirement is to include the carbon cycle in climate change integrations, in particular to evaluate the maintenance and stability of the higher level of CO<sub>2</sub> equilibrium concentrations foreseen in the future.

In addition to providing an integrating modelling framework within the programme, CLIVAR's global modelling programme will work together with other modelling efforts within the WCRP and IGBP towards the construction of more comprehensive and efficient climate models that will in time provide more accurate predictions, more realistic simulations of past climates and ultimately, more confident scenarios of future climates.

## 2.4 PALEOCLIMATE MODELLING

Paleoclimate modelling provides an important link between CLIVAR and the study of past climatic changes under PAGES. This approach both helps to improve our knowledge of the mechanisms of natural variability on the decadal to centennial time scale and to evaluate the capabilities of climate models to reproduce climate conditions different from today. Note that WGCM includes paleoclimate activities as noted above. Three areas will act to focus the modelling on paleoclimatic time scales over the next few years under CLIVAR

1. *The climate of the last millennium*

The simulation of the natural variability of climate over the last centuries up to the last millennium is a key task for coupled atmosphere-ocean general circulation models. Such long runs are beginning to be available and their number, resp. length will increase in the coming years with increasing computing power. Their evaluation will then be a challenge to the paleodata scientific community. To emphasise the purposes of CLIVAR's decadal to centennial thrust, an annual, and whenever possible subannual, resolution will be employed. Spatial resolution is also needed with a particular emphasis on the reconstruction of large-scale patterns (such as the ENSO/PNA/NAO) and their variability during the last 1000 years. Major uncertainties will arise from unknown forcing factors such as past solar forcing and past volcanisms, which may have played a role in the centennial scale variability and will therefore need to be better constrained from proxy-data.

## 2. The simulation of significantly different equilibrium climate states

This is an important way of evaluating climate models under different climates, such as the mid-Holocene (6000 years BP) and the last glacial maximum (21000 years BP), and such work has been conducted under the Paleoclimate Modelling Intercomparison Project (e.g. Fig. 3). In the coming years this methodology, which is restricted to a few key periods, will be extended to coupled atmosphere-ocean models and will complement the evaluation of such models. This evaluation requires the development of data syntheses under the PAGES/CLIVAR initiatives using multi-proxy approaches (see Section 5.3). Information on the past 10-100 year variability during such extreme events, for example using fossil corals, ice cores or tree-rings, will also help to evaluate the decadal to centennial variability of the past. On this time scale, biospheric changes are important. Coupled atmosphere-biosphere models under development will also complement the use of coupled atmosphere-ocean models and will help to improve our understanding of the feedbacks associated with major hydrological changes, e.g. during the mid-Holocene. This effort will strongly benefit from the reconstruction of biomes undergone within IGBP/GAIM (Biome 6000 project).

## 3. Abrupt events of the glacial and Holocene climates.

Abrupt events during the Holocene and glacial climates, such as the 8000 year BP, the Younger Dryas/glacial oscillations and Heinrich events, are important for understanding the transient response of the coupled system on the decadal to centennial time scale and, more especially the role of the thermohaline circulation. However, in a first step, modelling studies will be restricted to process studies using a hierarchy of climate models. Indeed, realistic simulations of individual events using coupled atmosphere-ocean models will first require a better knowledge of the forcing and initial conditions.

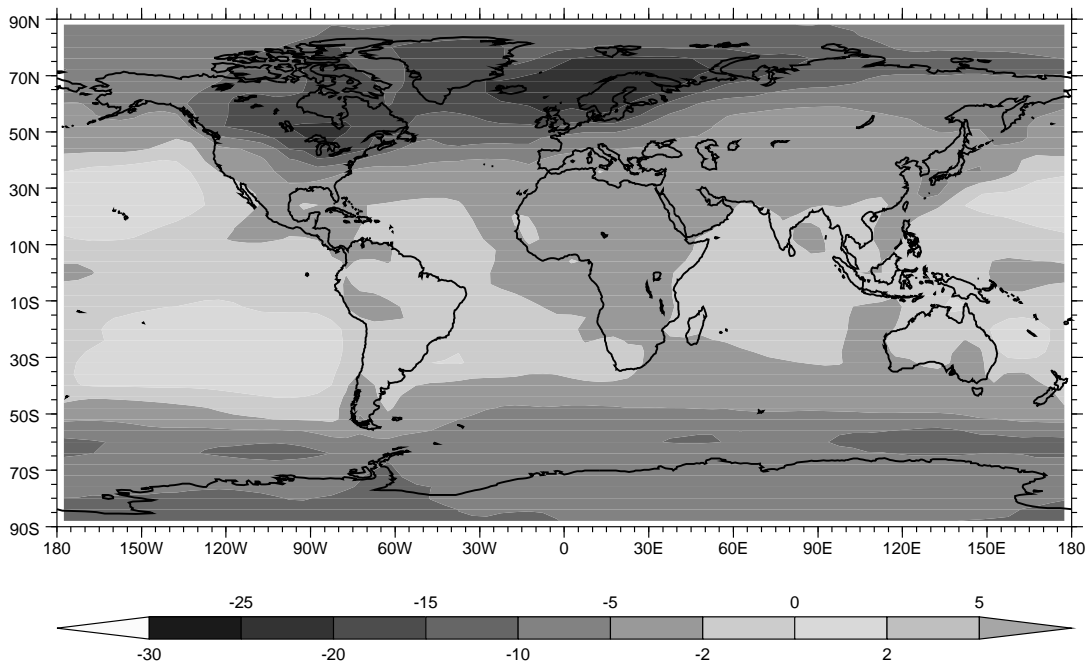


Fig. 3: Annual averaged difference in surface air temperature simulated for the climatic conditions of the Last Glacial Maximum, 21000 years before present, by seven climate models participating to the Paleoclimate Modelling Intercomparison Project (PMIP). The seven models have been run under the same identical changes in boundary conditions, i.e. glacial ice sheets,  $\text{CO}_2$ , changes in sea surface temperature and sea ice extent estimated from proxy data as well as small changes in the Earth's orbital parameters. Results from the seven models have been averaged on a common coarse grid (from Joussaume and Taylor, 1995).

## **2.5 DOWNSCALING**

A general problem facing climate modelling is that, although models will become more comprehensive in their coverage of spatial and temporal scales through the CLIVAR programme, their utility in predicting climate variations and change at the highly-detailed spatial scales required to predict impacts on society will remain constrained by computing power.

Although computing power will continue to improve, the need to incorporate more complex physical interactions (e.g. with the land surface) in the global models will continue to preclude running these models at the very high resolution needed for impact studies. So, there will be a continuing requirement for methods to “downscale” the model predictions from the relatively coarse grids of the global models, to the high spatial resolution required for impacts studies. This requirement is well understood for climate change experiments, but also exists for ENSO prediction and shorter time scales.

So, for the foreseeable future methods will be needed to “downscale” from the broad-scale climate predictions to the detailed spatial scales required by users of the predictions. Two approaches have been used in such “downscaling”. The first nests a high-resolution atmospheric model within the broader-scale coupled model. The nested model can run at higher resolution, forced by the broad-scale predictions from the broader-scale model, and provide a physically based interpolation to the spatial scales required by users, although at considerable expense. Alternatively, statistical schemes relating high-resolution climate variations to the broader predictions from the coupled model can be developed. Such approaches have been commonplace in weather prediction models in recent decades. They require extensive integrations of the model under current climate conditions, along with high-quality and high-resolution climate observations. As well, their use requires assumptions about whether climate variables in the future will be related similarly to current circumstances. They are, however, cheaper than the use of nested models.

Downscaling, by either of these methods or by a combination approach, will be required for predictions at all time scales, from the seasonal to climate change, and is a common problem over the range of CLIVAR time scales, streams, and principal research areas.

## **2.6 COMPUTATIONAL REQUIREMENTS FOR THE CLIVAR NUMERICAL EXPERIMENTATION PROGRAMME**

Numerical modelling experimentation is playing and will continue to play a key role for all components of the CLIVAR programme; GOALS, DecCen and ACC, as well as the focused Principal Research Areas. The extraordinary computational requirement for CLIVAR was identified from the outset. The modelling component was seen as a distinct pathfinder in formulating both prediction and simulation studies and for the support of field experiments and design of observational systems. Fully coupled climate models at high resolution were anticipated to play the same role for CLIVAR as the atmospheric modelling and prediction once supported GARP. Computational requirements as a whole can be arranged in three different groups:

Firstly, it will be necessary to make very long integrations, and at higher resolution than currently practical. In the case of DecCen and ACC, the integrations will have to be extended over several hundred years or longer. A number of such integrations will have to be undertaken by realistic models ultimately using horizontal resolutions of at least 1-2 deg lat./lon. (or equivalent in spectral resolution). Vertical resolution must also be high and encompass the stratosphere and sometimes the mesosphere, both of which need to be considered as an integrated part of the climate system on very long time scales. Such a resolution is higher by at least a factor of two compared to what is done presently. The reason is that many studies suggest that this higher resolution is needed for a realistic description of the evolution of characteristic synoptic systems and hence the interaction of these systems with the quasi-permanent centres of action and the feedback with ocean and land surfaces through surface fluxes.

Except for specific studies it is not anticipated that it will be required to have fully eddy-resolving ocean models, but horizontal resolutions of 0.5-0.25 deg lat./lon. will be required, again higher by a factor of two or so over what is presently being done in long climate integrations. However, this question needs to be revisited at a later time, when more experience is available.

Secondly, computational requirements will be high due to need for a large number of numerical experiments in the research mode. Based on the experience in medium-range prediction, systematic development and evaluation of model improvements require a wide range of experiments to encompass a broad range of atmosphere circulation types and different model parameter possibilities. Common experience suggests that improvements in processes do not necessarily immediately translate into improved performance of the model as a whole. Thus it is expected that model development, in particular on longer time scales, requires additional numerical experimentation and validation to assure a solid base for judging the merit of a model improvement. For a sound research programme, it is recommended that the order of 25-50% of the total computational resources of an individual research group should be allocated for model developments and testing.

Thirdly, climate change experiments require ensemble predictions. This is a new and important aspect which adds considerably to the computational need. Ensemble prediction has already been implemented operationally in medium-range weather forecasting and seems to be a necessary principle to follow also in climate prediction on all time scales, whether seasonal predictions of El Niño or projections of greenhouse gas-induced climate change. It provides a useful methodology enabling separation of signal (the common component to all ensemble members) from noise (the varying component) in long integrations. Climate prediction and simulation will always contain unpredictable components, which need to be properly identified in order to make these integrations practically useful. The size of a suitable ensembles will depend on the actual problem, but 5 - 10 is probably a minimal estimate and there are indications that double these numbers may not be enough at times because the need is to approximate the probability density function of the possible outcomes.

Finally, there are a number of additional problems, some of them related to the initialisation of coupled models, which are excessively computational demanding. Presently, these problems are handled on an ad hoc basis since sufficient computing power is not available. However, it may well happen that we may be able to initialise the coupled system in a way analogous to what is being done for the atmosphere, that is as a true initial value problem. Nevertheless, it is important to assure that proper resources will be made available for coupled model data-assimilation and initialisation.

CLIVAR does not maintain any form of common computational resource. Consequently, it is expected that nations will provide adequate computing to carry out the CLIVAR research agenda and to allow groups to participate in intercomparisons and other CLIVAR projects. It is apparent that the CLIVAR programme will require an overall enhancement in computational resources in most groups by a factor of 10-50 over the next few years to provide a serious contribution to the CLIVAR modelling programme. This means that the requirements for leading research groups should be increased to the order of a few hundred Gigaflops/sec. sustained overall performance, growing again by a factor of 5-10 over the next five years. Data handling resources must also be enhanced accordingly in order to match the computational facilities.

Of course this does not mean that smaller groups or groups with fewer computational resources can not contribute, as there is ample scope for regional model development and application, and more specialised process-oriented research with models. However, careful selection of the problems to be undertaken will be necessary for results to be robust and useful.

The above may seem as exhaustive requirements. Nevertheless, the climate modelling community not only needs this capacity, but it is generally also capable of using it soundly and efficiently. Otherwise, it will not be possible to carry through the CLIVAR numerical experimentation programme in a convincing way and the provision of sound guidance for the CLIVAR observational programmes will be severely hampered and progress in CLIVAR will be delayed.



## *II. Unifying Themes and Approaches*

### 3. GLOBAL-SCALE EMPIRICAL, ANALYTICAL AND DIAGNOSTIC STUDIES

Empirical studies and diagnostic analyses will be carried out to improve our ability to “describe and understand” what is occurring in nature and how such knowledge may be used to improve models. Empirical studies describe phenomenological relationships within fields and among fields of different variables, both in time and space. Diagnostic studies include quantitative analyses of processes and budgets of physical quantities that are conserved, and extend beyond empirical relationships. Both approaches should be concerned with the forcings of the atmosphere; the responses of the atmosphere and the ocean; the linkages, both local and remote, between the forcings and the responses; and the feedbacks.

CLIVAR empirical studies will improve the knowledge of the observational record, enhance our capabilities to make seasonal-to-interannual forecasts, improve understanding of decadal and longer-term variability and the processes involved in bringing it about, and improve the determination of the forcings of the climate system. Such studies encompass a broad spectrum of activities ranging from investigations that search for empirical relationships with predictive value to investigations intended to produce better understanding of processes and which thereby make improved parameterisations for models possible.

Empirical studies also provide a means of analysing model results and making comparisons with the observed record. The use of the “fingerprint” approach for the detection and attribution of climate change provides an example (see A2). Similarly, in some cases the most appropriate technique for determining physical fields is through the assimilation of data into models. An example is provided by the use of NWP models that assimilate a variety of *in situ* and satellite data. These products need to be evaluated but then can be used in empirical studies.

For the most part, empirical and diagnostic studies are carried out by individual researchers or small teams, and require little international co-ordination. Nevertheless, they are an important aspect of climate research providing a connection and some balance between the activities of modelling and observational programmes. They have an important role to play in CLIVAR.

Some foci for CLIVAR empirical studies:

- The observed record:

Re-appraisals of the observed record will continue. These are made possible by the availability of new data sets, such as the reanalysis data sets, better quality control and recovery of past data that upgrade and extend the data base, and new techniques for processing and mapping the information into global fields.

- Structures:

Proven and innovative analysis techniques need to be used to determine the spatial and temporal structure of variability in all components of the climate system. Investigations dealing with the time scales of anomalies, “events” such as ENSO, anomalous monsoon seasons, and description of decadal variations in ENSO, the PNA and the NAO are examples of such work.

- Inter-relationships:

Determining and refining relationships between various fields in the climate system are important as they often suggest physical mechanisms that influence the system and can indicate possible sources of predictability that can be exploited.

## II. Unifying Themes and Approaches

- Diagnosis and budgets:

Guided by theory and models of the coupled system and its components, diagnoses of the functioning of the climate system will be carried out. Budgets of mass, heat, energy, momentum, atmospheric moisture, fresh water (or salinity) in the ocean, and the surface hydrological balance on land are one common approach used for diagnosis, but many other approaches can be used and should be developed. For example, diagnostic studies could include calculations to determine the ocean mass, freshwater and heat transports, the surface heat and freshwater balance. They could also include how these quantities change with time, along with investigations of the role of Rossby and Kelvin waves in the ocean and the observational evidence for a “delayed oscillator” type mechanism in ENSO.

- Forcing:

Determination of the spatial and temporal distribution of the forcings of the atmosphere and ocean will be made. Also needed are studies to find which of these forcings are most relevant for climate variability on different time scales and why they change. An important hypothesis to be tested is whether the major latent heat sources in the tropics in association with the major radiative sinks, both of which are associated with ENSO, tropical SST anomalies and monsoons, have a primary role in seasonal-to-interannual forcing. Feedbacks associated with cloud radiative forcing and changes in atmospheric moisture distributions add complexity to the determination of effective tropical forcing.

- Responses:

The responses of the atmosphere and the oceans to climate forcings, both locally and remote (teleconnections), and further linkages, such as a remote response in the oceans via atmospheric teleconnections should be determined to within empirical limits. There are many questions concerning wave propagation and interaction of quasi-stationary waves with transients, which can be addressed empirically, as well as with modelling studies.

- Feedbacks:

The impacts of local and remote forcing on the hydrological cycle, especially over land, and the feedbacks to the atmosphere through changes in the ground hydrology and other land surface processes will be investigated. The role of snow cover and soil moisture over land in inducing anomalies in large-scale circulation needs to be determined. The extent to which land-surface anomalies are the result of long-term oscillations of the climate system or stochastic influences from extratropical weather events requires determination. The importance of other feedbacks such as those that occur through changes in storm tracks, interactions with sea ice and through effects of extratropical SST anomalies on the atmosphere must also be pursued.

- Predictability:

A topic of special relevance to CLIVAR is predictability on all time scales. Analogues can be used to determine the rate of separation of initially similar states of the coupled system but, because of the shortness of the data record, innovative approaches are needed to address the long time scales of interest. Empirical searches for regular behaviour, very low frequency phenomena and spatial, temporal or mechanistic links between elements of the coupled system may suggest predictable components.

## 4. GLOBAL SUSTAINED OBSERVATIONS

### 4.1 GENERAL CONSIDERATIONS

Many aspects of an enhanced observing system required to implement CLIVAR are either in place or the methods for implementing them are known through previous research and development, for example within TOGA and WOCE. The elements of this system are, to first order, those described in the TOGA implementation plan and those elements of the WOCE observational programme suited to monitoring climate variability on time scales of seasons and longer. More emphasis, however, is required on the quality and continuity of observations and less on the observational strategy that characterised the original “snapshot” concept of WOCE.

In the context of upper ocean observations, for example, it can be stated with certainty that the products obtained by CLIVAR from the global observing system must include:

- estimates of global sea surface temperature, obtained at least weekly;
- estimates of the global surface fluxes of momentum (surface wind stress); and
- estimates of global sea surface topography variability.

A similar set of basic requirements could be drawn up for atmospheric observations, although the observing system in place for routine weather forecasting already provides much of the basic systems and infrastructure for this purpose. However, the atmospheric component of the TOGA enhancements has suffered severe degradation since the end of the observational programme. The CLIVAR requirements with respect to properties of the land surface, including the cryosphere, must also be taken into account.

Almost all principal research areas outlined in this Plan have these basic requirements of the global observing system in common.

Based on past experience it is also expected that global and regional enhancements of these components will be required on a sustained basis. Thus, the CLIVAR observing system is envisaged as the combination of essential global components and appropriate sustained enhancements needed to observe the natural phenomena that are the focus of the principal research areas. Additional enhancements and intensified observation periods will be required from time to time for CLIVAR process studies. The CLIVAR observing system requirements will be made up from contributions from several sources, not all of which will be directly related to, or totally resourced by, the CLIVAR community. These include

- a) observing elements in place to satisfy objectives and needs independently of any specified for climate applications;
- b) observations provided by other research and/or operational activities, including GOOS/GCOS, which, through coincidence and convenience, can contribute to satisfying CLIVAR research objectives at effectively no extra cost; and
- c) additional observations that are required to fully satisfy CLIVAR research objectives and thus demand CLIVAR resources. These additional observations might be further subdivided into
  - (i) those observations required on a sustained basis, that is, effectively for the life time of CLIVAR; and
  - (ii) those observations required from time to time for specific, targeted experimentation (process studies).

## 4.2 REQUIREMENTS AND POTENTIAL CONTRIBUTIONS

The observing system required by CLIVAR depends fundamentally on the scientific objectives as given by the CLIVAR Science Plan. As the requirements follow from these objectives, the components of the observing system are selected for their ability and efficiency in satisfying these requirements. The requirements may change as improved understanding and technical capacity develop through the lifetime of CLIVAR, so it is to be expected that the make-up of the observing system will also evolve. However, one might expect the evolution of the basic system to be relatively slow and the time scale for changes of the sustained system to be of the same order as the lifetime of CLIVAR itself. Elements and components created for targeted experimentation (process studies) will be more changeable though one might expect some parts to become elements of the sustained system.

### 4.2.1 Ocean Observing Systems

For the ocean, where much of the need for additional sustained observations exists, the systematic examination of the complementary aspects of various components of the system is a major task. The contributions from observing elements of type a) and b) in section 4.1 need to be assessed for their ability to address CLIVAR science questions adequately. It is likely that existing individual elements by themselves will not be adequate, and that the synergy between different components, for example, between altimetric measurements, *in situ* temperature and salinity and wind stress, needs to be exploited, most likely through the use of data assimilation systems. In some areas, such as the Southern Hemisphere, where essentially there are no *in situ* observations, array designs need to be undertaken to estimate the *in situ* sampling required.

It is fortunate that considerable effort has already been expended assessing actual and potential contributions to the observing system, most notably in evaluations of the TOGA observing system and through planning for emerging operational activities. In this section “operational” is used to describe components which are maintained to satisfy permanent and ongoing applications, rather than research and experimentation. The report of the Ocean Observing System Development Panel (OOSDP, 1995) provides recommendations for an initial observing system consisting of existing observing elements and those that should be added now to meet a variety of climate-related objectives. While the OOSDP's recommendations for the initial observing system have been accepted by the responsible parent bodies, the reality is that much of it remains to be implemented on an operational basis. Although this may change somewhat through the use of mechanisms such as the GOOS Agreements Meeting to be held in the fall of 1998, it is essential that CLIVAR maintains its focus on obtaining those sustained observations necessary to meet its scientific requirements whether or not they are provided by GOOS/GCOS.

Although in this plan reference is often made to the initial ocean observing system of GOOS/GCOS, it is worth noting that GOOS and GCOS are rather different entities. The overall charge of ensuring there exists an observation system for meeting climate requirements rests with GCOS, and this is done co-operatively with GOOS where ocean climate observations are concerned (and with GTOS for terrestrial observations). GCOS however has no direct mechanism for implementing such a system and to meet identified climate needs GCOS in general relies on other bodies such as the World Weather Watch (WWW) and Global Atmosphere Watch (GAW) for atmospheric observations, GOOS and other programmes for the ocean, and GTOS for the land surface. The mandate of GOOS falls across the full range of ocean observing system requirements, and includes modules addressing the Health of the Ocean and Living Marine Resources. It also is closely allied with ocean operational agencies such as Integrated Global Ocean Services System (IGOSS) and Global Sea-level Observing System (GLOSS). The structure of GOOS includes an Intergovernmental Committee for GOOS which has as part of its mandate overseeing the implementation of all of GOOS, including what is referred to here as the initial ocean observing system of GOOS/GCOS meeting ocean climate requirements.

For the purposes of this plan, the observing system elements which are fundamental for meeting CLIVAR research objectives, whether or not they are part of b) or c) (i) as defined above, are referred to as the

CLIVAR sustained part of the observing system. Those defined by a and c) (ii) are referred to as the CLIVAR basic and intensive observation parts of the observing system, respectively.

### **Global Sustained Observations of the Ocean**

All the Principal Research Areas have some dependence on global sampling of temperature and salinity. The CLIVAR Upper Ocean Panel (UOP) (CLIVAR, 1998) concluded that this generic requirement was of sufficient importance that it should be the focus of a special CLIVAR effort. The UOP noted that the DecCen objectives, in particular, demanded global observations, sustained over long periods, and, in most cases, including both the thermal and steric fields.

The UOP was briefed on recent advances in observing technology and concluded that significant advances had been with float profiling techniques to the point where it was now both feasible and practical to contemplate a global, “thin” network of profiling floats measuring both temperature and salinity from the surface down to 1500-2000m. Around 3000 floats would give a new profile for each 3° square every ten days on average.

The UOP concluded that such a global network, integrated with other components of the CLIVAR observing system and, in particular, altimetry, would detect natural variability on seasonal to decadal time scales

- to monitor long term climate trends;
- to deliver products needed to calibrate and validate satellite data; and
- to provide data for validation of models and for the initialisation of climate forecasts.

The UOP concluded that such an integrated, global sustained observing system was essential if the goals of CLIVAR and its Principal Research Areas were to be met in an efficient and cost-effective manner. It was not practical for each Principal Research Area to propose and maintain its own observing system; integration of these needs was essential. Furthermore, in relation to the need for salinity data, the UOP concluded that the goals of DecCen could not be met without a major effort to measure the global salinity field, and the proposed float initiative offered the one practical way of satisfying this need.

### **GOALS**

Comprehensive ocean observing systems are needed to be in place in the three tropical oceans, i.e. the tropical Pacific, the tropical Atlantic, and the tropical Indian Oceans. An important application of these data is the initialisation of prediction models, especially in the tropical Pacific for ENSO prediction. In all basins there is a strong emphasis on ocean data to enhance understanding of the key mechanisms and processes.

As a legacy of TOGA, the tropical Pacific is at present the best-sampled of these regions and has a relatively mature observing system. It includes comprehensive sampling by island tide gauges, an extensive array of moored instrumentation for air-sea interface parameters, subsurface temperature observations and, in places, subsurface currents and salinity measurements, surface drifting buoys, VOS XBTs, and some systematic surface salinity sampling. A most important element of this system is the TAO array of subsurface moorings which provide a platform for measurement of important parameters, such as surface winds. This observing system serves as the testbed for examining synergy between the different observing elements and conclusions derived here will probably also be applicable in the other two basins. The tropical Indian and Atlantic Oceans by contrast have only a few XBT lines (with somewhat better sampling in the Indian Ocean) and a few tide gauges. Each basin is also sampled regularly by satellite radiometers (e.g. AVHRR)

## II. Unifying Themes and Approaches

and by satellite altimeters, the most accurate of these at present being TOPEX/Poseidon. It is clear that the challenges in meeting requirements of CLIVAR GOALS are different for the different ocean basins.

Sampling requirements in the Indian Ocean are driven by two factors: the need for sustained observations to understand upper ocean variability in general and its influence in seasonal-to-interannual predictions, and the need for targeted, process-oriented elements e.g. for the Asian-Australian Monsoon Project (G2). Discussions of the UOP have sharpened the scientific objectives associated with the first of these needs and, in particular, showed the power of the TOPEX/Poseidon (T/P) altimeter and remotely sensed SST to define the variability on large-scale and semi-annual, annual and interannual periods. This indicates that T/P observations, and those of future precision altimeters, in this basin (and globally) are a critical component of the CLIVAR system of sustained observations. Supporting *in situ* data, such as that provided by the Indian Ocean VOS XBT programme, are also required. Good surface wind products and, to a somewhat lesser extent, surface heat and moisture fluxes are also high priority. The requirements for monsoon studies will continue to evolve from the discussions of the CLIVAR Monsoon Panels and out of current and planned process studies.

For the Atlantic Ocean, a multinational effort, called PIRATA (Pilot Research Moored Array in the tropical Atlantic) is being planned to explore tropical and subtropical Atlantic variability. The project consists of designing and implementing an array of measurements that would contribute to the description and understanding of the dominant modes of variability in the coupled atmosphere-ocean system of the tropical Atlantic. The modes are the so-called interhemispheric SST dipole and an ENSO-like mode of variability concentrated near to the equator. The array is implemented initially for a three-year period, 1997-2000, in order to demonstrate its feasibility and to investigate its complementarity with other measurements (from VOS lines, satellite altimeters, etc.). Should PIRATA meet its scientific and technical objectives in this process study phase, it is anticipated that it would be sustained for a longer period. The project involves co-operation between Brazil, France, and the USA (see also G3 and D2).

The final phase of the WOCE measurement programme is being completed in the North Atlantic during 1997/98. Of particular interest to both the GOALS and DecCen streams of CLIVAR is the US Atlantic Circulation and Climate Experiment (ACCE) with its tropical surface layer study. Around 50 ALACE/PALACE floats will be deployed on a 600-km grid between 6°S and 40°N, cycling to the surface every two weeks from 800 to 1000 m depth. In general, the developing profiling float technology provides an attractive alternate sampling strategy for vertical thermal structure, particularly in regions not visited by merchant vessels and for which mooring technology is not practical. The CLIVAR UOP (CLIVAR, 1998) has indeed recommended that such a strategy be adopted for CLIVAR as a whole.

The main challenge for the tropical Pacific is to assess the appropriate blend of measurements required for ENSO prediction, and the additional sustained observations required for improved understanding of the key processes determining predictability in this region. The second meeting of the UOP focused on sea level variability and the important role that tide gauges play in the observing system (CLIVAR, 1997). It also became clear that, at least in the western Pacific, a systematic salinity-sampling programme is required for the upper 200 metres to adequately capture variability in this region and to make effective use of the T/P data.

The surface wind measurements provided by the TAO array are still essential because existing wind products still contain significant errors. Future studies will focus on the contributions made by surface drifters, the VOS XBT programme, the subsurface sampling provided by TAO, and sea level as provided by the tide gauges and T/P in defining the initial conditions required for forecast models, data sets for testing and improving models, and documenting the heat and freshwater budgets.

*DecCen*

It is likely that the main scientific thrusts for DecCen initially will be studies of the decadal variability of ENSO and coupled interactions in mid-latitudes, for example decadal variability related to the PNA and NAO phenomena. In the Atlantic the intense sampling programme that is being carried out by ACCE provides a strong foundation for CLIVAR research, but action is required to sustain this effort over the lifetime of CLIVAR. Present plans call for about 70 PALACE floats to be deployed in the 25°N to 35°N latitude band to study the formation of 18°C water in the upper 1000 m of the water column, and around 40 PALACE floats equipped with salinity sensors will be deployed between 6°N and 16°N to examine the salinity balance of the tropical region. About half will be deployed at 800 m and contribute to the 600-km grid of the North Atlantic; the remainder will provide enhanced resolution where the hydrological cycle is most intense and cycle to 1800 m.

In the Pacific the PNA problem and the intra-decadal to decadal variability of ENSO require similar observations, though the possible mechanisms for the latter place greater emphasis on subsurface data. There is a requirement to extend the measurement systems out from the near tropics into mid-latitudes, especially in the Northern Hemisphere, say from 20°S to 50°N. An essential part of the ocean dynamics and physics associated with these problems is the adjustment of the subtropical gyre, either from regional coupled interactions in mid-latitudes or from changes in forcing arising from teleconnections to mid-latitudes from the tropics and adjustment back to the tropics via the ocean. Examination of the tide-gauge records near the centre of the North Pacific gyre indicate that the rms low frequency signal is of the order of 5 cm. The annual cycle also has amplitude of this order. Current T/P estimates of sea level have an uncertainty of the order of 2-4 cm. Current model-based analyses also have errors of this magnitude or slightly larger. Hence it is likely that to address this gyre adjustment problem, both more accurate altimetry and additional *in situ* measurements will be required.

Subsurface salinity variability on these time scales needs to be documented in order a) to examine its utility as a potential tracer, b) to interpret T/P data in terms of subsurface variability, and c) to understand the processes underlying variability on these time scales, among other things. The consensus that has emerged is that surface and subsurface salinity are important for a range of scientific problems in CLIVAR and that therefore a significant effort should be mounted to sustain a global temperature and salinity measurement programme (see above).

Evidence is accumulating that there are substantial changes in water mass properties and distributions throughout the global ocean and that these are not confined to the upper ocean but are detectable at all depths. The understanding of the causes and possible long term influences of these changes is as yet rudimentary but evidence in the North Atlantic suggests a link to changes in atmospheric forcing. Feedbacks to the atmosphere cannot be ruled out but are as yet unproven and thus sustained full depth observations will be required to address CLIVAR DecCen and ACC issues.

Thus, on decadal and longer timescales repeated occupations of hydrographic sections and the continuation of the small but valuable set of full depth hydrographic time series stations and sections will remain a high priority for CLIVAR. The interpretation of water mass changes will depend not only on the collection of temperature and salinity data to high accuracy but also on the measurement of anthropogenic tracers. The exact choice of high priority hydrographic sections will need to be made such that the definitive WOCE observations can be used as a reference baseline against which change can be measured. The sections will also need to be distributed globally in order to link high latitude atmospheric-forced effects to the global ocean interior.

The DecCen problems suggest emphasis should be given to high quality, coherent long records. While enhanced remote sensing capabilities, such as T/P class altimetry, allow better description of the (present) spatial and temporal variability, long-records which capture previous decadal-scale “events” are of critical importance. For DecCen objectives it is essential that as many as possible of these records are preserved and maintained. The OOPC has recommended that two time series stations (at least) be maintained as part of the GCOS/GOOS observing system and, hence, as part of the CLIVAR sustained observing system. It is likely CLIVAR will recommend support for other stations in the future.



## ACC

On longer time scales the large-scale global ocean circulation must be monitored, especially in high latitudes, since it is likely that formation of intermediate and deep water masses as well as the thermohaline circulation vary at these time scales. The salinity field plays a critical role in this regard. Many of the salinity (and circulation) sampling issues north of about 20°S will be addressed under the GOALS and DecCen requirements already mentioned, though it should be stressed that ACC places a very high premium on continuity, quality and length of record.

An examination of requirements for the Southern Hemisphere is needed. The availability of precision altimetric (T/P) data is critical for examination of the variability in this region, though there are limitations at high latitudes. *In situ* sampling of the three-dimensional circulation with vertical temperature and salinity profiles is required to complement and help interpret the T/P data in terms of heat and salt flux variability.

Sea level and bottom pressure records provide one of the most useful sources of information on long-term change. The recent revisions of the GLOSS Implementation Plan and the OOPC/CLIVAR Workshop on Sea Level Network (OOPC/IOC, 1998) provide a detailed account of the significance and importance of sea level measurements for DecCen and ACC applications, and recommendations for the implementation of a network of *in situ* and remote measurements of sea level. In addition, for the determination of oceanic variability and its dependence on, and feedback to, the atmosphere on the longest time scales, emerging cost-effective and integrated measurements such as acoustic thermometry, electric field measurements and automated replacements for the, presently, ship-based time series may play an important future role.

### 4.2.2 Elements of the Ocean Observing System for CLIVAR

The discussion here will consider the observing system needed to meet CLIVAR's need for sustained observations. It will acknowledge whether they have been identified as part of GOOS/GCOS initial observing system but, as noted above, CLIVAR must seek to have the complete observing system meeting its requirements implemented, whether or not it is partly funded by nations through GOOS/GCOS. The design of the initial observing system as defined in the OOSDP report and accepted by GOOS/GCOS provides a basis for meeting the CLIVAR requirement for upper ocean sustained observations as is to be expected given the overlapping objectives and the limited types of instrumentation and platforms available. However, in general the operational GOOS/GCOS observing system will only meet part of the CLIVAR research requirements.

A simple example is provided by the observing system required in the tropical Pacific to address ENSO. The OOSDP limited and prioritised its recommended observing system on the basis of what could be justified for the operational initialisation of ENSO predictions. The CLIVAR observing system needed to improve these predictions through better understanding of ENSO processes is clearly more extensive and in fact is similar in scope to that presently in place as a legacy of TOGA. It should also be noted that most of this larger observing system of TAO moorings, XBTs and tide gauges supported by the USA has recently been given operational status. It is to be hoped that this transition from research funding to an operational system will occur for other elements of the CLIVAR system of sustained observations and the initial GOOS/GCOS observing system given the proper stimulus and justification. Figure 4 show some examples of elements that will contribute to a global observing system.

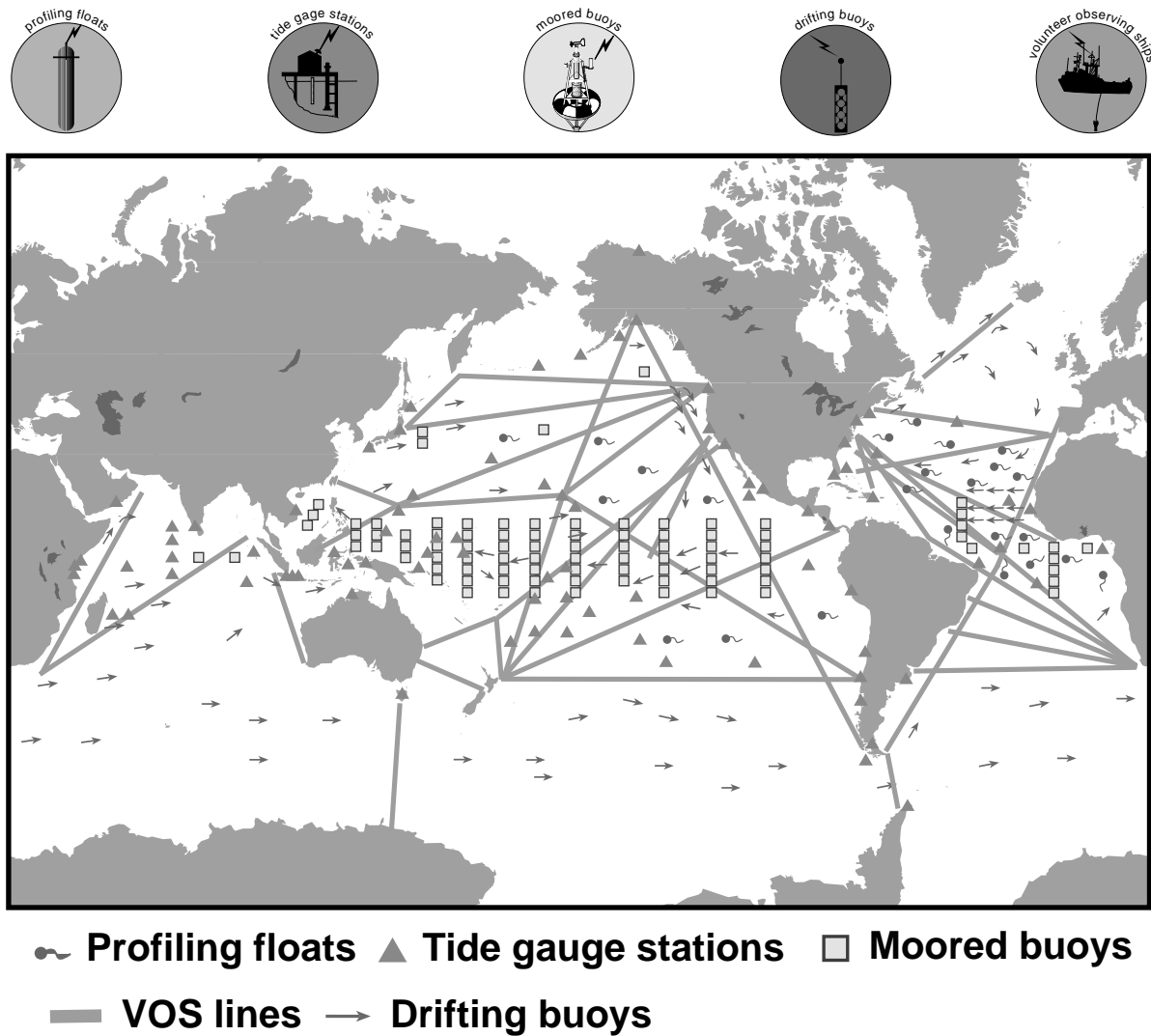


Fig. 4: Some of the (mainly) existing elements that can contribute to the CLIVAR requirement for sustained observations (courtesy of NOAA/OGP). Many of the elements below are not included.

The fundamental fields that need to be observed for CLIVAR have been identified by the UOP as:

- sea surface temperature
- surface wind
- surface heat and fresh water flux
- upper ocean temperature
- ocean circulation (currents)
- surface and subsurface salinity

## II. Unifying Themes and Approaches

- heat and water transports and budgets (deep T and S)
- sea level
- sea ice

The discussion here will be ordered accordingly. In each case we will break the observing system elements into a basic system of existing operational systems, including external contributions unrelated to the climate-related objectives of GOOS/GCOS or CLIVAR (for example, the weather related AVHRR observations or the output of NWP models), and the elements which need to be implemented to meet CLIVAR's requirements for sustained contributions. For each field, the accuracy and resolution required of the analysed field are stated and a strategy and benchmark accuracy for sampling stated where it is known. Some parameters such as the fluxes of heat, momentum, and fresh water can be derived indirectly from the output of operational global weather forecast models that assimilate a variety of *in situ* and remotely sensed information

The measurement platforms that are available for these purposes consist of satellites, ships, moored surface and sub-surface buoys, drifting surface buoys, and autonomous floats. Moored buoys and ships provide attractive platforms because they provide the means to make direct measurements *in situ*, and because sensors and electronics can be recovered periodically for calibration. Ships are attractive because they are manned, have power, and in the case of merchant ships, can be cost-effective. Unfortunately costs and logistics prohibit dense sampling arrays of ships and, probably, moored buoys on a global basis. Drifting buoys and subsurface floats offer one practical possibility of obtaining extensive *in situ* data in remote regions. Satellite methods provide large-scale coverage for some variables but have the disadvantage that considerable care and substantial resources are required to provide ground truth for the remotely sensed data, to verify sensor calibration, to correct data quality problems associated with looking at the sea surface through the atmosphere, and to relate surface "images" to the subsurface fields.

Some detail is given below of the required observational elements and of the required sampling frequency and accuracy in order to meet a specific CLIVAR objective. Further information of the required observations for the Pacific Ocean is provided in CLIVAR (1997) and within the discussion of individual Principal Research Areas in this volume. Much of the additional detail is reproduced from the recent work of the OOPC and can be found in the report of GCOS/GOOS Implementation Workshop (GCOS, 1998c).

### Sea Surface Temperature

Global sea surface temperature (SST) analyses are considered fundamental and essential to progress in CLIVAR.

#### *Contributions from the basic system*

- Global satellite measurements of SST using AVHRR.
- Moored and drifting buoy network measuring and reporting SST.
- VOS fleet measuring and reporting SST.

Note that some of these contributions might be classed as external since they were established and continue to be maintained largely for objectives other than climate.

*Elements needed for a sustained CLIVAR contribution*

- A subset of existing VOS and research fleet enhanced with improved (hull contact) sensors.
- Improved quality control of VOS to increase accuracy of analyses.
- Additional SST observation from drifting buoys, especially in regions lacking VOS coverage.
- Use of other satellites systems, such as ATSR and GOES, to improve SST estimates by establishing transmission errors, etc.

*Characteristics desired of the processed signal*

- a) In support of NWP which will supply stress and heat flux estimates for CLIVAR: 0.2-0.5°C on 100 km square x 3 days resolution.
- b) For ENSO prediction: 0.2-0.3°C on 200 x 30-100 km x 5 days in the tropics. The bias requirement is more severe in the convective regions, less severe in the central to eastern Pacific. Meridional resolution has a high premium attached to it.
- c) For climate change detection: 0.1°C, 2-500 km square x monthly.

The diurnal cycle is a potential source of error for most of these signals.

*Sampling strategy and benchmark accuracies*

- Use geostationary and polar orbiting satellite data for spatial resolution and to reduce geophysical noise in climate signals.
- Use *in situ* data for calibration and to produce blended products with optimised bias reduction.
- The requirement for remotely sensed SST is 10 km resolution and 3-6 hr. sampling, the latter to reduce aliasing error, with 0.1-0.3°C relative error. The temporal sampling implies increased utilisation of geostationary platforms. NWP applications are the dominant determinants of resolution while climate applications are the most demanding in terms of error.
- The sampling for *in situ* elements is controlled by the need to remove bias from the satellite product, mainly for climate change applications, but also in the event of unexpected aerosol interference. The best estimate remains at 0.1°C on 500 km square by weekly time scales O(25) samples with accuracy ~ 0.5°C. ENSO requires an adjustment in the tropics as suggested by the scales mentioned above.

*Indirect sources of information*

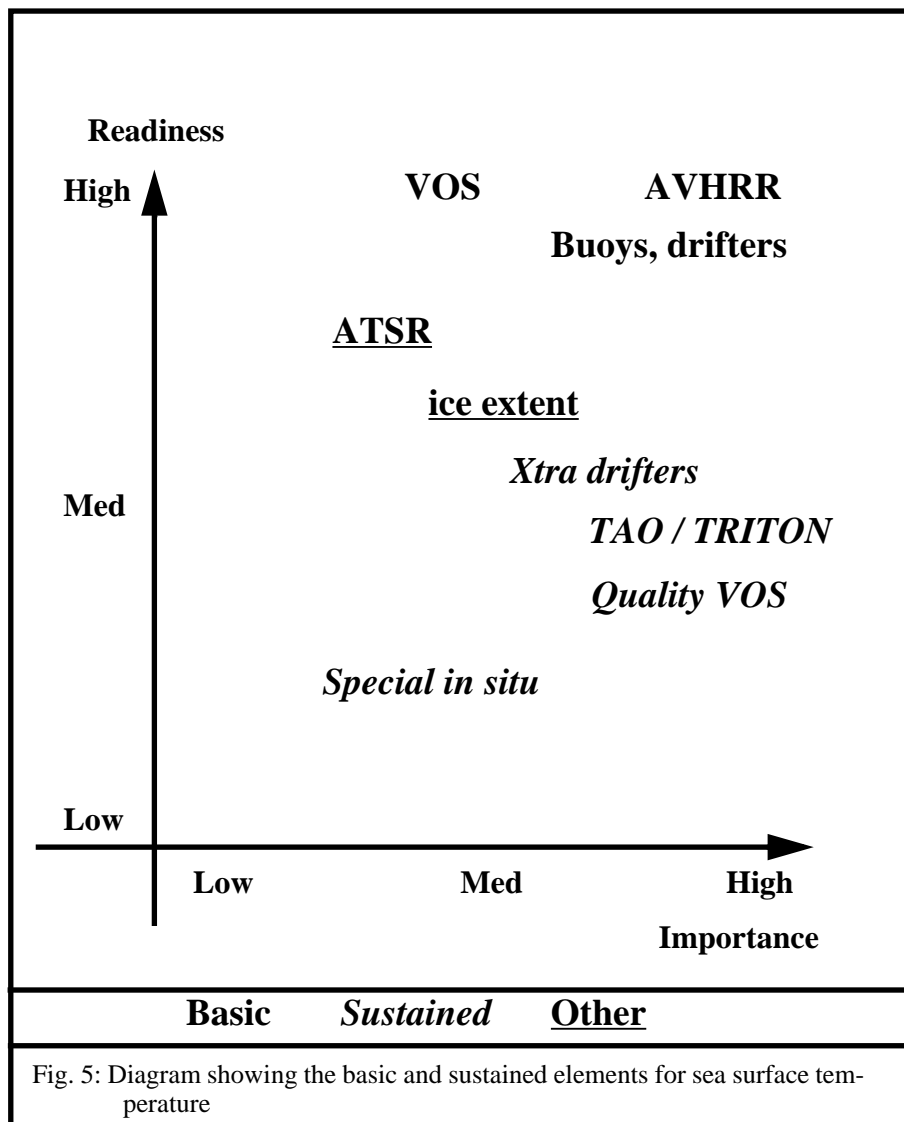
Virtually none. None of the operational analysis systems use model predictions or assimilation to great effect. It remains a field that is far easier to observe than model.

*Trends*

CLIVAR may require resolution of the diurnal cycle and improved accuracy of products in the tropics (0.1°C). There remain some issues concerning the use of bulk, near-surface and skin temperatures in climate applications. This is likely best addressed through greater use of mixed layer models. Accurate high-latitude SSTs might also become more important; satellite sampling is often poor in high latitudes, so *in situ* programs become more important.

Relevance to scientific objectives

The relative importance of the various components in the list just given in providing an SST field that can meet CLIVAR requirements can be illustrated by the use of a diagram as is given in Fig. 5. It provides a schematic representation showing the elements of the basic and sustained components of the observing system with a qualitative judgement of their relative “importance” in meeting CLIVAR objectives and their “readiness”, which can represent factors such as their state of development, maturity of use and perhaps some measure of the practicability of their use because of cost. Diagrams of this type were introduced by the OOSDP to illustrate the relative impact of observing elements required to meet their stated objectives for the initial GOOS/GCOS operational observing system. For SST, CLIVAR requirements are essentially identical for the global system and differences should only arise from changing technology or understanding of its appropriate application. The system required to meet other objectives of CLIVAR and GOOS/GCOS can differ substantially. They may also vary depending on the relative importance given to one principal research area with regard to others. Nevertheless, the initial observing system design provided by the OOSDP and their use of figures such as Fig. 5 have much relevance to the design of the observing system to meet CLIVAR's need for sustained observations. Note that in Fig. 5 only elements which have perceived potential for the basic plus sustained system are included, “intensive observing” elements are not included here.



SST is important for virtually all the Principal Research Areas. In general, the required SST signal becomes smaller and of larger scale as we go from GOALS problems to those of ACC, so the dependence on quality *in situ* data, particularly with regard to bias, also increases, and the demand for a more even global distribution is greater. In many problems (e.g. subtropical seasonal prediction) knowledge of SST is the most critical input. There are likely to be some changes in emphasis in CLIVAR from those of TOGA and the OOSDP, for example with respect to the diurnal cycle, with consequent implications for sampling and prioritisation of elements and platforms. All of the elements in the sustained list are included in the GOOS/GCOS initial observing system and are likely to be pursued by the GCOS/operational meteorological community and so should not be of prime concern to CLIVAR.

### Surface Wind

Global surface wind analyses are a fundamental and essential requirement for CLIVAR research.

#### *Contributions from the basic system*

- Numerical weather prediction surface wind field analyses.
- Meteorological observations from VOS.
- Sea level pressure and surface wind measurements from meteorological buoys.

#### *Elements for a sustained CLIVAR system*

- Enhanced use of wind estimates from satellites such as ERS-1, ERS-2, and SSMI.
- Winds from moorings such as the TAO array (hereafter TAO is assumed to include both the ATLAS moorings maintained by the US, formerly referred to as TAO, and the Japanese TRITON moorings which are to be used west of the dateline).
- Increased numbers of drifting buoys reporting sea level pressure and, as feasible, surface wind.
- Implementation of measures to improve VOS wind data.

#### *Characteristics desired of the processed signal*

Estimates come from both NWP and from direct analyses of wind data (e.g. the FSU product). Re-analysis products are also popular in the research community.

- For ENSO applications  $5^\circ \times 2^\circ \times 1$  month  $\times$  (5% dirn; 0.5 m/s speed) estimates are required. For longer periods the accuracy requirements are slightly weaker, but a global resolution of  $2^\circ \times 2^\circ$  is desirable (such products are not used directly for detecting change but for driving climate models studying climate change).
- Some climate applications seek much finer temporal and spatial resolution. Research applications also have demanding requirements.

#### *Sampling strategy and benchmark accuracies*

OOSDP (1995) did not give a specific sampling rate, citing the many different applications as one of the mitigating circumstances. The following has been recommended by OOPC:

$2^\circ \times 2^\circ \times 1$ -2 days  $\times$  0.5-1.0 m/s in the components is the benchmark accuracy for climate applications

## II. Unifying Themes and Approaches

### *Indirect sources of information*

Clearly NWP and forecasts based upon previous data are an important source of indirect information, as are the other contemporary atmospheric and ocean surface data (e.g. cloud drift winds; MSLP). Atmospheric assimilation systems continue to have problems ingesting surface wind data, so direct estimates are essential, particularly in the tropics (e.g. TAO).

### *Trends*

ADEOS/NSCAT showed that estimates of around 2 m/s accuracy every 2 days could be obtained, at a spatial resolution of around 50 km. If such an instrument were flying operationally, then the role of *in situ* data might be more like that of *in situ* SST data for SST estimates. That is, providing ground truth for bias correction.

The reanalysis projects have yielded improved products, which are popular, but which have shortcomings with respect to quality and resolution. The demand for better resolution, particularly for cyclones and hurricanes and other higher-frequency variations, is growing. There is consensus that at least one operational double-swath scatterometer is justified, and an emerging case for two to eliminate aliasing of these higher-frequency variations into the climate signals.

### *Relevance to the scientific programme*

Surface winds are needed for all of the GOALS objectives. The importance of thermohaline fluxes increases, while that of wind forcing decreases, as we move to longer time scale problems. Nevertheless, changes in wind stress, in particular the wind stress curl, are very important. Global winds are not useful for ACC studies, at least in the form of ocean surface forcing. Like SST, the over-arching importance of surface wind stress means that GOOS/GCOS will be active in pursuing implementation of many of the elements of the sustained system which for now cannot be classed as part of the basic operational system. For example, continuity of platforms supporting scatterometer sensors, such as that flown on ADEOS/NSCAT, is not yet guaranteed.

## Surface Heat and Fresh Water Flux

### *Contributions from the basic system*

- Flux estimates from analyses of atmospheric observations by NWP models.
- Marine data from VOS and drifting and moored buoys.

### *Elements for a sustained CLIVAR system*

- Satellite based systems for estimating radiation, precipitation, and evaporative fluxes.
- Improvements of the present coverage and accuracy of VOS data.
- Deployment of a small number of flux measurement packages on VOS ships or buoys.
- Utilisation of ocean budget analyses, either directly from *in situ* data or ocean data assimilation products, to estimate these fluxes.
- Implementation of several flux reference sites.

*Characteristics desired of the processed signal*

Heat flux: 10 W/m<sup>2</sup> accuracy over 2° latitude by 5° longitude by monthly bins.

Precipitation: 1-5 cm/month over 2° latitude longitude by monthly bins.

*Sampling strategy and benchmark accuracies*

Use flux estimates from NWP/re-analysis projects and adopt the sampling requirements of WWW.

Direct calculations based on surface marine data, both satellite- and ocean-based (e.g. FSU, SOC). O(50) observations of the main parameters (wind, air temperature, humidity, MSLP, SST) per bin. Specific high priority actions include

- Improved SST, air temperature, humidity, MSLP, precipitation and absolute wind velocity on selected VOS;
- Short-wave and long-wave radiometers on selected VOS;
- Satellite-based estimates of radiation and precipitation; and
- A number of flux reference sites to provide high-quality verification.

*Indirect sources of information*

There are no direct methods for measuring the global net heat and water surface fluxes, though there are methods for measuring some components. NWP takes advantage of many indirect (non-ocean) sources of information. Ocean budget techniques, such as employed in TOGA COARE, have proved quite effective for estimating the net heat flux; a similar technique can be employed for net water flux based on salinity (water) budgets. Ocean models with assimilated ocean temperature data can also be used to infer surface fluxes.

*Trends*

As noted above, there is increasing emphasis on the oceanic water budget, so at-sea measurements of precipitation (e.g. from TAO, VOS) are becoming increasingly important. Several methods are available based on satellite data (e.g. TRMM) and high-quality *in situ* data are needed for algorithm development and calibration. NWP prediction estimates are still plagued by large uncertainties and systematic bias, particularly in those components influenced by cloud cover. Ocean models are extremely sensitive to bias errors, so the sampling strategy must endeavour to provide as much ground truth as possible. This strategy then places a high premium on data quality, and hence on improving the quality of *in situ* data streams.

*Relevance to the scientific objectives*

None of the developing ENSO prediction systems is heavily reliant on surface fluxes (compared with wind and temperature data). For the remaining GOALS objectives surface fluxes would most likely fit on the third level of importance, though this may change as knowledge increases of the monsoon systems. The exception is short wave radiation which is needed irrespective of the quality of SST products. For DecCen problems, such as D1 and D3, knowledge of surface heat and water exchanges is very important. Surface flux fields cannot be measured with the accuracy needed to detect climate trends (for heat flux, the signal is of the order of a few W/m<sup>2</sup>) so are of little importance in ACC studies. Marked improvement in NWP products remains elusive. Knowledge of air-sea exchanges assumes greatest priority in process studies (COARE, for example, in TOGA) and there is likely to be continuing emphasis on these aspects in CLIVAR within the monsoons thrust.



## II. Unifying Themes and Approaches

### Upper Ocean Temperature

#### *Contributions from the basic system*

- The northwest Pacific upper ocean monitoring system currently operated by Japan.
- Parts of the low-density broadcast mode XBT programmes primarily initiated by WOCE and TOGA (on balance, it seems more appropriate to consider these as part of the basic system even though there remains considerable work to be done to ensure adequate participation in a programme that is under threat of funding reductions).

#### *Elements for a sustained CLIVAR system*

- Measurements from moored arrays, such as TAO in the Pacific, including internationalisation of the support for these arrays.
- Indirect estimates from precision altimeters and sea level gauges.
- Temperature profiles from profiling floats and frequently-repeated XBT lines.
- Development and enhancement of ocean data assimilation systems to optimise the utility of the existing *in situ* and remotely sensed observations.

In the past, upper ocean thermal networks have largely been the province of research. Making significant parts of these networks operational is one of the aims of the GCOS/GOOS IOS, and remains a high-priority issue.

#### *Characteristics desired of the processed signal*

- 2-500 km square bimonthly global maps of the heat content and the first few vertical modes of variability; climatologies on 1° resolution. Accuracy is useful ~ 0.5°C.
- 1° latitude x 5° longitude x 10 day x 500m (mixed layer depth + O(5) vertical modes) fields for ENSO forecasts. Accuracy 0.2-0.5°C.
- For climate trends, need better than 0.1°C/year accuracy, on large space scales.

#### *Sampling strategy and benchmark accuracies*

- Maintain TOGA/WOCE broad-scale VOS sampling (1 XBT per month per 1.5° latitude x 5° longitude box). Priority to lines with established records, of good quality, and in regions of scientific significance (e.g. tropics, particularly outside the domain of TAO, and the TRANSPAC region).
- Maintain TOGA Pacific network, in particular TAO (OOSDP did not specify part or all of the present array, but did suggest “close to” 1994 levels). Around 4 samples every 5 days per 2° x 15° bin, with 10-15 m vertical resolution is deemed satisfactory.
- Boost routine sampling of the polar regions (at broadcast mode levels)
- Use of profiling floats to implement a truly global observing system. This is a technology that is developing rapidly and real-time data are now available; sampling strategies have yet to be formally defined for the sustained observing system but a T(z) profile per 2-300 km square every 10 days from the surface to 2000m might be feasible.

*Other sources of information*

Clearly altimetry offers complementary data. For the tropics, it is likely that a good model plus SST and wind-forcing may be able to forecast subsurface temperature structure with useful skill. However, at the present time, there is no reason to lessen the requirements outlined above. Acoustic thermometry has good potential, particularly for long-term change and in regional modelling. It seems highly unlikely that an *in situ* solution will be found for the mesoscale applications. Rather, it is likely a mix of moorings, XBTs and profiling floats may be used to pin-down the global, large-scale thermal structure, and a mix of altimetry, SST and colour used to specify the horizontal structure of the mesoscale field.

*Trends*

Profiling floats are arousing a great deal of interest and seem to offer the one real chance for global temperature sampling (VOS are limited in terms of geographic coverage, and moorings are better suited to tropical and boundary regions). As noted previously, the CLIVAR UOP (and GODAE) have recommended immediate actions to implement a global network of profiling T and S floats, at around the resolution mentioned above. It is the opinion of the UOP that such a network is necessary if CLIVAR is to fulfil its goals. A programme called PIRATA is testing a TAO-like array in the tropical Atlantic, and the Japanese TRITON programme is testing moorings for mid-latitude climate studies, and for Indian Ocean studies.

*Relevance to the scientific projects*

For many of the GOALS objectives, and in particular G1, G2 and G3, upper ocean temperature is an important field, probably at the second level of importance after SST and wind stress. The shorter time scales of the monsoon problem imply less importance for thermal memory and subsurface temperature. Conversely, for the time and space scales of DecCen, knowledge of the thermal storage and transport is very important. The role of upper ocean temperature data for ACC is restricted, though some use has been made of longer time-series records of repeated hydrographic sections and stations.

Ocean circulation (currents)*Contributions from the basic system*

- Estimations of surface drift from operationally supported surface drifter programmes.

*Elements for a sustained CLIVAR system*

- Measurements from moored arrays, such as TAO.
- Estimation of surface geostrophic currents from altimeters.
- A systematic programme to collect and quality control acoustic Doppler current meter data from VOS and research cruises.
- Subsurface current vectors from floats and surface currents from drifters.

*Characteristics desired of the processed signal*

The OOSDP (1995) report was vague with respect to the need for velocity measurements, principally because there were few, if any, operational applications. They recommended a minimal array from moorings and VOS ADCPs for validation of models. Accuracies of the order 5 cm/s for monthly averages would be the benchmark for the tropics.

## *II. Unifying Themes and Approaches*

The global surface drifter programme does yield good surface currents estimates. The benchmark is global coverage of one drifter measurement per 600 km square per month, with current-following accuracy of around 2 cm/s, which would give estimates of the mean velocity good to 10% of the eddy variability.

Several groups are experimenting with surface current estimates derived by combining altimetry, drift measurements and/or estimates inferred from SST-pattern following techniques.

### *Trends*

There is considerable interest in gravity missions (e.g. GOCE, GRACE) which potentially would allow altimeters to determine the absolute sea level variations and hence directly infer the surface geostrophic flow. Quoted accuracies are of the order 1 cm at 200 km resolution.

### *Relevance to scientific objectives*

For GOALS projects surface and subsurface current data provide an important validation of ocean model transports and advection and of horizontal convergence patterns. None of the present ENSO forecast systems use ocean currents in the initialisation process, though this should change during CLIVAR. Velocity data are important for understanding equatorial ocean dynamics. At the longer time scales of DecCen, knowledge of the strength and variability of the major gyres becomes important as do estimates of the meridional transports of heat and fresh water. There are few applications for current information in ACC problems except perhaps measurement of deep currents for transport.

## Surface and Subsurface Salinity

### *Contributions from the basic system*

- Basically none.

### *Elements for a sustained CLIVAR system*

- A programme to introduce more quality thermosalinographs into the VOS programme and maintain those currently operated by France and others;
- Measurements from a subset of the moored arrays, and where feasible from drifting buoys;
- Salinity from profiling floats (see previous discussion under temperature);
- Measurements on research cruises from XCTDs or CTDs; and
- Time-series stations.

### *Characteristics desired of the processed signal for surface salinity*

While surface salinity products remain largely in the research community, the OOSDP expressed a strong desire for improved monitoring of SSS. At high-latitudes, surface salinity is known to be critical for decadal and longer time-scale variations associated with deep over-turning and the hydrological cycle (the rms annual variation is around 0.2, while the interannual is typically 0.2-0.5). These are relatively large-scale signals. In the tropics, and in particular in the western Pacific and Indonesian Seas, and in upwelling zones salinity is also believed to be important (rms variation ~ 0.3). A surface product with 250 km square monthly resolution with 0.1-0.2 accuracy would be satisfactory for most CLIVAR applications.

Monthly subsurface products are required with 0.01 accuracy on 3° square boxes.

*Sampling strategy and benchmark accuracies*

- At the surface, one sample per 200 km square every 10 days with a benchmark of 0.1 accuracy (the signal to noise ratio is typically not favourable). The tropical western Pacific and Indian Oceans, and high latitudes are the highest priorities.
- Subsurface seek 4 profiles per month per 3° box at better than 0.02 accuracy.

*Indirect sources of information*

Precipitation estimates provide some useful indirect estimates of SSS. In theory, a combination of altimetry and ocean temperature should also be useful for inferring SSS, but this has yet to be demonstrated in practice.

*Trends*

There does remain some possibility of remotely-sensed SSS, at the threshold level. The need for improved surface salinity networks has been a theme in CLIVAR and in the OOPC, principally because of the significant interest in the tropics and the interest in decadal-to-centennial variations.

As noted previously, improved technology does open up the real possibility of global sampling of subsurface salinity. Reliable sensors are under-development and the UOP recommends that, as soon as is practicable, floats should be used to implement a global sustained network. Studies using a combination of altimetry, sea surface salinity and ocean temperature have shown promise for estimating subsurface salinity. CLIVAR is intent on pursuing a better description of the hydrological cycle which implies greater emphasis on subsurface salinity

*Relevance to the scientific objectives*

A strong theme emerging from CLIVAR scientific discussions is the increased importance being attached to surface and subsurface salinity. Salinity in the western Pacific may play a role in ENSO prediction, (G1) and is of known importance in regions of the Indian Ocean. Knowledge of salinity (the climatology at a minimum) is important for interpretation of altimetric measures of dynamic height variability. Salinity is a very important signature of variability on DecCen time scales, particularly in the sensitive high-latitude deep and bottom water formation regions (D1, D3, and D5) and has been used in climate change assessment.

Heat and Water Transports and Budgets

*Contributions from the basic system*

- Monitoring of river discharges.

*Elements for a sustained CLIVAR system*

- Transocean hydrographic sections at key locations;
- Repeat sections for watermass formation estimates; and
- Selected time-series stations (locations to be determined).

The OOSDP recognised that observing changes in the ocean circulation and its inventories of heat and fresh water would require the use of PALACE floats, precision altimetry, knowledge of the surface forcing fields, etc. which are discussed elsewhere in this section. In addition, transocean sections at key lat-

## *II. Unifying Themes and Approaches*

itudes and in regions of watermass formation would be required. The OOSDP report, which was published at the end of 1994, states that, although repeat hydrography and transocean sections are essential, they lacked some urgency as part of the initial ocean observing system because of the global coverage being provided by WOCE and the expected repeat time of five to ten years. At this time, roughly four years later, it is timely that the role of sections be reconsidered since they are a required element of both DecCen and the ACC. Such a review has been proposed by the OOPC to decide the appropriate location and frequency of such sampling. It should be noted that D1, D3 and D4 propose locations for some repeat hydrographic sections but not for all ocean basins. Any review by the OOPC must take CLIVAR scientific requirements into account.

### *Characteristics desired of the processed signal*

- For the estimates of the variability of meridional heat and fresh water fluxes, measurements are required at key latitudes with station spacing that resolves mesoscale variability, 25-100 km, with a repeat time to be determined based on the experience of WOCE.
- For the measurement of water mass formation, sections are required to resolve interannual variability and a station spacing adequate to sample region.

### *Sampling strategy and benchmark accuracies:*

The sampling strategy, desirable accuracies and operational procedures for deep sea hydrographic observations are fully described in the documentation prepared for WOCE implementation and can be seen in WCRP (1988 a, b) and WOCE (1991), WOCE Hydrographic Programme Office (1994).

### *Trends*

Hydrographic sections remain the fundamental tool for observing changes in watermasses and the ocean transport of heat and fresh water. The availability of profiling floats measuring T and S, moored profiling instruments, and precision altimetry combined with the increasing power of ocean dynamical models and techniques for assimilating observations could lead to more comprehensive approaches in the future.

### *Relevance to scientific objectives*

While much of our knowledge of heat and freshwater transports will be inferred from CLIVAR sustained observations of other fields, in particular surface and subsurface temperature, salinity and currents as well as estimates of surface heat and freshwater fluxes, full depth hydrographic sections remain a necessity for both DecCen and the ACC. They are a key element of D1, D3, and D5. Meridional transocean sections are proposed at mid-latitudes in both the Northern and Southern Hemispheres. Additional sections are proposed at the “choke points” around Antarctica and other key locations.

### Sea Level

Global estimates of sea level variability are a fundamental and essential requirement for CLIVAR, particularly outside the tropical region where the dominant scales of variability proscribe against *in situ* sampling.

### *Contributions from the basic system*

- Tide gauges from the GLOSS network; and
- Geodetic positioning for a small set of tide gauges for calibration of altimeters.

*Elements for a sustained CLIVAR system*

- High precision global altimetric missions (e.g. T/P, ERS, JASON);
- Enhanced *in situ* sampling in selected regions.

The OOSDP report discussed long-term trends and ocean variability needs, but was not specific with respect to the *in situ* gauges or altimetry. The OOPC and CLIVAR, and NOAA, convened a Workshop to refine these requirements, and conjunction with the GLOSS Implementation Plan.

*Characteristics desired of the processed signal*

- Annual global sea-level change on large space scales ( ~ 500 km square), with accuracy of around 1-2 mm/yr.;
- Estimates of sea surface topography anomalies (for ENSO and ocean variability studies), for 10-30 day periods, with accuracy of 2-5 cm and spatial resolution:
- 500 km zonal x 100 km meridional in the tropics
- 2° x 2° elsewhere;
- Estimates of mesoscale variability 25-100 km square every 5 days with 2-10 cm accuracy; and
- Ocean circulation (estimates of absolute sea level) with 200 km square and around 2cm accuracy (dependent on a gravity mission).

*Sampling strategy and benchmark accuracies*

Long-term trends require a dual strategy. The preferred observing strategy comprises:

- altimetry for global sampling, at approximately 10 day intervals;
- approximately 30 *in situ* gauges for removing temporal drift;
- additional gauges at the margins of the altimeter (e.g. continental coasts and high latitudes); and
- a programme of geodetic positioning.

An alternative observing system, proposed due to the lack of guaranteed availability of altimetric data and due to the lack of experience and confidence in the application of altimetry to measuring long-term trends, would comprise

- a globally distributed network of *in situ* measurements, with similar effect to the GLOSS Long-Term Trends (LTT) set; and
- a programme of geodetic positioning.

For large-scale variability, sites for *in situ* measurements are limited. The TOGA network should be maintained (at higher priority than assigned in OOSDP, 1995), with increased focus on the tropical western Pacific and Indonesian Throughflow, and in the western boundary current regions. The GLOSS Implementation Plan and OOPC/CLIVAR Sea Level Workshop (GCOS, 1998b) detail priority stations for monitoring large-scale variability. Topex/Poseidon-class altimetry with 100-200 km resolution and ~2cm accuracy is also highly recommended. Altimetry, in general, is now rated far more highly than it was at the time of OOSDP (1995).

## II. Unifying Themes and Approaches

Mesoscale variability is only accessible with multiple altimeters, at least one, but preferably two, being T/P class. The optimal (combined) sampling is ~ 25 km square by 2 days by 2-4 cm accuracy.

### *Indirect sources of information*

For long-term trends there are no viable alternatives, though acoustic thermometry may offer some sort of alternative measure. For ENSO monitoring and prediction, there is redundancy between wind, SST, sea level and subsurface temperature; sea level data sets have the advantage of a history stretching back into the 1970's, and the fact that it measures the joint effect of thermal and steric variations. For large-scale variability in general, thermal data offer similar information. However their complementarity would seem a more powerful attribute. There is no alternative to altimetry for mesoscale variability.

### *Trends*

For ENSO prediction, sea level is enjoying a revival, courtesy of Topex/Poseidon and improved methods for assimilating sea level information. There is more confidence in altimetry for long-term trends (c.f. OOSDP 1995). For the mesoscale, the number and type of altimeters required still remains open. Gravity missions, such as GRACE and GOCE will provide an opportunity to exploit absolute measures of sea level.

### *Relevance to scientific objectives*

Sea level records provide some of the longest oceanic records and so are well suited to ACC problems. Blended altimeter and *in situ* products provide good estimates of both the temporal change and spatial pattern. Recent results indicate sea level data should be useful for GOALS prediction. For regions of the globe where alternative information sources are scarce, such as the Indian Ocean, altimetry will have increased importance. Sea level data is also an important element of several of the DecCen objectives.

## Sea Ice

### *Contributions from the basic system*

- Monitoring of the extent and concentration of sea ice using both passive and active microwave sensors globally and synthetic aperture radar in specific regions.

### *Elements for a sustained CLIVAR system*

- Maintenance and optimisation of the Arctic and Antarctic drifting buoy networks, in co-operation with ACSYS.
- Enhancement of existing research networks using *in situ* measurements to estimate ice thickness regionally, including possible declassification of submarine data and future submarine sections under sea ice.
- Improve dynamical ice models by developing estimates of ice velocity fields from SAR/AVHRR and buoys that can be used with forcing fields to estimate ice concentrations and transport.

### *Characteristics desired of processed signal*

- Sea ice extent: daily 10-30 km resolution using passive microwave and, where feasible SAR (for finer accuracy). *In situ* techniques largely insignificant

- Sea ice concentration: 2-5% in concentration, measured daily
- Sea ice drift: Measurement of drift as opportunities arise, using buoys and pattern-tracking from remote sensors (SAR, AVHRR)
- Sea ice thickness: 2-500 km<sup>2</sup> mapping of ice thickness on monthly time scale, with accuracy O(0.2m), using upward-looking sonars and other devices

*Other comments:*

Operational systems are more advanced in the Northern Hemisphere than in the Antarctic. Work in the Antarctic is largely driven by climate concerns. In the Arctic operational real-time prediction of sea ice is also a major issue. For decadal-to-centennial variability, properties of the ice-covered oceans remain a key issue. Surface salinity and sea-ice export estimates are complementary. For models to be useful for sea ice prediction (on short time scales), good wind data are essential.

*Relevance to scientific objectives*

Sea ice measurements are relevant to the DecCen and ACC objectives. Lack of a viable method for obtaining large-scale estimates of ice thickness and thus of ice volume, especially in the Antarctic, remains a problem for climate studies

Time Series Stations

Time series stations do not neatly fit into the above field-by-field description. Time series stations provide long records with temporal resolution short compared with the characteristic scale of the dominant variability, as well as co-located measurements of several different variables, sometimes including chemical and biological parameters. These attributes make such data sets powerful and complementary to the data mentioned previously, particularly for physical and phenomenological studies. The OOPC/CLIVAR Ocean Time Series Workshop (IOC, 1998) discussed the merits of time series as a strategy for both GCOS/GOOS and CLIVAR, as well as JGOFS. Table II.1 (page 46) provides a summary of the attributes of time series stations relevant to the objectives of CLIVAR. It is subjective, and the uncertainty in assignments is likely greater than the difference between one grade and the next. The purpose is to provide guidance, rather than precise evaluation. Note that other forms of time series data sets, such as surface reference sites and repeated sections, are discussed previously and have not been mentioned here.

Toward the end of the table are “ratings” against two possible benchmarks. Benchmark 1 refers to DecCen-type applications and attempts to indicate the level of relevance of a particular time series to long-term monitoring and the generic goals of DecCen; 1=below the threshold of usefulness, 2=at and above the threshold; 3=very useful. The two attributes which matter most, aside from a judgement of the relevance to CLIVAR goals, are the length of record (referenced to 2010, the end of CLIVAR) and continuity. Benchmark 2 tries to indicate whether the station contributes at a useful level to the general scientific goals of CLIVAR, be that for understanding processes, monitoring signals other than those referred to in Benchmark 1 (e.g., the Antarctic Circumpolar Wave), and so on. Here the availability of supporting surveys, broad suites of measurements and scientific exploitation are the most relevant attributes. A separate entry for modelling has been include but not with any relative assessment (see IOC (1998) for a discussion).



**Table II.1: Time-series Stations relevant to CLIVAR**

	Bermuda (BATS)	Hawaii (HOTS)	Bravo	Canary Is. (ESTOC)	Kerguelen Is. (KERFIX)	OWS Mike	Papa Line P	TAO
Record Length	"S": 44 BATS: 9yr	10 yrs.	35 yrs.	4 Kiel 276?	4 yrs.	49	49	5-19 yrs.
Sampling/continuity	Excellent	Excellent	Broken	Good	OK, but problems	Excellent	Some gaps alt method	Very good
Quality, metadata	Excellent	Excellent	Good	Good	Good	OK	Good	Excellent
Breadth & context	Excellent	Excellent	V. good	V. good	Limited	V. good	V. good	Excellent
Availability	V. Good	Excellent	V. good	Good	Good?	Low	Good	Excellent
Logistics	V. Good	V. good	Difficult	V. Good	V. Difficult	V. good	Good	Good
Cost against return	Low?	Medium	Medium	Medium?	High	High?	Medium	Medium
Alternates (proxies)?	Some	None?	Some	Some	None	Perhaps	Various	None
Exploitation	High	High	V. High	Medium	Medium	Low	High	Excellent
Opportunity	Neutral	Neutral	Neutral	Yes	Yes	Yes	Neutral	Yes
Model validation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Benchmark 1	"S": 3 BATS: 2	2	3	1	1	3	3	2
Benchmark 2	3	3	3	3	3	2	3	3

**Summary against CLIVAR**

Panularis/"S": The quality and length of the Panularis/"S" record, plus its location, are its principal strengths. The fact that it has been complemented by BATS for a decade also is a big plus (greater exploitation). Logistic issues are not trivial but its multi-purpose pushes it toward high cost-effectiveness. It is an important element of the observing system for Principal Research Areas D1 and D3.

*Conclusion: "S" should become part of the GCOS/GOOS observing system (i.e. maintained indefinitely).*

HOTS: Has yielded several surprises and is an important source of information on T-S relationships in the upper part of the sub-tropical gyre. Like BATS, HOTS as an excellent record in terms of data availability, exploitation and quality. The limited record suggest it is more relevant to process/BECS studies. The CLIVAR IP does not suggest HOTS is highly relevant to the programme (e.g. D4), though Pacific BECS does allude to the importance of the data. The commitment of U. Hawaii to the station, and the fact that the physics can to some extent piggy-back on the JGOFS needs, are pluses.

*Conclusion: HOTS does not seem to be an indispensable part of CLIVAR plans but does make important contributions as a “laboratory”.*

**Bravo:** The BRAVO data set has a useful but broken record, mostly of good quality. Much of the data reaches the bottom which is essential. The data have demonstrated utility for climate monitoring (a sensor). The time series are accompanied by good metadata and the data sets have been distributed widely. Its principal relevance at present is to the goals of the DecCen and ACC. Its location in the Labrador Sea poses challenging logistic problems and the cost is significant.

*Conclusion: The BRAVO site rates well on most attributes and offers one of the best opportunities for monitoring annual to decadal variability. It should be maintained under GCOS/GOOS (indefinitely).*

**ESTOC:** Its principal strengths are its location, the relevance to the NAO, local and other commitment to the station, and JGOFS support. Like HOTS, the CLIVAR IP does not explicitly attach importance to ESTOC, but there is every reason to believe it will make important contributions to understanding key processes in the eastern Atlantic. The passage of eddies does cause difficulties in terms of signal-to-noise for long-term studies, but a good supporting research program and satellite data alleviate this problem.

*Conclusion: ESTOC will make its most valuable contribution as a site for understanding processes important for the N. Atlantic gyre.*

**KERFIX:** KERFIX is an “exploratory” site located 60 nautical miles south of Kerguelen Island. The record is young but it is in a climatic region where little is known about oceanic variability or about the details of physical and biogeochemical interactions. Thus it rates very highly on novelty and scientific relevance. Its biggest drawback is the harsh environment which imposes severe logistic problems. The extra cost is outweighed to some extent by the political attractiveness of operating a site in Antarctic waters. The uniqueness of the data that have been collected is its dominating asset.

*Conclusion: The KERFIX time series station was a valuable exploratory contribution and strong encouragement should be given for continued maintenance of time series observations in the Southern Ocean.*

**Mike:** Mike is the longest running of all the time series and is approaching its 50th anniversary. There continues to be strong support for the maintenance of the station. For CLIVAR, greater exploitation of the data are needed in order to understand its significance for monitoring the North Atlantic. Its location and known links with variability at locations like Bravo suggest it may be an under-explored resource.

*Conclusion: Mike has the potential to match, perhaps even exceed, the value of Bravo and "S" for DecCen studies of the N. Atlantic. It should be supported as part of the sustained OS.*

**Papa:** In some ways the attributes of Papa appear stronger than those Bravo, though there have been gaps. The CLIVAR IP does not ascribe the same value to Papa as it does stations like Bravo and Panularis, principally because it does not seem to be in a region with strong interannual signals. However, like HOTS, the data are proving useful for monitoring the N. Pacific gyre and there is commitment to trial new technology at the site.

*Conclusion: Papa is a strong contributor for both DecCen and general CLIVAR science, but it lacks the compelling case of stations like "S" for DecCen, or HOTS for science.*

**TAO:** The TAO array will be maintained principally because of its key role in seasonal-to-interannual prediction. However it does also have some long records, stretching back to the late eighties, and, in terms of “breadth” (i.e., supporting surveys and ancillary data), is unsurpassed. It has proved an excellent laboratory site as well as contributing to monitoring and prediction.

*Conclusion: A TAO array is essential on several accounts. The one question for CLIVAR is whether the whole array should be sustained for CLIVAR (as the main focus) or whether greater advantage should be taken of its “laboratory” and experimental role.*

### 4.2.3 Atmosphere and Land Surface Observing Systems

CLIVAR has not developed a programme of atmosphere or land surface observations as part of its sustained observations even though a number of the principal research areas, especially those of GOALS and ACC, require such observations. Instead, for the present CLIVAR is relying on the efforts of GCOS through its joint WCRP/GCOS Atmospheric Observations Panel for Climate (AOPC) to develop such observing systems. The following material on these systems is derived from the GCOS Home Page description of the present state of the GCOS network. Planning for a terrestrial observing system for climate is also being developed by GCOS in association with the Global Terrestrial Observing System (GTOS). Of concern are climate related observations of the biosphere, hydrosphere and cryosphere. Such observations have been identified as of importance to several CLIVAR research areas, especially A1, A2, G2, and G4. The GCOS/GTOS plan for terrestrial climate-related observations is given in GCOS (1997a).

#### The GCOS Surface Network (GSN)

The WMO Commissions for Climatology (CCI) and for Basic Systems (CBS) are working jointly with GCOS to establish a global reference network of land surface observation stations which would include observed data from most land areas, including many mid-oceanic islands, at an approximate density of one station per 250 000 square kilometres. This density of stations is considered adequate, in combination with representative sea surface temperature data, to monitor global and large hemispheric temperature variability and would permit some multi-element analysis. It is intended that the network be regarded as a standard for developing and improving denser national networks and that the existence of the network will encourage the preservation and exchange of data into the future.

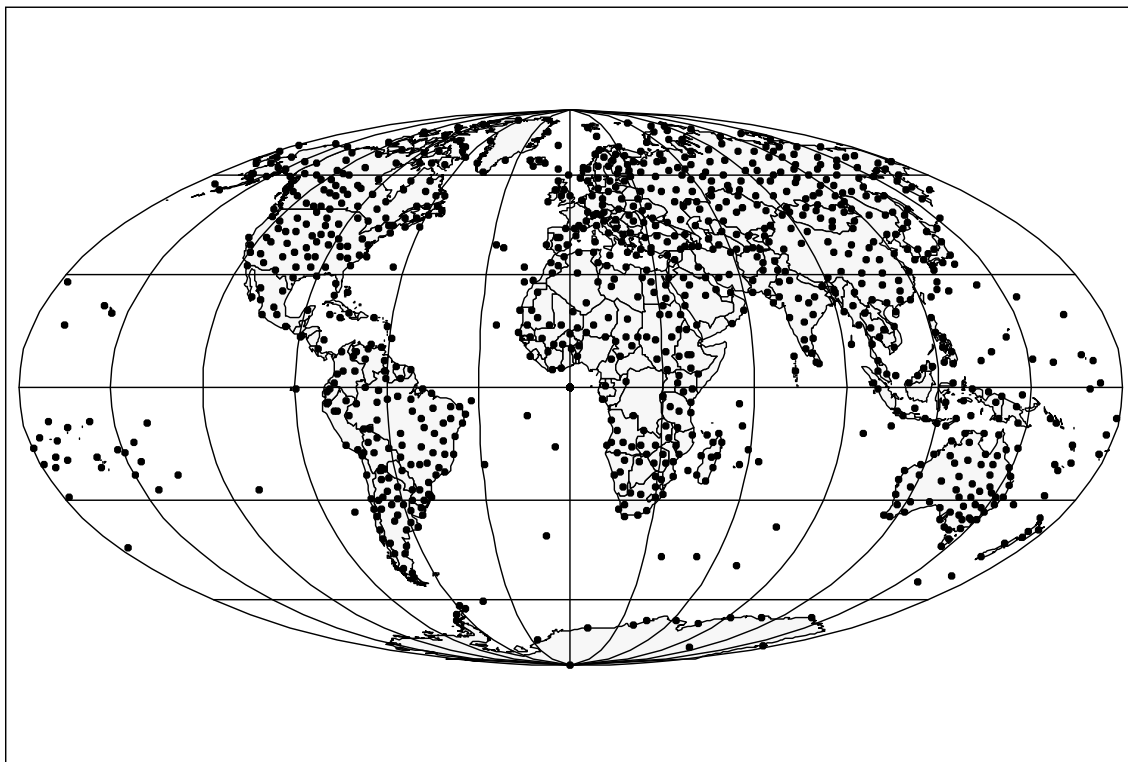


Fig. 6: The initial GCOS Surface Network (GSN) (courtesy of GCOS Joint Planning Office, 1998)

Although currently a large number of weather stations report internationally over synoptic or CLIMAT networks, these stations may not be the best stations for meeting GCOS requirements for climate monitoring. Indeed, many are recently introduced stations that do not have the long records needed for climate studies and the spatial distribution of these stations is very uneven. The selection of GSN stations, by contrast, needs to be based on the suitability of data for climate analysis resulting in a well distributed network of the very best long-term climate stations in the world. The procedure to initially select stations for the GSN was based on a specially developed computer algorithm. WMO members will be informed on this process and will be asked to review and comment on the selection of stations in their country. This overall process is described in the reports GCOS (1996b, 1997b, 1997c). Figure 6 shows the location of the initially selected stations.

#### The GCOS Upper-Air Network (GUAN)

The purpose of the GCOS Upper-Air Network is to ensure a relatively homogeneous distribution of upper-air stations to meet requirements of GCOS. The key issue is to establish a network of stations with reliable prior records, and which can be relied upon to continue in the future. The criteria used by the Atmospheric Observation Panel for Climate to select presently-operating World Weather Watch Global Observing System (GOS) stations to be included in the Network are, in order of importance: (1) the remoteness of the station, which determines its relative contribution to as homogeneous a distribution as possible (given the global land/ocean distribution); (2) the performance of the station in producing high quality observations; and (3) the existence of a reasonable length of historical record.

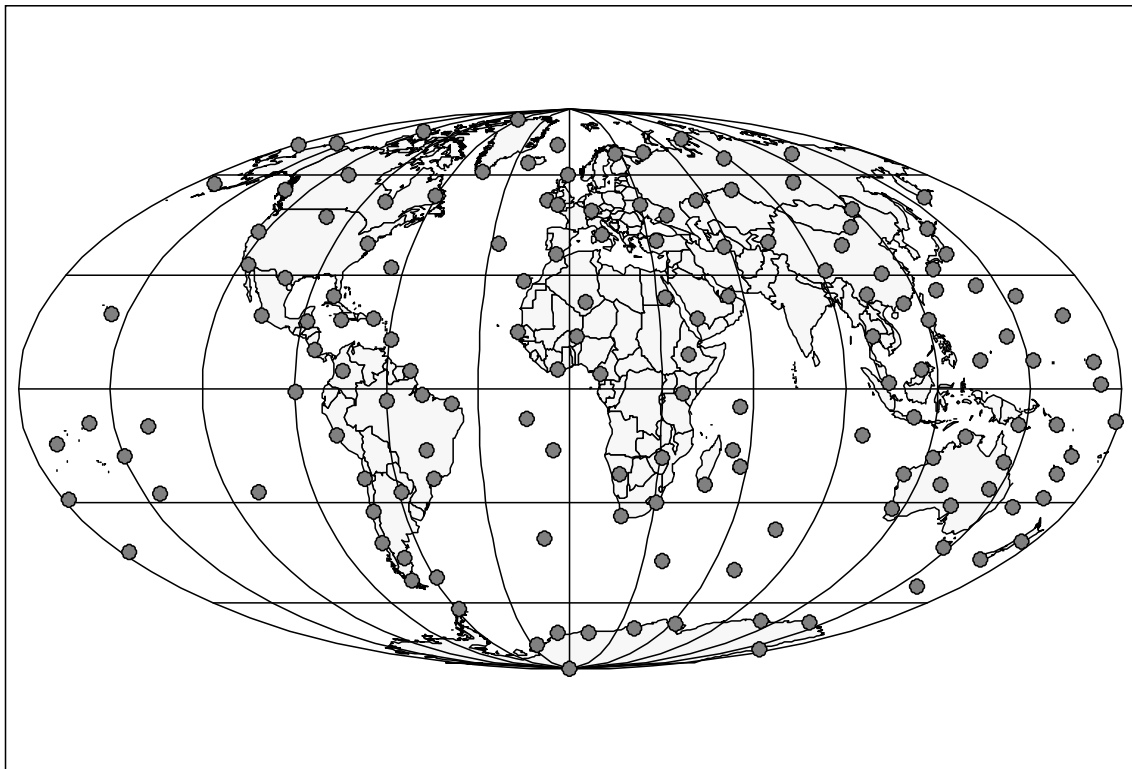


Fig. 7: The initial GCOS Upper-Air Network (GUAN) (courtesy of GCOS Joint Planning Office, 1998)

The selection process considered performance records of existing GOS stations and station quality information from the Lead Centre quality monitoring programme of the WMO Commission for Basic Systems (CBS). It has been noted that the present GOS has experienced and continues to experience problems

in the number, availability and quality of its upper-air network in some areas of the world. Although a number of geographically isolated, and therefore important, sites have been closed for logistic and economic reasons, the density and performance of stations is generally adequate for the GCOS Initial Observing System objectives over the major land areas of the Northern Hemisphere. The situation is not as bright for much of the tropics and the Southern Hemisphere. The current performance of the GOS upper-air network, compared with the performance ten years ago, can be judged by the fact that in 1985 approximately 1500 soundings per day were produced by the GOS while in early 1994 that number was reduced to about 1050 per day. Moreover, it now appears likely that key stations, in particular island sites, will not continue in the future unless action is taken to reverse the decline of the GOS.

The network has been reviewed by the CBS Working Group on Observations and presented to members of WMO responsible for its operation. Members have provided their comments on the proposed stations which in nearly all cases have been accepted by the AOPC. The members have consequently agreed to provide data from these stations as a contribution to GCOS. At the second session of the AOPC (GCOS,1995b), a set of guidelines were developed. The concept of “best practice” was proposed whereby the operators of the stations should consider, inter alia, the following elements:

- long-term continuity;
- provision of detailed metadata;
- use of high altitude soundings (to reach 5 hPa, if possible);
- rigorous quality control;
- back-up release in case of failure or major data loss;
- co-location with atmospheric constituent measurements where possible.

The stations in the network and candidate stations for inclusion are shown in Figure 7.

### **4.3 IMPLEMENTATION AND OVERSIGHT MECHANISMS**

In order to meet its requirement for sustained and intensive observations, CLIVAR will need to have mechanisms in place to ensure that the observations are of the required quality and that this quality standard can be assured, that they have an appropriate spatial and temporal distribution, that where necessary they incorporate the latest technological advances (and that observing method changes do not lead to instrumental biases), that data are delivered to researchers in a timely and user-friendly fashion and that data (along with appropriate metadata) are finally and securely archived.

To some extent CLIVAR will be able to rely on the foundations provided by earlier WCRP projects (in particular WOCE and TOGA), continuing WCRP projects (ACSYS, GEWEX, SPARC) and existing and developing operational mechanisms being used by GOOS/GCOS (WWW, GLOSS, IGOSS, DBCP). However CLIVAR in its own interest must assure that the requirements set by its own particular scientific objectives can be met through the co-ordinating and oversight mechanisms that are being established internationally or through systems that it chooses to institute.

One important conclusion of the GCOS/GOOS Implementation Workshop (GCOS, 1998c) was that the implementation of ocean climate measurements would now be rationalised and streamlined under a single body, provisionally named the Joint Commission for Ocean and Marine Measurements (JCOMM). An interim group is being established among existing mechanisms and the OOPC to assist in this transition. Under JCOMM will be three measurement programmes: (1) A Surface and Marine Programme, (2) A Sub-surface Observations Programme, and (3) A Sea Level Programme. It is expected that much of the sustained observing network recommended here would be implemented through this structure. The recommendations

of the Sydney Workshop have yet to be ratified by either the WMO or IOC but, regardless of these decisions, the Workshop clearly indicated a strong desire to take action on the implementation of the GCOS/GOOS ocean climate observing system, and in a way that offers improved co-ordination and efficiency.

The example of WOCE, which although a massive programme was more limited in terms of the range of its scientific objectives, can show the scope of the oversight task facing CLIVAR. In order to co-ordinate its field programmes, WOCE established the following panels:

- The WOCE Hydrographic Programme Planning Committee (WHPPC) which had a staffed WOCE Hydrographic Planning Office for support
- jointly with TOGA, the TOGA WOCE XBT/XCTD Planning Committee (TWXXPPC),
- also jointly with TOGA the Surface Velocity Programme Panel
- the Moored Array Panel
- the Float Programme Planning Committee, and
- the Geochemical Tracers Panel.

A WOCE Data Management (which became Data Products) Committee was required to oversee the establishment and maintenance of mechanisms to ensure satisfactory data quality and flow (CLIVAR data management issues are discussed in the next section).

As WOCE (and TOGA) advanced, observational methods and networks matured, and the field programme approached its completion, WOCE panels have been dissolved. Recently the functions of SVP and TWXXPPC were formally transferred into the CLIVAR Upper Ocean Panel. As its field programmes are implemented, CLIVAR must ensure that either existing operational oversight mechanisms will be sufficiently responsive to the programme's needs or establish additional appropriate oversight panels that will work in conjunction with operational agencies. The OOPC has performed an important function in this interim period, liaising closely with CLIVAR and the UOP in the determination of the sustained observing system.

#### **4.4 CONCLUDING REMARKS**

GOOS, GCOS, GTOS and CLIVAR share the responsibility for implementation and maintenance of the required networks. Hopefully GOOS/GCOS will take responsibility for the implementation of much of their initial observing system of ocean observations with little or no resource implications for CLIVAR. Nonetheless, CLIVAR requires implementation of the full system of CLIVAR sustained observations and must continue to provide stimuli on the importance of these networks for research and co-operation in terms of scientific advice. For those cases where CLIVAR sustained observations exceed the recommended GOOS/GCOS initial observing system (for example, in the tropical Pacific for G1) responsibility for the sustained network may well fall to CLIVAR, except for those cases where transition to routine operation has been recommended and it might be expected that GOOS/GCOS would assume lead sponsorship in the near future.

## *II. Unifying Themes and Approaches*

## 5. DATA SET DEVELOPMENT, POLICY AND MANAGEMENT

To be useful, measurements of climate variability must be consistent, continuous in duration and of sufficient accuracy and resolution that climate signals can be distinguished from instrumental noise and from high-frequency geophysical signals unrelated to climate variability. CLIVAR anticipates that the existing and emerging operational observing programmes for weather and climate will strive to maximise the benefit of routine observations for climate research use. To improve our knowledge of past climates and develop data sets for validation/comparison of climate model runs, we have to work with what already has been collected or with what can still be teased out of proxy records. A major CLIVAR activity is to improve the quality, consistency and availability of the existing climate data sets. Through data rescue and the use of proxy records, CLIVAR will expand these data sets in time and space to make them more useful for examining climate variability and addressing the issues related to climate change detection and attribution.

In CLIVAR the emphasis will often be on fields of variables, using output from different measurement systems and platforms. For example, SST analyses should utilise observations from ships of opportunity, drifting buoys, moored buoys, and various satellite instruments, perhaps using multivariate analysis and four-dimensional data assimilation. Continued development is required of methods to combine output from different sources as well as of new objective analysis and assimilation techniques, especially for ocean variables. In CLIVAR, the goal will be not only to ensure that climate data are captured, quality controlled, archived and distributed but also that global data products using this data are produced and distributed to CLIVAR participants and climate community at large.

CLIVAR is a research programme completely dependent on the availability of data from a wide variety of sources. Although some of the required data arises from operational sources and is available from the GTS, weather services, space agencies, etc. Other data will be obtained using research funding, sometimes by individual scientists or groups of scientists for their own scientific purposes. Most deep ocean observations, for example, fall in the latter category. To be credible as a coherent collaborative scientific programme, CLIVAR requires a data management and exchange policy which explicitly addresses the unified nature of the programme and its products.

### 5.1 HISTORICAL DATA

Because CLIVAR is concerned with seasonal and longer time scales it is important to make the record of the behaviour of nature as long as possible so that many samples of phenomena are available. To facilitate this

- a. Continued efforts will be made to improve the quality and volume of the historical database through data archaeology and support for the development and evaluation of data sets. Typically there is a need to correct and adjust historical data in various ways to accommodate changes in the manner the measurements were made, changes in locations and temporal sampling, changes in spatial coverage with time, etc. These data are used to determine the past climate record and thus to provide estimates of the variability on interannual and longer time scales. Such variability includes both the natural and anthropogenic components.
- b. Support will be given to ongoing efforts to extend the historical data base, including
  - Comprehensive Ocean-Atmosphere Data Set (COADS) for surface marine data
  - The Comprehensive Aerological Reference Data Set (CARDS) for rawinsonde data in the free atmosphere
  - Data Rescue (DARE)
  - The World Climate Data and Monitoring Programme's Climate Computing Project (CLICOM)



- Global Oceanographic Data Archaeology and Rescue (GODAR)
- The rescue of cryospheric data from the Former Soviet Union

Many data are believed to exist in developing countries that could for their own benefit help in reconstructing the climate record locally and at the same time contribute to the global picture which could place any local climate change in a wider context. These data need to be put into computer compatible form and made available.

Where different compilations of historical data have been prepared, such as for COADS and the U.K. Meteorological Office marine database, continuing efforts should be made to merging them.

The preparation of high-quality, historical climate data sets for climate change detection will be pursued through the CCI-CLIVAR Joint Working Group for Climate Change Detection. This Working Group has the expertise and access to data and station documentation necessary for the detection and removal of inhomogeneities in the historical data. (See A2). The GCOS Data and Information Management Panel (GCOS-DIMP) also has a role in this area. Close co-ordination between the Joint Working Group and the GCOS-DIMP should ensure that duplication of effort is avoided, and that the best quality data sets are produced for climate change detection studies.

## **5.2 REANALYSES**

Past operational analyses are not ideal for climate studies because they contain inhomogeneities resulting from shifts in methodology and because they have been tuned for forecasting purposes rather than for accuracy. For this reason, support for efforts to reanalyze historical data should continue and should be applied to

- atmospheric data
- oceanographic data
- satellite-based products

Current atmospheric reanalysis activities were initiated for the purpose of understanding and predicting seasonal-to-interannual climate variations (Bengtsson and Shukla, 1988).

Presently three reanalysis data sets are available covering different time periods: ECMWF (Gibson et al., 1997) 1979-1994 (Feb.), NCEP (Kalnay et al., 1996) 1958-present, and NASA/DAO (Schubert et al., 1993) 1980-1995. All data sets have their merits and deficiencies and the analysis producers have found errors in their analysis-forecasting schemes. Therefore all three centres are preparing to produce a new data set.

Having a system frozen in time means that any bad points or shortcomings are also frozen in time. Several problems are apparent already in current atmospheric reanalysis efforts: some data are not properly assimilated, treatment of future data is rudimentary, treatment of the Earth's surface is unrefined. Since assimilation techniques will improve, it is expected that reanalysis will become a routine activity starting over again at regular intervals, perhaps every 5 to 10 years.

However, the data base being used in the reanalyses is not temporally uniform and it is essential that numerical experiments be carried out to assess the impact of this non-uniformity. For example, satellite data have had a substantial positive impact on Southern Hemisphere analyses, so it is important to assess whether present analyses are viable in the absence of space-based observations. Reanalyses can only be expected to be as good as the data on which they are based and this must be taken into account in their use.

The most difficult task in carrying out reanalyses is the organisation of the input data base. For the largest part for the atmosphere this is at present being carried out at NCAR. It is worth noting that the assembling and organisation of the data base itself is an extremely valuable activity for climate studies. Complementary efforts are being made with the upper air data base at the National Climate Data Center under a programme called CARDS (Comprehensive Aerological Reference Data Set). These provide an organizing principle for the future archival of data that is incorporated into the operational suites such as in CDAS (Climate Data Assimilation System) at NCEP. This task has to be done only once although data bases can always be improved so that future reanalyses will be much easier to perform, being largely a question of available computer time.

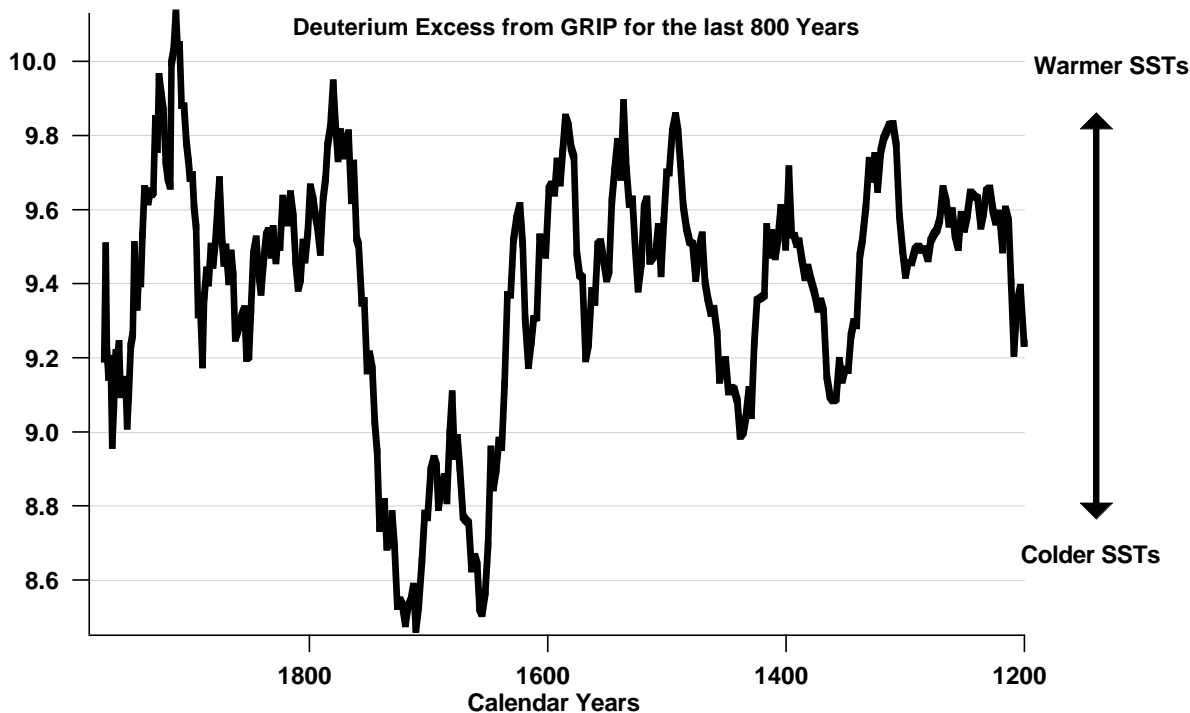


Fig. 8: The Deuterium Excess  $d = dD - 8 \cdot d^{18}O$  of the central Greenland ice core GRIP. The original data are smoothed by a running mean over one year. The precision of the  $d$  measurements is  $\pm 0.9$  permill. The excess signal is interpreted as a signal transporting informations on the climatic conditions (temperature, relative humidity) in the vapour source region to the deposition site. The anomalous low deuterium excess in 18th and 17th century indicates about 1 degree cooler conditions in the subtropical North Atlantic and thus corresponds to a cool period in Europe known as the Little Ice Age (courtesy of G. Hoffmann and J. Jouzel).

### 5.3 PALEOCLIMATIC DATA SETS

Instrumental records are too short to record the full range of climate variability. Consequently, paleoclimatic data sets will be generated in order to provide a comprehensive record of natural (non-anthropogenically-forced) seasonal to interdecadal variability and to put the last 100 years, well-documented by meteorological observations, in the context of the last millennium. Instrumental data available over this period will be used for calibrating paleoclimate proxy.

Time-series of proxy data covering the full length of the last millennium with an annual resolution will be derived mainly from tree ring records or ice cores, but only in a few locations. However, fields of proxy data for air or sea surface temperature and precipitation will be developed at a global-scale for the last 400 years using information provided by corals, tree rings, ice cores, marine and lake sediments, together with available historical data (see Figure 8). Support will be given to ongoing efforts such as the Annual Records of Tropical Systems (ARTS) project, and the international tree-ring network.

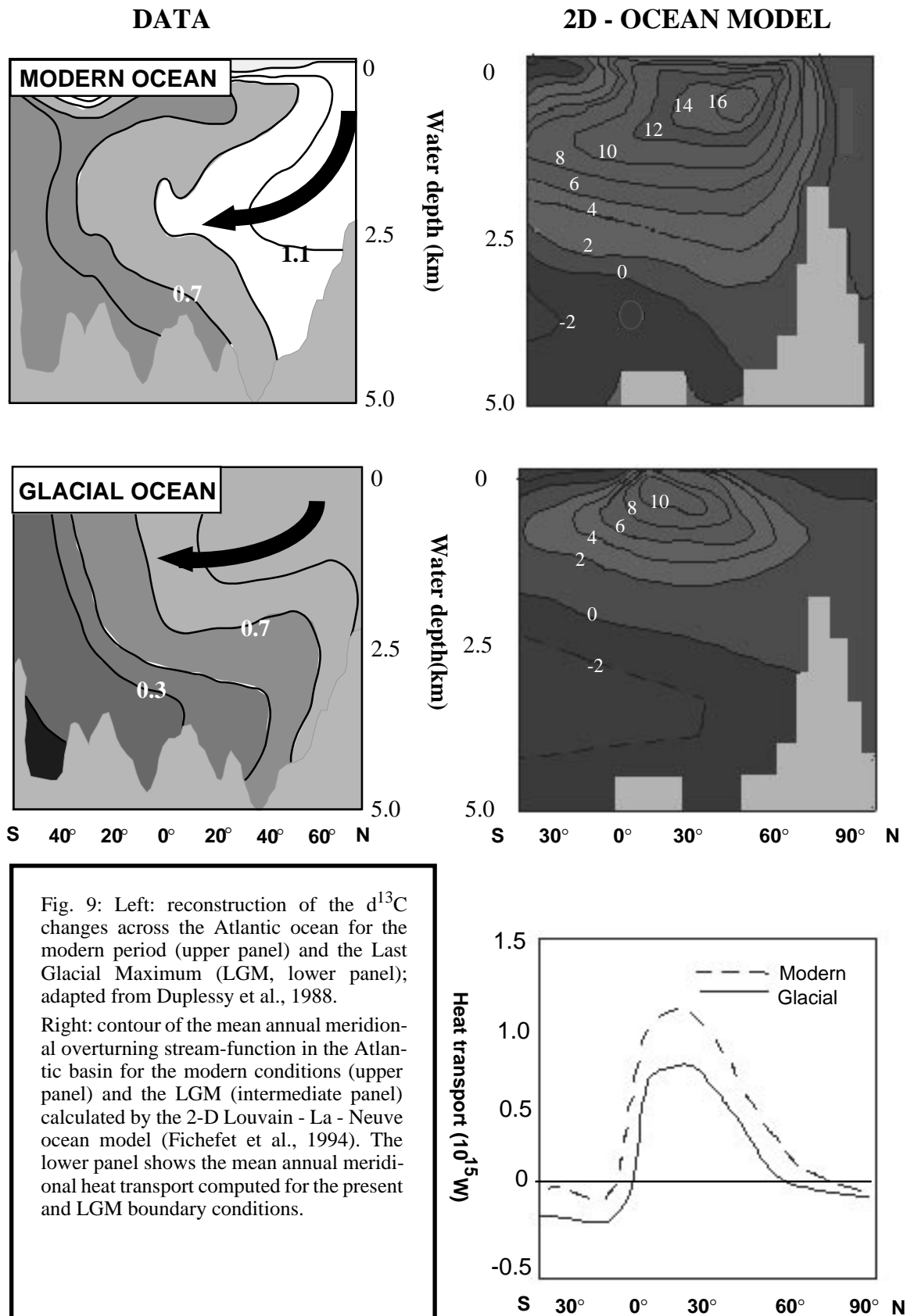


Fig. 9: Left: reconstruction of the  $d^{13}C$  changes across the Atlantic ocean for the modern period (upper panel) and the Last Glacial Maximum (LGM, lower panel); adapted from Duplessy et al., 1988.

Right: contour of the mean annual meridional overturning stream-function in the Atlantic basin for the modern conditions (upper panel) and the LGM (intermediate panel) calculated by the 2-D Louvain - La - Neuve ocean model (Fichefet et al., 1994). The lower panel shows the mean annual meridional heat transport computed for the present and LGM boundary conditions.

Time-series of proxy data (corals, tree rings, ice cores, marine and lake sediments) spanning the mid - Holocene and the last glaciation will be generated to document the climate variability, given climatic states and forcings that are different from today. Specific attention will be given to reconstructing, understanding and modeling climate variability of 6000 and 21000 before present in conjunction with the Paleoclimate Model Intercomparison Project (PMIP) (Fig. 9).

Rapid (<100 years) and abrupt climatic changes that have occurred during the last glacial period and the transition towards the present climate should be investigated in detail. Their geographical pattern and phase relationships need to be established through high resolution synchronised deep-sea, ice core and continental records from both hemispheres. Study of rapid climatic transitions during the Holocene and the previous interglacial (between 120000 and 130000 before present), two most recent examples of warm climatic states, is also likely to be relevant to the possibility of rapid future changes.

Continued effort will be made to improve the volume of paleoclimatic data stored within the existing PAGES data management at the World Data Center-A for Paleoclimatology, and to make them readily available for analysis and model validation

#### 5.4 DATA MANAGEMENT POLICY

Although a detailed data management and exchange policy for CLIVAR remains to be formulated, the general characteristics of such a policy are clear if it is to meet the needs of the Programme. The data management requirements of CLIVAR are similar to those of the preceding research programmes WOCE (see WCRP, 1988) and TOGA. CLIVAR can build on their experience. CLIVAR data management policy must also be fully compatible with that of GOOS and GCOS (GCOS, 1995a; OOSDP, 1995) that have a responsibility to provide an observing system to meet much of CLIVAR's needs for sustained global observations.

**Principles for CLIVAR data**

- Free and open exchange
- Timely exchange
- Quality control
- Metadata (full documentation)
- Preservation of data
- Plan for reuse in reanalyses
- Easy access
- Use of existing mechanisms and centres

A fundamental objective is the free and open sharing and exchange of CLIVAR related data and products among CLIVAR participants (free in the sense that the exchange does not place unwelcome substantive costs on the originator of the data or product). Much of the data required by CLIVAR will need to be made available in near-real time so that it can be assimilated into models to provide fields of physically relevant variables. Other data, such as that obtained from the deep sea, may only be available after a period of time

necessary to assure quality control and, in some cases, to protect the initial rights of scientists that have made large personal investments in obtaining the data. In this context it should be noted that the needs of TOGA and WOCE for the timely exchange of data and recognition of the overall benefit of such exchange has led to some changes of practice in this regard in the oceanographic community. However, lack of adherence to a policy of timely data exchange is potentially a problem for CLIVAR.

Preservation of all data needed by CLIVAR is required. Internationally agreed standards meeting CLIVAR requirements must be used for the acquisition, processing, archival and distribution to the extent possible. Because of the requirement to produce long-term high quality analysis of climate variables, CLIVAR will request that all data, including that submitted in real time, should be submitted in a delayed mode to undergo quality control and full documentation procedures before entering final CLIVAR data archives and products. Where feasible existing international mechanisms for the exchange and storage of oceanic and atmospheric data should be used by CLIVAR. In order to facilitate the quality control, exchange and storage of data required by WOCE and TOGA, these programmes have put in place a number of Data Assembly Centres and Special Analysis Centres. This system is described in Appendix 4 and in part is being adapted and carried forward to meet CLIVAR requirements.

## **5.5 THE GLOBAL OCEAN DATA ASSIMILATION EXPERIMENT (GODAE)**

GODAE is a programme with relevance to CLIVAR that has arisen from an initiative of the GCOS/GOOS/WCRP Ocean Observations Panel for Climate (OOPC) (GCOS, 1996a). It has the general objective:

- to provide a practical demonstration of real-time global ocean data assimilation in order to provide regular, complete depictions of the ocean circulation, at high temporal and spatial resolution, and consistent with a suite of space and direct measurements and appropriate dynamical and physical constraints.

GODAE is founded on the belief that such a demonstration is vital if we are to ever realise a permanent, global ocean observing network and prediction system, with all components functional and operating on a global domain, and delivering useful products in a timely manner. GODAE will emphasise integration of the remote and direct data streams, and the use of models and data assimilation to draw maximum benefit from the observations.

The opportunity presented by GODAE exists because of the development and maturity of remote and direct observing systems that make global real-time observations feasible; the steady advances in scientific knowledge and our ability to model the global ocean and assimilate data at fine space and time scales; and the critical advances provided by research programmes like TOGA and WOCE. From the user side, many opportunities exist for (near) real-time ocean products, including coastal prediction, open-ocean analysis and prediction, and climate forecasts.

GODAE is not a research programme, but a practical test of our ability to deliver useful products, derived from a global ocean data set but assimilated into a skilful model in order to extract greater benefit from the information, and delivered in a timely manner. The emphasis is quite clearly on the ocean, not on the coupled ocean-atmosphere or land-ocean systems. However, there is significant diversity in the objectives and applications, so that GODAE will be a truly multi-purpose experiment.

The initial scientific and technical strategy will be built around several projects, including

- (a) real-time North Atlantic Ocean data assimilation;
- (b) North Pacific Ocean analysis and prediction, with initial focus on the western Pacific, the Kuroshio, and Pacific open-ocean systems;
- (c) using the Equatorial Pacific as a test bed for testing estimation, observing networks, etc.;

- (d) The development of appropriate global surface fields;
- (e) encouragement of prototype global assimilation systems.

Although an initiative of the OOPC, GODAE will exercise a level of independence from existing scientific and operational programmes in order to develop independence, provide freedom of development, and to build a GODAE resource. GODAE will attempt to attract investment, not “recommend” it, in an incremental process. The target for its realisation is 2003-2005. See GCOS (1998a) for details.

## *II. Unifying Themes and Approaches*

## 6. LINKAGES

CLIVAR is a WCRP programme that is global in scope and its area of research encompasses most of the important processes that determine the rich variations of the earth's climate system. It follows that CLIVAR must work effectively with the wide range of national and international programmes that are already in place or are being planned to investigate components of the climate system and the interactions between the climate system and the bio-geochemical fabric of the Earth. Central to this requirement for co-operation are CLIVAR's links to its companion programmes within the WCRP and the core projects of the International Geosphere Biosphere Programme (IGBP). Additionally, the CLIVAR observational programme will rely strongly on the existing and emerging structure and observing systems of the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), the Global Terrestrial Observing System (GTOS) and various operational mechanisms of the IOC and WMO (e.g. IGOS, IODE, WWW). Collaboration with the IPCC process and the International Human Dimensions Programme (IHDP) provide important linkages to climate applications and the social impacts of climate change. Appendix 5 provides an overview of the established or planned linkages to such programmes. More information can be obtained by using the WWW addresses provided by most of the programmes.

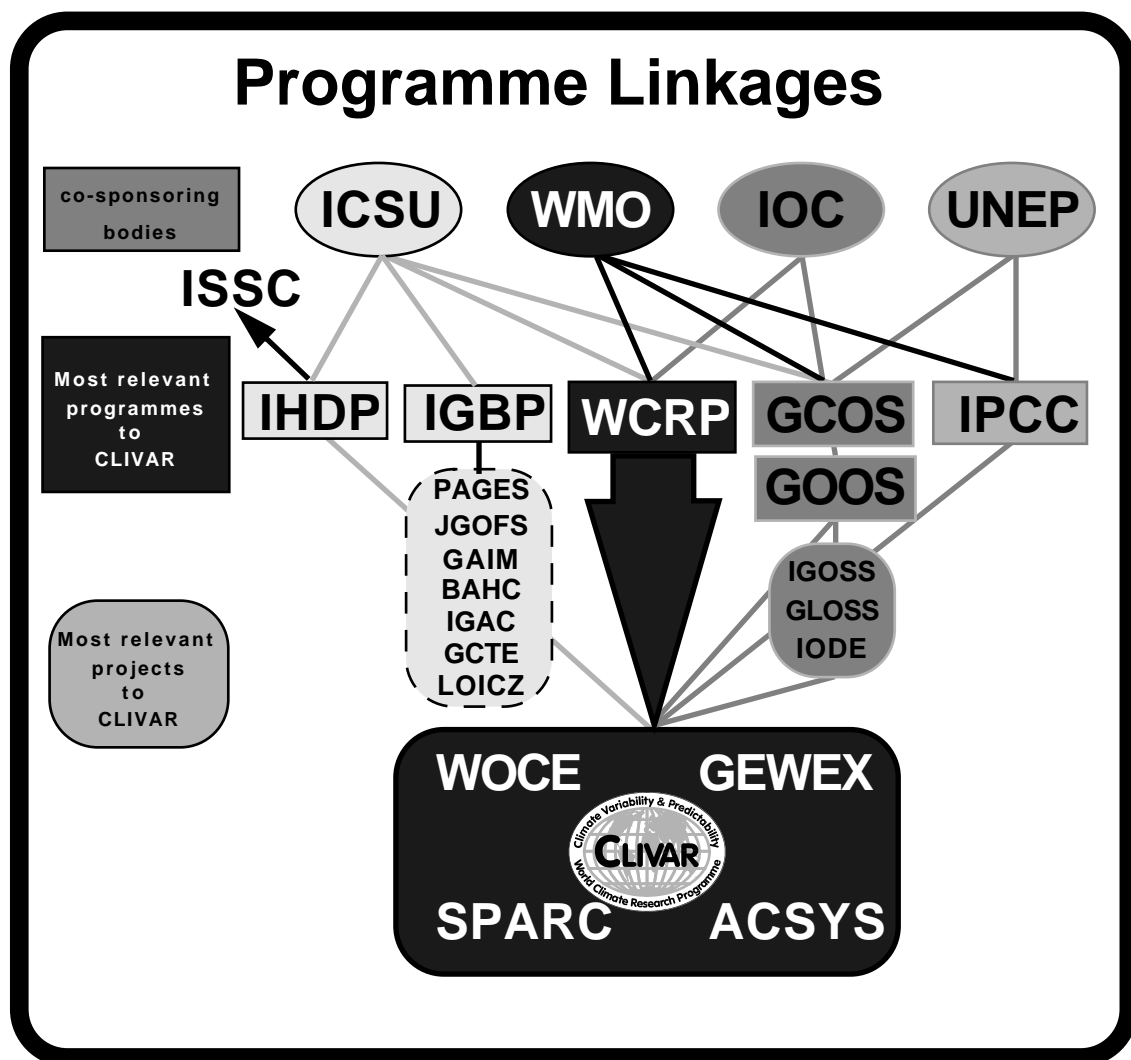


Fig. 10: CLIVAR's most important linkages.



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### III. THE CLIVAR PRINCIPAL RESEARCH AREAS

As explained in the introduction, CLIVAR is being developed along its three streams, the Global Ocean Atmosphere Land System (GOALS), Decadal to Centennial Climate Variability (DecCen), and Anthropogenic Climate Change (ACC). In addition, the initial implementation of CLIVAR will proceed along nine principal research areas with “natural” phenomena at their respective cores (four for GOALS and five for DecCen) and two addressing the prediction and attribution of climate change (ACC).

The previous chapters of this plan have addressed issues that are common to GOALS, DecCen and ACC and their associated principal research areas. In the following chapters, the principal research areas are addressed in some detail and, to the extent feasible and depending on their state of development, the steps that are needed for their implementation, including modelling and observational requirements, are specified. Before the set of principal research areas for each of the three streams of CLIVAR are discussed, a brief description of the overall scope and objectives of the stream itself is provided.

#### (i) CLIVAR GOALS

From 1985-1994 the WCRP developed, planned, and undertook the TOGA Programme, a major study of climatically important air-sea interaction processes in the equatorial Pacific. TOGA succeeded on several fronts:

- describing and making major strides towards understanding ENSO;
- showing that certain levels of predictability of sea surface temperature (SST) in the tropical Pacific exist;
- demonstrating that skillful predictions of SST in the tropical Pacific indicate some skill for temperature and precipitation predictions in selected other parts of the world; and
- demonstrating further that these predictions could be usefully applied for the amelioration of adverse climatic conditions and for the exploitation of beneficial climatic conditions.

Even with these accomplishments of TOGA, the level of research and its application is as yet rudimentary and further progress in understanding, modelling, predicting and applying predictions skilfully can be anticipated by continuing focused efforts. Accordingly, CLIVAR-GOALS has been established to study seasonal to interannual climate variability and predictability of the Global Ocean-Atmosphere-Land System (GOALS) thereby broadening the scope of TOGA to the global domain and encompassing all sources of variability.

The scientific objectives of CLIVAR GOALS are:

- developing observational capabilities to describe seasonal and interannual climate variability, including continuation of the TOGA observing system;
- further developing models and predictive skill for SST and other climate variables on seasonal to interannual time scales around the entire global tropics;
- building understanding and predictive capabilities of the interaction of monsoons with the Indian Ocean, ENSO and land surface processes;
- understanding climate variability and predictability arising from the interaction between the tropics and extra-tropics;

### III. The CLIVAR Principal Research Areas

- exploring the predictability of extratropical seasonal to interannual climate variability induced by the interaction of the atmosphere with oceans, land surface processes, and sea-ice processes and developing means to exploit any such predictability.

TOGA focused on the climate variability and predictability arising from the ENSO phenomena in the tropical Pacific, the importance of which stems mostly from latent heating from large-scale anomalous rainfall that drives atmospheric teleconnections around the world. Other sources of major latent heating in the tropics arise from variations in monsoon systems which also have implications on the global circulation and are of critical importance for peoples living on tropical continents directly affected by changes in rainfall. Accordingly the GOALS strategy is to expand the domain of interest from the ENSO phenomena in the tropical Pacific to encompass global monsoon variability as well as other sources of variability and predictability arising in the extra-tropics.

Predictions of SST need coupled atmosphere-ocean models. Because climatic predictions require initial data, in particular the internal state of the upper tropical ocean and winds, enhancements to the existing operational observing system in the Pacific were initiated under TOGA to provide these data. The heart of these enhancements is the array of moored buoys straddling the equator across the entire Pacific Basin - the Tropical Atmosphere Ocean (TAO) and TRITON (TRIangle Trans Ocean buoy Network) array. Because the system was designed with prediction in mind, it makes data available in real-time: the state of the tropical Pacific Ocean is telemetered automatically through the Global Telecommunication System and is freely available to users. While the system was designed and implemented for research, it is still operative and is now essential for climate prediction. Extension of moorings with the capability of TAO to other regions of the tropical oceans is envisioned as part of GOALS.

The models employed so far have been relatively simple. The use of more complex models with a greater probability of correctly simulating the wide range of physical processes known to be involved offers the possibility of higher forecast skill, skilful prediction at longer ranges, and an expanded geographical range of useful forecasts. Learning to use better the data that exist, increasing the quality, geographic extent, and density of the data, and improving data inputs to the models offer the possibility of still greater forecast skill and range. Other challenges exist in the extra-tropics and in regions more remote from the Pacific that are affected through teleconnections. The need is to improve forecasts of teleconnection patterns and modelling capabilities so that regionally specific information can be given. Learning how to shape, disseminate, and apply the forecasts for useful societal benefit clearly promises a closer and healthier relationship between scientists and the societies that support them.

Special institutions like the International Research Institute for seasonal to interannual prediction (IRI) have been established to accelerate the accomplishment of this task in collaboration with the existing international framework for disseminating meteorological and climatological information.

Major research foci will include improved analyses and model initialisation, modelling and prediction in the tropics, prediction of the extra-tropical atmospheric circulation, and assessments. In order to develop and improve the skill of ENSO-based predictions, it will be necessary to maintain and upgrade an observing system that will require continuing evaluation of its capacity, especially for prediction. There is a need to establish a better scientific foundation for monitoring, to address how different measurement systems can be used together, and how best to use the measurements we have. An important activity is ongoing data-set development and the use of such data-sets for diagnostic and empirical studies, that will improve our description and understanding of what is occurring in nature and how such knowledge may be used to improve climate models and prediction. Focused research projects in CLIVAR GOALS will include field programmes and regional emphases, which will require intensive measuring systems in the ocean and atmosphere from time-to-time.

A major process study called TOGA-COARE (the Coupled Ocean-Atmosphere Response Experiment), took place in the "Warm Pool" region of the tropical Pacific and work needs to continue to capitalise on the field phase of that study. It is important to extend the empirical, process and modelling studies outside the Pacific to other parts of the tropics and, especially, the monsoon systems and their variations. The latter are important for the multitudes of peoples that live in regions directly under their influence. However, as

the monsoon rains vary from year to year, so to do the major latent heat sources in the tropics, which may also be important through teleconnections to climate variations around the rest of the world.

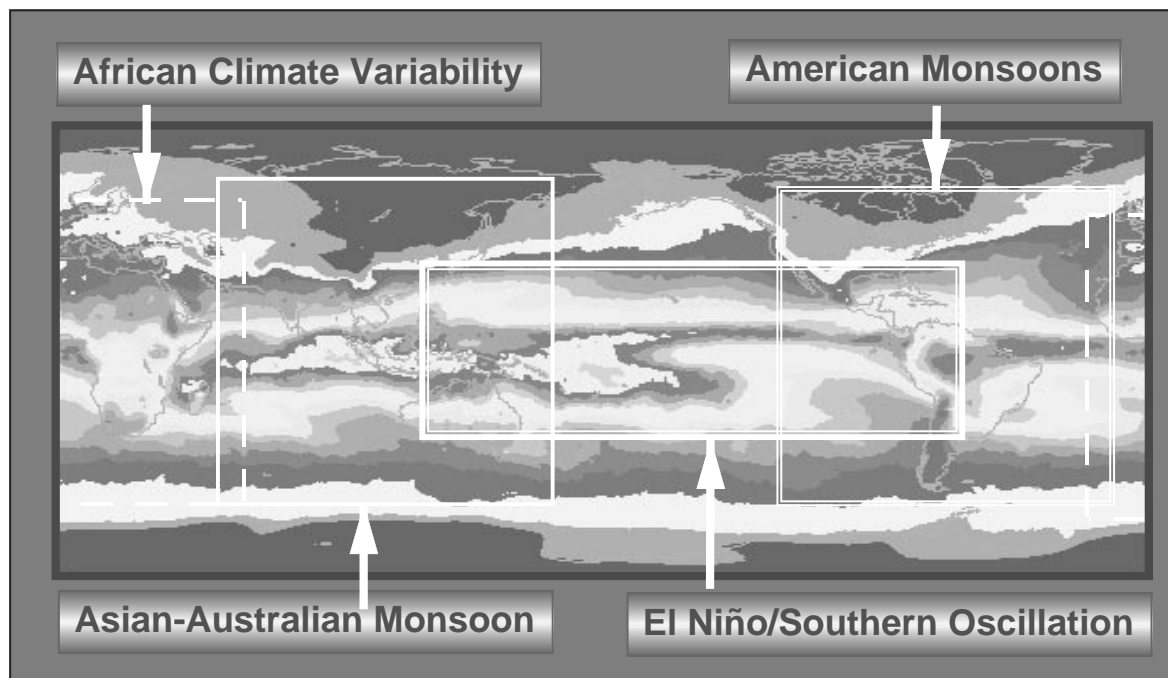


Fig. III.1: The domains of interest of the CLIVAR GOALS principal research areas straddle the tropics but also extend well into extra-tropical regions.

CLIVAR GOALS will extend our understanding, analytical, modelling and predictive capabilities of natural climate variability on seasonal to interannual time scales. Because GOALS has an emphasis on prediction, it will also take an interest in slow components of the climate system that give it a memory. The approach will be to focus on the following principal research areas (see also Fig. III.1):

- ENSO: Extending and Improving Predictions (G1):  
Advancing understanding and observations of climate variability associated with ENSO and global teleconnections to improve prediction and applications.
- Variability of the Asian - Australian Monsoon (G2):  
Developing better understanding of the mechanisms of interannual and interseasonal variations of the Asian-Australian monsoon and to improve their prediction.
- Variability of the American Monsoon Systems (G3):  
Developing better understanding of the Pan American monsoon, its interannual variations, and its origin and links to the Pacific and Atlantic.
- African Climate Variability (G4):  
Initiating studies of the interannual variability and predictability of the African climate and the dependence on SST changes to improve predictions of African climate.

### *III. The CLIVAR Principal Research Areas*

# 1. ENSO: EXTENDING AND IMPROVING PREDICTIONS (G1)

## 1.1 SCIENTIFIC RATIONALE

The WCRP developed, planned, and undertook a major study of the ENSO phenomenon (Fig. 1.1) based in the Equatorial Pacific, the TOGA Programme, which began in 1985 and concluded at the end of 1994. See WCRP (1995) for a summary of the final TOGA conference; NRC (1996) for a comprehensive discussion of the accomplishments and legacies of the TOGA Programme; and Trenberth (1997) for a review and suggestions for future directions, some of which are included below. The TOGA Programme succeeded in not only describing and making major strides towards understanding ENSO, but in also showing:

- that certain levels of predictability of SST in the Tropical Pacific exist (e.g. Chen et al., 1995, see Fig. 1.2);
- that skilful predictions of SST could be made;
- that SST predictions indicate some skill for temperature and precipitation in selected other parts of the world (Fig. 1.3); and
- that these predictions in selected parts of the world could be usefully applied for the amelioration of adverse climatic conditions and for the exploitation of beneficial climatic conditions.

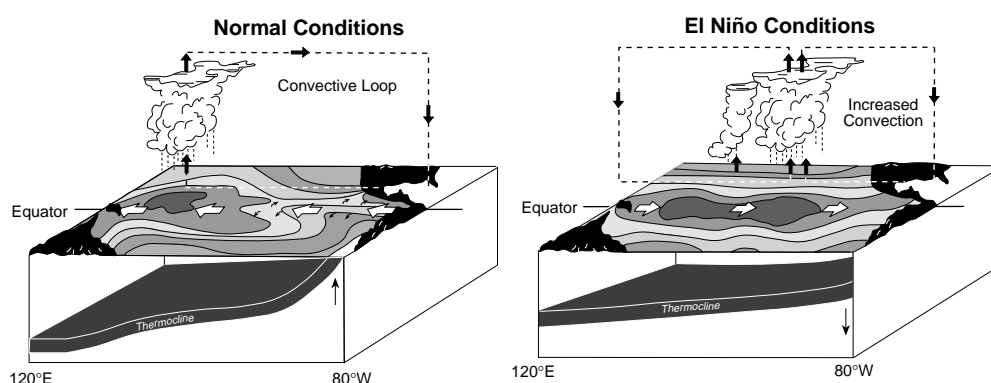


Fig. 1.1: Schematic diagram of the ENSO cycle (courtesy of NOAA/PMEL).

The SST predictions use coupled atmosphere-ocean models. Because the climatic predictions require initial data, in particular the internal state of the upper tropical Pacific ocean and the winds, an enhancement to the existing operational observing system was deployed (originally the TOGA Observing System, now the CLIVAR Observing System) to provide these data. Because this observing system was designed with prediction in mind, it makes data available in real-time: the state of the tropical Pacific Ocean is now telemetered to the Global Telecommunication System (GTS) and is freely available to all the day it was taken. While the Observing System was designed and implemented for research purposes, it has proven so essential for prediction that it has survived the end of the TOGA Programme and is still operative. The latter refers not necessarily to the transitioning of the system to an operational agency but merely that the infrastructure exists to sustain an ongoing commitment to making the necessary observations. An example is the TOGA TAO array of moored buoys in the tropical Pacific, as outlined by Hayes et al. (1991) and McPhaden (1993, 1995). The latter is maintained by a multinational group spearheaded in the United States by the Pacific Marine Environmental Laboratory (PMEL) of NOAA. There are many other examples.



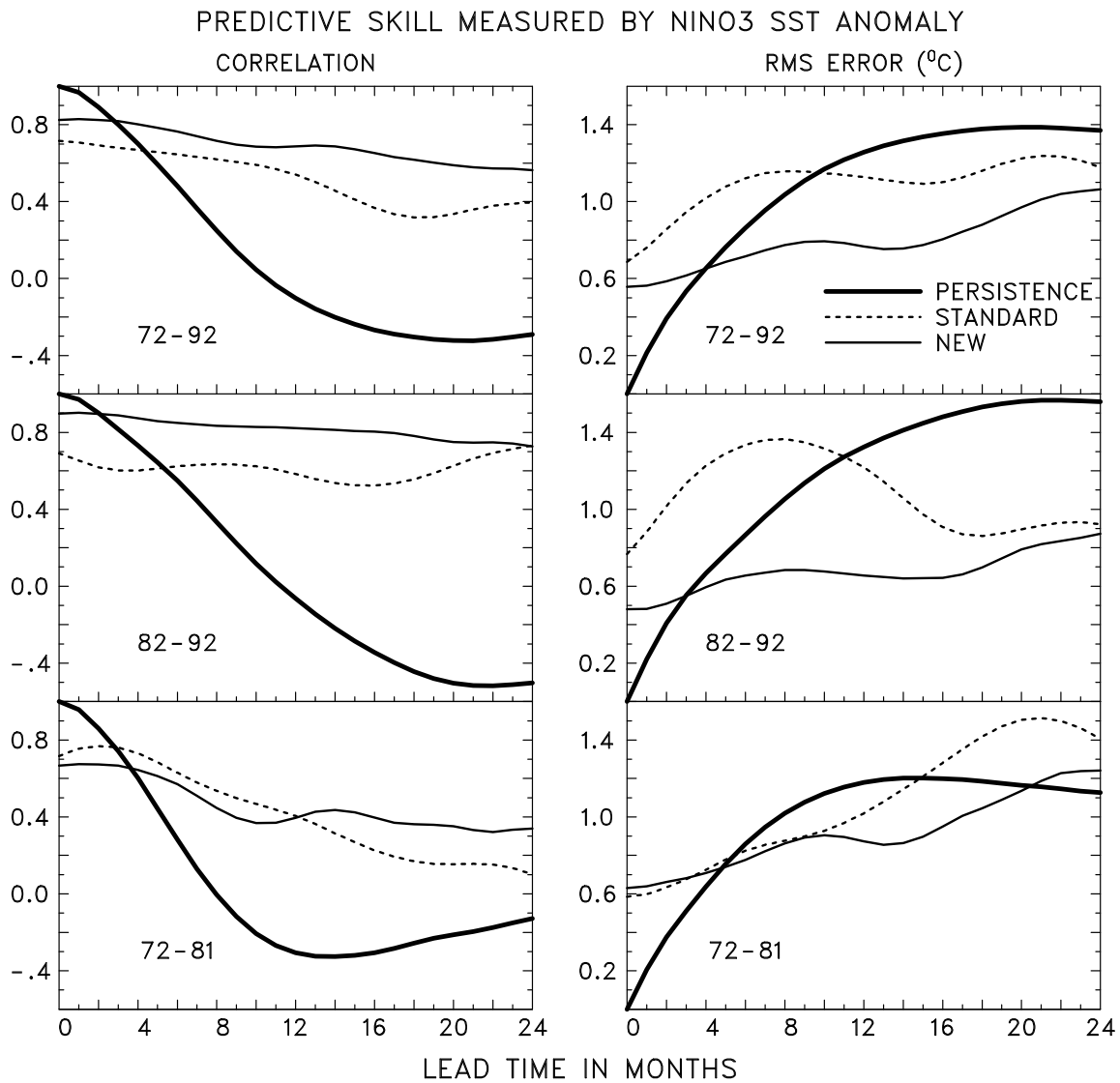


Fig. 1.2: Correlations and rms errors between predicted and observed Niño-3 SST anomalies for three different time periods. Results are shown for the standard Lamont model of Zebiak and Cane (1987), the improved (new) model and persistence (from Chen et al. (1995)).

Some skill of SST prediction has been demonstrated by a long series of monthly hindcasts and forecasts. Approximately 300 of these forecasts have been performed and useful skill in forecasting SST in the tropical Pacific out to a year in advance has been shown to exist (Fig. 1.2). The climatic variability of a number of far-flung regions of the world correlates so strongly with SST variability in the tropical Pacific on times scales up to interannual that forecasts of these SSTs have some predictive value. Precipitation and/or temperature in parts of Australia, Indonesia, Borneo, Sulawesi, Peru and Chile, in particular, have high predictive value while Zimbabwe, Brazil, Ethiopia, and the north-western part of the North American continent currently have lower predictive value (Fig. 1.3). Some of these countries and regions have learned to use what predictive skill the forecast offers for applications to agriculture and water resources. They have generally found the results beneficial (although it is far from obvious how to use to best advantage a forecast of future climatic conditions that contains uncertainty). Those poorer countries that endure in semi-arid local climatic conditions have found the forecasts especially useful-indeed having major societal benefits. The provision of climate forecast information in a form that countries can use to benefit their societies is a welcome and exciting way in which the wealthier countries of the world can help the poorer countries to help themselves.

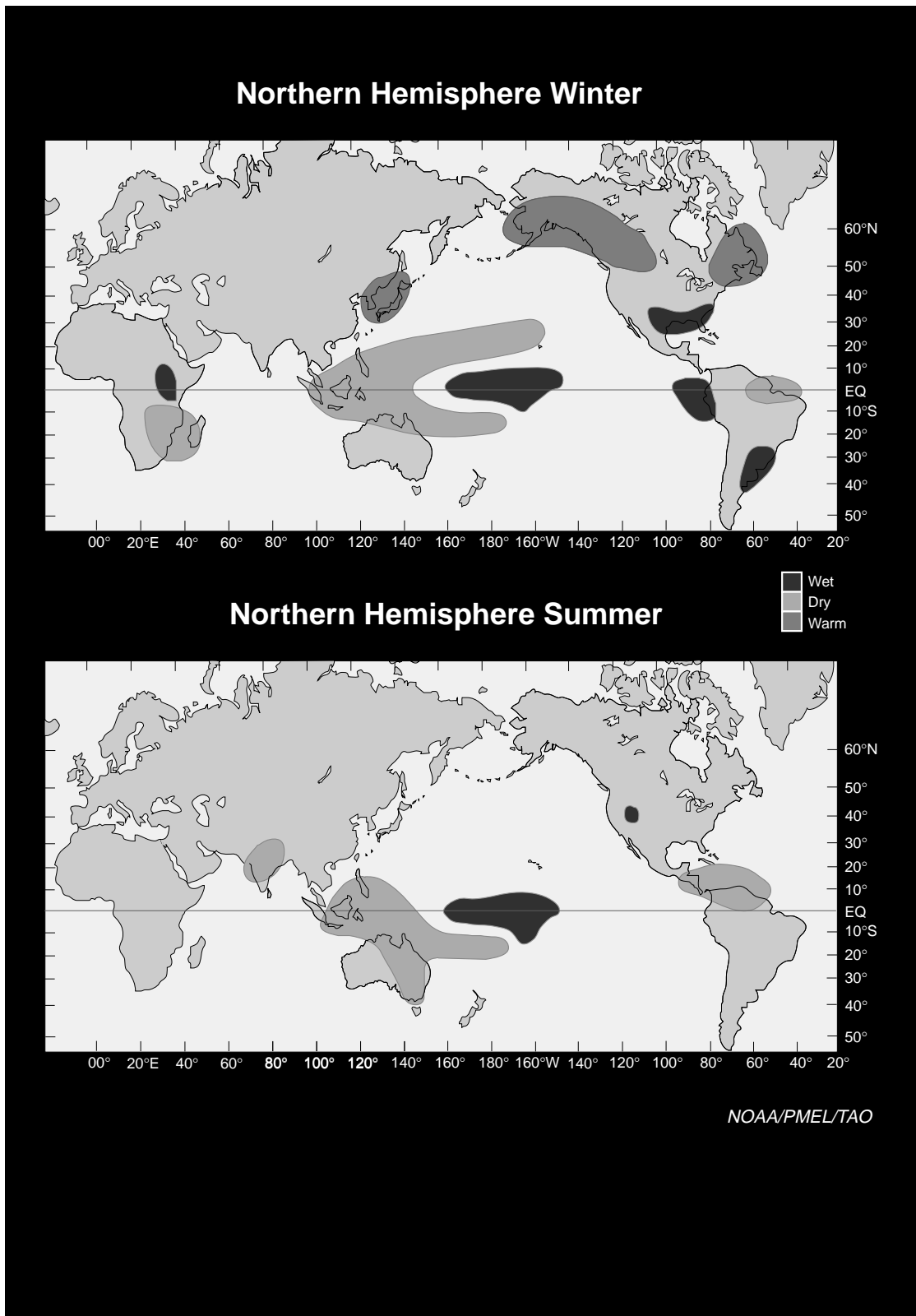


Fig. 1.3: Schematic of temperature and precipitation anomalies generally associated with the warm phase of ENSO during the northern winter and summer seasons. To a good approximation, relationships with the cold phase of ENSO are simply reversed in sign. [After Ropelewski and Halpert (1986, 1987, 1989), Halpert and Ropelewski (1992) and supplemented by Aceituno (1988)] (courtesy of NOAA/PMEL).

While the efforts up to now have been beneficial to societies and energising to scientists, the effort is as yet rudimentary and much further progress in understanding, modelling, prediction, and in applications of the predictions can be anticipated by continuing focused efforts. The models so far have been relatively simple. The use of more complex models with a greater probability of correctly simulating the wide range of physical processes known to be involved offers the possibility of higher forecast skill, skilful prediction at longer ranges, and an expanded geographical range of useful forecasts. Learning to use better the data that exist, increasing the quality, geographic extent, and density of the data, and learning how better to initialise the models offers the possibility of still greater forecast skill and range. At present predictions exhibit some indications of seasonal and decadal changes in reliability, which is an element of on-going research (see Latif et al., 1998). Other challenges exist in the extra-tropics and in regions more remote from the Pacific that are affected through teleconnections. The need is to go beyond simple correlations and improve forecasts of teleconnection patterns and modelling capabilities so that regionally specific information can be given. Finally, learning how to shape, disseminate, and apply the forecasts for useful societal benefit clearly promises a closer and healthier relationship between scientists and the societies that support them. All these issues need to be addressed on a continuing basis and in a focused manner—the pay-offs, both scientific and societal, could be enormous. It is worth noting that this research activity builds on the heritage of the TOGA Programme and the TOGA observing system. This provided an incentive for building infrastructure to capitalise on the beginnings of predictive skill and because of the great potential for socio-economic benefits in many countries.

In particular, the International Research Institute (IRI) for seasonal-to-interannual climate prediction was proposed as part of the TOGA Programme by the Intergovernmental TOGA Board and is being moved towards international implementation. As originally proposed at UNCED and confirmed in the November 1995 “International Forum of Forecasting El Niño: Launching an International Research Institute”, the United States is providing initial support for the IRI. At the same time it is pursuing discussions with other interested countries and organisations which will lead to the establishment of a fully multinational institute. Acting under a co-operative agreement with the U.S. National Oceanographic and Atmospheric Administration (NOAA), Columbia University's Lamont-Doherty Earth Observatory, in collaboration with the University of California's Scripps Institution of Oceanography, is focusing the initial effort on the establishment of an IRI core facility. This facility will provide the necessary scientific and institutional focus for a comprehensive programme of climate prediction on seasonal-to-interannual time scales. An important point to note, however, is the word “research” in the title of this budding institute as it is clear that much more needs to be done to make predictions really useful and to know how to use the somewhat uncertain information most profitably. Major weather forecasting centres around the world, in Europe, Australia, and the United States also have operational programmes designed to capitalise on the predictability that is already under way. In NOAA within the United States, an operational programme has been developed called the Seasonal-to-interannual Climate Prediction Program (SCPP). As the IRI becomes established as a truly multinational centre, it will be essential to develop co-operative research endeavours. This role is rather different than the research programme established under the TOGA programme, where there was little infrastructure in place.

## **1.2 ANALYSES, MODELLING AND PREDICTION**

### **1.2.1 Analyses and model initialisation**

The operational flow of information begins with basic observations, many of which are telemetered to user sites via satellite links and through the Global Telecommunications System. The TOGA Programme emphasised the importance of real-time reporting of climatological observations. The observations are assembled and quality controlled, and then analysis takes place of all the observations of one or more variables into spatial fields, often in conjunction with operation numerical weather prediction. Commonly this results in maps or gridded fields of one or more variables. There are always assumptions, approximations, extrapolations and/or interpolations involved as well as some kind of model, whether statistical or physically based, to produce these fields. The most complex physically based model is a full model of the climate system, or perhaps a component of it such as an AGCM which is used as an integral part of a four dimensional data assimilation (4DDA) process. In 4DDA, the model is initiated from a previous analysis and a forecast

is made of the state of the fields at the time of interest. The forecast fields are then combined in a statistically optimal way with all the new observations to produce a dynamically and physically consistent set of fields. This means that the error characteristics of the forecast must be known and accommodated, and the analysis is multivariate and takes into account the dynamical relationships among the climate variables and their spatial and temporal scales of variability. Similar methods are now being applied in the ocean (Ji et al., 1995).

To utilise dynamically based models for prediction, it is essential to initialise the fields of many variables. Most important is the tropical Pacific Ocean, but emerging information indicates the importance of also spinning up and initialising the land surface conditions, and the soil moisture in particular, to improve land surface process feedbacks and precipitation forecasts. The tropical Pacific is less sensitive to the atmospheric initial conditions.

As models are developed, the technical aspects of coupled data assimilation must proceed concurrently. The basic problem of data assimilation is to use the existing atmospheric and oceanic data properly combined with the model to give an optimal estimate (not a perfect characterisation) of the state of the coupled system at any given time (Chen et al., 1995). For complex coupled ocean atmosphere GCMs, this is a formidable task but is an essential element in initialising a forecast and is also essential in providing an analysed data set for diagnostics and analysis. The estimate of the state of the coupled system may be good but it may not be compatible with the model, so that the model predictions can be erratic. Each coupled model has its own peculiarities and idiosyncrasies and accepts initial data in different ways. A way must be found to initialise each model so that the forecast error at the initial time (the 'nowcast' error) is at a minimum and that the model does not create unrealistic shocks that would degrade the future evolution of the forecast. It is important to realise that the best analysis and best-initialised state may not be the same thing, although as models improve, presumably these converge to the same thing.

### 1.2.2 Modelling and prediction in the tropics

We have learned that the ENSO phenomenon depends essentially on the interaction of the atmosphere and the ocean. The most appropriate basic tool of ENSO simulation and prediction, therefore, is the coupled atmosphere-ocean model of either the tropical Pacific region alone, or of the tropical Pacific region embedded in a larger geographical region. Allowing the coupled model to run freely allows the characteristics of the freely evolving ENSO to be simulated, and initialising the system at its present value allows predictions to be made. In practice the atmosphere in the tropics depends mostly on the SST (at least on monthly and longer time scales) so that it is mainly the ocean that needs to be initialised. The coupled system is then allowed to evolve freely for however many months forecast is desired.

The inception forecast was made with a simplified, coupled model that was designed to capture the essential physical processes of the ENSO phenomenon (Zebiak and Cane, 1987). It assumed the annual cycle was given and unchanging for all time. The model had the advantage of simplicity: it was relatively easy to analyse, was computationally efficient and could therefore be run for long periods of times, and/or many forecasts could be performed. We have learned now that some omitted physical processes could be important at certain times and in certain regions. Further, the data have become more detailed than the simplified model was designed to accept. Consequently, the construction and testing of more complex models, in particular coupled models, each consisting of an atmospheric GCM coupled to an oceanic GCM, has begun.

Coupled GCMs are computationally slow, difficult to understand and analyse, and still do certain processes poorly, especially those concerned with clouds. The processes concerned with the annual cycle have in particular proven unusually (and unexpectedly) difficult and progress has been slow. Their very size and complexity make data assimilation and model initialisation difficult and unwieldy. While future progress is expected to be slow, the coupled model development effort is absolutely essential for improving future simulations and predictions of ENSO. Coupled GCMs are currently being scrutinised in an intercomparison as described with regard to WGCM.

### 1.2.3 Prediction of the extra-tropical atmospheric circulation

SST variations in the tropical Pacific can have considerable impact on the extra-tropical mean state. In the tropical atmosphere, anomalous SSTs force widespread anomalies in convection and large-scale overturning, with strong upper tropospheric divergence and convergence. The latter directly or indirectly results in teleconnections which arise through Rossby wave forcing, dispersion, and propagation and which are complicated by interactions with stationary planetary waves and non-linear effects, as well as feedbacks from changes in storm tracks (Fig. 1.4). The response of the extra-tropical atmosphere naturally induces changes in the underlying surface, so that there are changes in extra-tropical SSTs and changes in land-surface hydrology and moisture availability that can feedback and influence the total response. Land surface processes are believed to be especially important in spring and summer.

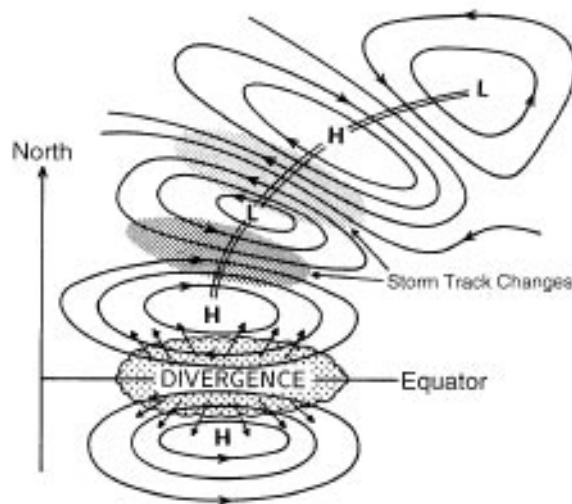


Fig. 1.4: Schematic view of the dominant changes in the upper troposphere, mainly in the Northern Hemisphere, in response to increases in SSTs, enhanced convection, and anomalous upper tropospheric divergence in the vicinity of the equator (scalloped region). Anomalous outflow into each hemisphere results in subtropical convergence and an anomalous anticyclone pair straddling the equator, as indicated by the streamlines. A wave-train of alternating high and low geopotential and streamfunction anomalies results from the quasistationary Rossby wave response (linked by the double line). In turn this typically produces a southward shift in the storm track associated with the subtropical jet stream, leading to enhanced storm track activity to the south (dark stipple) and diminished activity to the north (light stipple) of the first cyclonic centre. Corresponding changes may occur in the Southern Hemisphere (from Trenberth, 1997).

It is desirable to determine a “signal” of tropical SST anomalies in the extra-tropical atmosphere. However, any such signal will be embedded within the “noise” of natural variability associated with mid-latitude weather systems. The noise must be regarded as unpredictable, while the signal might be potentially predictable given a very good model and a good forecast of the tropical SSTs. The signal-to-noise ratio provides a measure of the predictability. If the same SST anomaly is used for many cases with different starting conditions, an ensemble is created that can be used to generate statistics of the results. In this case, the signal is the reproducible component while the scatter among the members of the ensemble is a measure of the noise. The signal can be regarded as “externally” forced, while the noise depicts the “internal” variability. As well as being useful for predictability studies, this approach is used for making forecasts, although results depend on the veracity of the model and thus are model-dependent (see Trenberth et al., 1998).

Although the ensemble mean is but one candidate among many AGCM integrations for possible predictions, it offers the particular advantage that it is also the region of maximum likelihood for individual events and thus it is the best possible prediction. The ensemble also provides other information and the spread can be regarded as a measure of the second moment, while the total distribution of forecasts is an approximation to the probability density function (PDF) of atmospheric states. Any point on the PDF is a possible realisation for that variable (or the spatial pattern) and knowledge of the PDF allows probabilities to be assigned. Because the observed value may be on the wings of a PDF, it follows that even with a perfect model the skill of the ensemble prediction need not always be high.

As well as enhancing the signal through ensembles, another prospect for increasing signal-to-noise ratios from those for monthly means is to take longer time-averages. Here the enhancement depends upon the time averaging not unduly affecting the atmospheric signal but leading to a reduction in the unpredictable noise. Indeed results show that increased time-averaging leads to some reduction in the external variance as a consequence of non-stationarity of the atmospheric signal, but nonetheless, time averaging improves the signal-to-noise ratio and this has practical forecasting implications because only one possible outcome is realised. For 5 month time-means, SST forcing results in a 55% signal-to-noise ratio compared with 21% for the monthly means for 200 hPa height over the Pacific-North American region (defined as 180°W-60°W and 20°N-80°N) (Trenberth et al., 1998).

All of these extra-tropical predictions depend upon reliable forecasts of SSTs, and tropical Pacific SSTs in particular. For coupled prediction systems, errors in the SST forecast also have an adverse impact on atmospheric predictions. To a certain extent, the prediction errors in the SSTs can be corrected by statistical intervention and the AGCM can be re-integrated with corrected SSTs. Such “two tiered” schemes for SST-based seasonal prediction are the first logical step towards a fully coupled seasonal prediction system (Bengtsson et al., 1993). While the accuracy of tropical Pacific SST predictions is expected to improve, analysis of the AGCM ensemble integrations forced with observed SSTs indicates that for the extra-tropical atmosphere, the usefulness of the tropical SSTs as predictors may be limited. The dominance of the extra-tropical natural variability over modest SST-related signals implies that the extra-tropical atmosphere is only weakly constrained to select the SST-forced signal. Alternatively, it is only when the expected anomalies of SST are large in the tropics that a reliable forecast can be expected for the extra-tropics. An example is given for 1982-83 in Bengtsson et al. (1993).

Because predictability depends on both signal and the noise, it is important to analyse the dependence of the internal variability on SST forcing. Predictability activities must deal with better definition of the signal and the noise, and how they are model dependent. The predictability will be a function of location, time of year, and variable, and may depend on the kind of regime operating at the time. It is fairly well established that it is only when the expected anomalies of SST are large in the tropics that a reliable forecast can be expected for the extra-tropics. It will be important to determine the relative importance of various physical processes and develop better parameterisations of them. Predictability of higher order statistics, such as the number and distribution of storms, the sequences of precipitation, and extremes will become more important. Research into prediction should be done with real initial conditions and boundary conditions, and a determination made of those aspects is most important. Case studies should be carried out. As noted above, AGCMs can be very useful but it is difficult to separate out the signal from the weather-noise, and ensembles must be generated. Moreover, the models are not perfect so that results concerning predictability are model dependent. The use of ensembles to provide estimates of the probability distribution function and thus to provide more useful information to users will be at the frontier of much of this research. Prediction is the ultimate test of the models and our understanding, and it has the biggest payoff.

#### 1.2.4 Prediction and assessments

With the analysed and predicted fields in hand, a synthesis is made of what all the fields together imply for the current situation. Use is made of these fields for climate monitoring and actual forecasts are likely to be based upon not only dynamically based predictions but also statistical and empirical techniques and simpler models. It is likely that secondary models will need to be developed to predict societally relevant

quantities. Finally, an overall assessment may be made of all the information on the situation at the current time, resulting in the issuance of an advisory and/or a forecast and possibly impact statement for up to a year in advance which could be followed by various actions. In addition, the original observations and various products generated along the way must be archived and made available to various users.

In order to improve the skill of predictions and to recognise and evaluate the reasons for that skill, commitment must be made to continuing regular and systematic prediction, and to a regular and systematic diagnosis and evaluation of the skill achieved. Since we do not yet have much experience with prediction by coupled GCMs, and since it is not yet clear what makes a coupled model skilful for forecasting, it is important to use several models and carefully intercompare their successes and failures. Extensive diagnosis and evaluation of models and the real world together are a key part of developing and testing models.

Another activity that has proven very fruitful in highlighting model shortcomings and providing incentives for improvements are model intercomparisons of various sorts. Not only are the models compared under constrained conditions, but also the modellers are brought together to exchange information and ideas on model developments and applications.

Application of forecast information is inherently done locally. This highlights the importance of regionally specific information, whenever possible. Accordingly, an activity that must be fostered is the “downscaling” of information to the local level. The most promising approaches to do this at present are using statistical methods and regional climate models embedded in the global models. The latter are usually applied after the global model has been run so there is only one-way interaction. Results depend on the location of the boundaries of the limited area high-resolution domain and such approaches can not overcome problems in the large-scale models, but show considerable promise for refining results by better taking into account the detailed topography and land surface properties.

#### **1.2.5 Current projects**

A major part of the overall on-going programme of modelling studies co-ordinated through NEG-1 are of importance for G1 research (see Section II 2.2.1 for a description of NEG-1 activities). While all of the initial focused project being addressed by NEG-1 have some relevance to G1, those dealing with the intercomparison of Niño-3 predictions and predictability and the ENSO Intercomparison Project (ENSIP) have particular relevance. As G1 progresses, the modelling programme of NEG-1 will address additional G1 issues.

### **1.3 OBSERVING NEEDS**

In order to develop and improve the skill of ENSO prediction, it will be necessary to maintain an appropriate observing system. Recent evidence from predictive models suggests that it may be necessary to extend the present TAO/TRITON arrays to other tropical oceans. Such an observing system will build on the existing elements of the CLIVAR sustained observations in the tropical Pacific as well as the meteorological network. This includes the observations required to determine SST, winds, upper ocean temperature, surface and subsurface salinity, currents and sea level. The platforms used include the important moored TAO array (to be supplemented by TRITON), VOS, drifting buoys, tide gauges and the satellites carrying AVHRR, altimeters, scatterometers, etc. The location of the mooring arrays and VOS lines is shown in Figure 4, Section II 4.2.1). From time-to-time, additional observations will be required for special research initiatives but at present these have not been developed.

The TOGA observing system (McPhaden et al., 1998) was constructed and is being maintained to provide the data for development of prediction systems and on-going predictions of ENSO. The heart of the system, the array of TAO and TRITON moorings (see Fig. 2.8, page 103), was designed to capture the major scales of variability of the wind. While the designers had ENSO prediction in mind, it was not designed specifically for ENSO prediction since that was impossible at the time. It is not clear that the number or placement of the moorings is optimal (or even adequate) for future predictions. On the other hand, it may

turn out that the overall observing system has elements that either can be better (or more inexpensively) measured some other way or are not needed at all. For example the availability of high quality scatterometer and SSMI winds could completely alter perceived needs, provided a scatterometer system can be sustained and is reliable.

The maintenance of an appropriate observing system requires a continuing evaluation of its capacity with the skill of forecasting being the ultimate, if not immediate, arbiter of its acceptability. Important research questions are to establish the science behind monitoring, to address how different measurement systems can be used together, and how we can best use the measurements we have. This includes observing system evaluation and establishing the need for observations and the right degree of redundancy to allow for error checking. An important principle for the observing system is that it should not be developed in isolation. The focus should be on fields of variables, independent of the platform used to obtain the actual measurements. Frequently, multiple platforms will be both necessary and desirable. This is especially the case, for example, in utilising space-based observations because ground truth is required and the *in situ* observations should also be fully exploited. The research programme will provide information on the optimal mix of observations from different platforms as the technology and economics of each change.

There is a need for a much stronger link between those taking the observations, and the users of the observations and various derived products. The IRI can potentially play a strong role in better establishing this link. By focusing on fields of variables, there is also implicit a strong link to one or more users, so that a constant evaluation of the quality and utility of the products should be built in. Use of models is an inseparable part of this process because models of some sort are required to translate the disparate individual asynoptic observations into global, or at least regional, fields. More comprehensive land and ocean data assimilation is needed. Moreover, modelling studies, known as observing system simulation experiments (OSSE) (see 1.4) can provide definitive information on the optimal design and blend of observations.

It is hoped that the research programme will have a stable and reliable base of climate observations under the Global Climate Observing System (GCOS), which will include an international framework for dealing with both *in situ* and space-based observations. The free and open exchange of data in a timely manner is of crucial importance for all the research programmes.

## 1.4 FOCUSED RESEARCH PROJECTS

Other focused research projects in CLIVAR will involve field programmes, undoubtedly with extensive measuring systems set in place in the ocean and atmosphere. A major process study under TOGA took place in the “Warm Pool” region of the tropical Pacific called TOGA-COARE (the Coupled Ocean-Atmosphere Response Experiment), and work needs to continue to capitalise on the field phase of that study. While the possibilities for focused process studies under G1 should remain open, the initial focus for process studies under GOALS is detailed by the other GOALS projects, especially G2 and G3. One focus under G1 is to evaluate observing system design from the prediction point of view, so that special observing system simulation experiments (OSSEs) should be done. Another very recent focus is the 1997-98 ENSO event.

### 1.4.1 Observing system evaluation

The ideal method, using prediction skill as a measure, begins by performing a long run of a coupled atmosphere-ocean model with basically all the data being saved—this is the control run. In particular, a long record of SST will be generated and results from a good model should replicate the SST anomalies with the characteristic statistics of the real ENSO. The long record of model data, the control run, provides both an initialising and validating data set.

Imagine a proposed (or actual) design for an observing system. The complete data at time  $t_0$  is sampled at the observing system sites with added errors characteristic of the actual observing system to provide a simulated initial field at time  $t_0$ . The first measure of the quality of the observing system is the difference between the simulated initial field at time  $t_0$  and the control field. This measures the ability of the observing



system to reconstruct the actual fields, which are known perfectly at  $t_0$ , and indicates that the observing system is dense enough to measure the correct scales of variability of the initial field. While this is an important measure for producing an initial analysis, it is by no means a sufficient measure to guarantee skill in prediction because rapidly growing initial errors may have a structure different from the scales of variability of the initial fields.

To provide a forecast measure of adequacy of the observing system, forecasts have to be made from the initial field. The forecast is made for  $n$  months and the prediction at  $t_n$  is compared with the full data sampled at the observing system sites at time  $t_n$ . The combined skill is computed by a long series of forecasts beginning, say, at successive months. An alternate observing system design is then tested in the same way and the new skill computed. The design with the higher skill is preferred. The optimal observing system design has the highest skill for that model. In practice, costs of the observing system must also be factored in, so the question might be changed from “What is the best observing system?” to “What is the best observing system given certain resources (funds, ship-time, etc.)?”

Using prediction skill as a measure of observing system design is clearly what is needed, but because each design requires a long series of predictions, the technique may be too unwieldy. Alternate measures may be developed on shorter series of predictions, on an individual prediction, on the growth of errors in the prediction, or on other alternatives. A caution is that results are apt to be model dependent, and so results must be carefully evaluated.

#### 1.4.2 The 1997-98 ENSO event

While the implementation plan was being developed, nature has brought us a major El Niño event which, by some measures, is the biggest on record. It is also by far the best observed on record and, moreover, was predicted ahead of time by CLIVAR scientists. While many parts of the forecasts were successful, others were not and in some areas the response was not classical (as expected from previous events). In addition, the magnitude of the event was generally under predicted. As well as record high sea surface temperatures in the central and eastern Pacific, SSTs were also exceptionally high in the tropical Indian Ocean and were above average in the tropical Atlantic. Sorting out the role of all these SST anomalies on the atmosphere is but one of many projects that CLIVAR will pursue, mostly under the banner of G1 but perhaps also under GOALS more generally. Accordingly, plans are developing to comprehensively describe and analyse the full evolution of the event to improve understanding and modeling capabilities as well as the use and utility of information provided, the impacts and responses, and how to improve public understanding of uncertainties in climate forecasts.

### 1.5 DATA SET DEVELOPMENT, DIAGNOSTICS AND EMPIRICAL STUDIES

As regular and systematic forecasting proceeds through the years, the record of all the data taken for the purposes of forecasting grows longer. To the extent the forecasts are found to be useful, the observing system is supported and maintained and the data record grows. Thus for upper air data, we now have approximately 50 years of data. Similarly, the climate record, especially in the ocean, can be expected to grow.

Each time a forecast is made, an analysis of the “optimum” state of the coupled system is performed. Over long periods of time, these initial analyses form a model record of the climate of the system. In this sense, regular and systematic forecasting extends the coupled atmosphere-ocean record in the same way that weather forecasting extends the atmospheric record over the time that weather forecasts have been done. Since it will undoubtedly be true that the models and assimilation and initialisation techniques will change as the regular and systematic forecasts are performed, there will be discontinuities in the analysis due to these changes which, in the absence of other information, would be misconstrued as climate changes.

As in weather prediction, the only way to counter this is through retrospective reanalysis of all the data. Periodically, the entire record must be reanalysed by hindcasting through the entire record using the

best available model and data assimilation and initialisation techniques. The homogeneity introduced by subjecting the entire record to a single consistent analysis method, guarantees that changes in the record are mainly caused by climate, not by the change of analysis technique. The other variable is the changing database, and tests must be run to assess how that has influenced the results. At each point in time, this is the best that can be done.

Once the sets of raw and analysed data sets exist, they can be used for empirical studies and to test various theories of ENSO in the tropical Pacific. Empirical studies and diagnostic analyses are an important complementary activity and should be carried out to improve our ability to “describe and understand” what is occurring in nature and how such knowledge may be used to improve models. Empirical studies describe phenomenological relationships within fields and among fields of different variables, both temporally and spatially. Diagnostic studies extend beyond empirical relationships by including analyses of processes and budgets of physical quantities that are conserved, such as heat, moisture, energy, and momentum, in both the real world and models to illuminate particular processes.

An important task is the development of diagnostic tools. It is desirable to determine better the forcings of the atmosphere and the ocean, and the response of each component. The latter includes better definition of the feedback processes, such as the role of storm tracks and land surface processes, and the role of various internal waves in both the atmosphere and the ocean. Empirical studies include the elaboration of spatial, temporal and multivariate relationships, and time scales of anomalies and “events”. Further details are included under Section II.3 from a global perspective.

## **1.6 LINKAGES WITH OTHER ELEMENTS AND PROGRAMMES**

Regular and systematic forecasting of tropical Pacific SST using GCMs is being and undoubtedly will be undertaken in many different institutions throughout the world, as noted above. Development activities are already occurring in a number of national forecasting centres, in universities, and in other modelling institutes and, because of the complexity of the problem, must continue if substantial progress is to be made. The IRI is intended to be a major part of CLIVAR and will not only do prediction science needed to make skilful forecasts, but it will interface with application centres in the various countries to try to apply the forecasts for the benefit of those countries and regions involved. It is expected that the work involved with CLIVAR and that of the IRI (as well as other national prediction centres and institutes) will be tightly intertwined and closely co-ordinated.

One scientific prerequisite to any useful application is the regionalisation of the forecasts, so that the specific climatic conditions of the region are considered. This will depend heavily on improvements in forecast of the teleconnection patterns and the use of ensemble techniques. It may also be done statistically and/or by embedding higher resolution models (with resolution high enough to resolve the local topography and orography, and detailed land surface processes) in global coupled GCMs. In either case the applications of ENSO forecasting will rely on and interface closely with studies on regional climate change.

The applications of ENSO prediction to agriculture, water resources, etc., involves more than understanding the physical system. Physical systems are embedded in social and political systems, which can affect the utilisation of climate information and affect the ultimate success of the outcome. For example, in order to apply ENSO predictions to water resources, it may be necessary to understand how to distribute the forecast in a way the local population, with a greater or lesser education, can understand. It may be important to understand the competing demands of the various consumers of water and how the social structure determines the success of the competition. It may be important to understand the political backdrop of the region and to understand who gains and who loses politically by the more efficient utilisation of water resources through the applications of ENSO forecasting. And it is important to realise that improved agricultural yield, for example, does not necessarily mean improved profitability. All of these are social problems, as opposed to physical problems, and the International Human Dimensions Program on Global Environmental Change (IHDP) of the IGBP was organised to deal with these sorts of problems.

Planning and initial implementation activities related to the IRI include a focus on research and demonstration projects related to the practical applications of seasonal-to-interannual forecasts in affected re-

### *III. The CLIVAR Principal Research Areas*

gions. Application research should provide insights into the regional consequences of climate variability, the vulnerability of communities and development sectors, the identification of opportunities to exploit climate forecasts for economic development and the value of new forecast information to support decision making in the public and private sectors. IRI demonstration projects are being designed to facilitate access to forecasts, support local and regional capacity-building, and establish mechanisms to ensure continuous dialogue with potential users of seasonal-to-interannual climate forecast information.

As the applications of ENSO information and prediction activities mature it will be important to co-ordinate with the IHDP, national meteorological and hydrological services, the WMO CLIPS Programme and the IRI. Indeed CLIPS may also play a role in co-ordinating research and development of operational climate prediction, especially empirical aspects, in many countries.

It has become clear since 1990 that ENSO is being modulated by decadal variability in the Pacific in a way that models up to now have not yet recognised. This decadal modulation is the equivalent of a non-stationary climate state upon which the interannual ENSO rides. In addition, it has been suspected for some time that there may be precursor signals for the onset of warm and cold phases of ENSO, which originate in the Indian Ocean. Both the decadal question and the relationship of ENSO with the Indian Ocean mean that ENSO Prediction must interface and co-ordinate with element D4 (Pacific and Indian Ocean Decadal Variability) the DecCen component of CLIVAR.

When the tool of climate prediction is global coupled models, and when global atmospheric GCMs are used to teleconnect the predicted SST variability in the tropics to elsewhere, there is no alternative to producing good land models which are embedded in the atmospheric GCM. The location of the great regions of persistent precipitation, which drive the tropical atmospheric circulation are partly over land, and snow cover in the Tibetan Plateau has been shown to affect the Asian monsoon which can in turn affect ENSO. Consequently, land processes can have a direct effect on the prediction of ENSO. Collaboration with the WCRP Global Water and Energetic Experiment (GEWEX) and some of its land programmes (such as the GEWEX Asian Monsoon Experiment GAME, and the GEWEX Continental International Project GCIP) are essential. The focal point for these aspects in GOALS will be G2, G3 and G4.

Another major linkage is with the prediction and detection of long-term climate change, elements and A2 of the Anthropogenic Climate Change (ACC) component of CLIVAR. ENSO is a climate process and affects the mean climate of the globe in a number of separate ways. ENSO affects the magnitude and distribution of mean surface temperature and the net uptake of CO<sub>2</sub> by the ocean. ENSO is itself affected by the addition of radiatively active constituents to the atmosphere and, because ENSO naturally produces droughts and heavy rains in different places around the world, the enhanced hydrological cycle expected to accompany global warming could exacerbate these events. Comprehensive climate models used to simulate and predict the response to anthropogenic addition of radiatively active gases and aerosols must therefore be able to include the interactive effects of ENSO and its possible modifications by these additions.

There is no CLIVAR standing committee to co-ordinate G1 research, although the CLIVAR panels NEG-1 and the UOP as well as the IRI and CLIPS will all play a role. Nevertheless, it will be important to foster co-ordination and exchanges through the organisation of conferences and workshops perhaps triennially.

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*III. The CLIVAR Principal Research Areas*

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## **2. VARIABILITY OF THE ASIAN-AUSTRALIAN MONSOON SYSTEM (G2)**

### **2.1 INTRODUCTION**

The Asian-Australian (AA) monsoon is a key component of the earth's climate system affecting the livelihood of more than 60% of the world population. Almost all facets of societal and economic activities in the AA-monsoon region are critically dependent on the variability of the monsoon. For example, Fig. 2.1 shows that a large part of the major crop production over south Asia can be accounted for by the fluctuation of Indian monsoon rainfall. Because of the strong linkages of the AA-monsoon region to the rest of the world through coupling with the global climate and economic systems, variability and major shifts in the AA-monsoon climate affecting economic productivity will have major global impacts. Therefore, better prediction of the AA-monsoon will greatly benefit the social and economic well-being of not only the population of the AA-monsoon region but also of the whole world. Improved predictions of the AA-monsoon require enhanced understanding of the monsoon system through well-co-ordinated international scientific research efforts. The CLIVAR AA-Monsoon Panel is charged by the CLIVAR Scientific Steering Group (SSG) with the responsibility of developing an implementation plan to provide scientific to promote international monsoon research including facilitating the co-ordination of existing national programmes. The Asian - Australian Monsoon Implementation Plan (AAMIP) as outlined in this document has evolved and will continue to evolve from inputs of panel members as well as international monsoon scientists and experts. The basic content of the AAMIP was formally adopted during the First CLIVAR AA-Monsoon Panel Meeting held in Goa, India, November, 1996 (CLIVAR, 1997).

### **2.2 SCIENTIFIC RATIONALE**

The prediction of the monsoon is limited by the high frequency variability associated with its internal dynamics. As a working hypothesis, it is proposed that monsoon predictability can be enhanced by improving our understanding of how the slowly changing boundary conditions such as sea surface temperature, snow cover and other slow variables within the tropical climate system modulate the high-frequency behaviour. Past studies have shown that the AA-monsoon is linked to interannual variability of the tropical ocean-atmosphere system, in particular ENSO (Shukla and Paolino, 1983; Nicholls, 1989, and Li, 1990). There is now a body of scientific evidence indicating that the Asian monsoon may strongly influence ENSO (Yasunari, 1990, 1991; Webster and Yang 1992, and Lau and Yang, 1996). Other studies also suggest that the Asian monsoon may impact the climate outside the monsoon region, including extratropical North America (Yasunari and Seki, 1992, Lau, 1992). In view of these considerations, the CLIVAR AA-Monsoon Panel adopts the following primary goals for the CLIVAR Implementation Plan:

1. to explore and determine the limits of predictability of the monsoon climate system;
2. to quantify the relative contribution to monsoon predictability from the slowly varying boundary conditions and internal dynamics within the monsoon system;
3. to determine the role of the monsoon on the predictability of the global climate system, in particular those related to ENSO.

To achieve these goals, the effort will be focused on seven specific focus areas relating to interaction of the AA-monsoon with the annual cycle, intraseasonal oscillations, ENSO-monsoon coupling, tropospheric biennial oscillations, oceanic processes, land surface processes and tropical-extratropical interactions. The interrelationships among these subsystems and the monsoon climate are illustrated in Fig. 2.2. A brief scientific rationale for each of the focus areas follows.

## Relationship of Indian Rice Production and Indian Rainfall

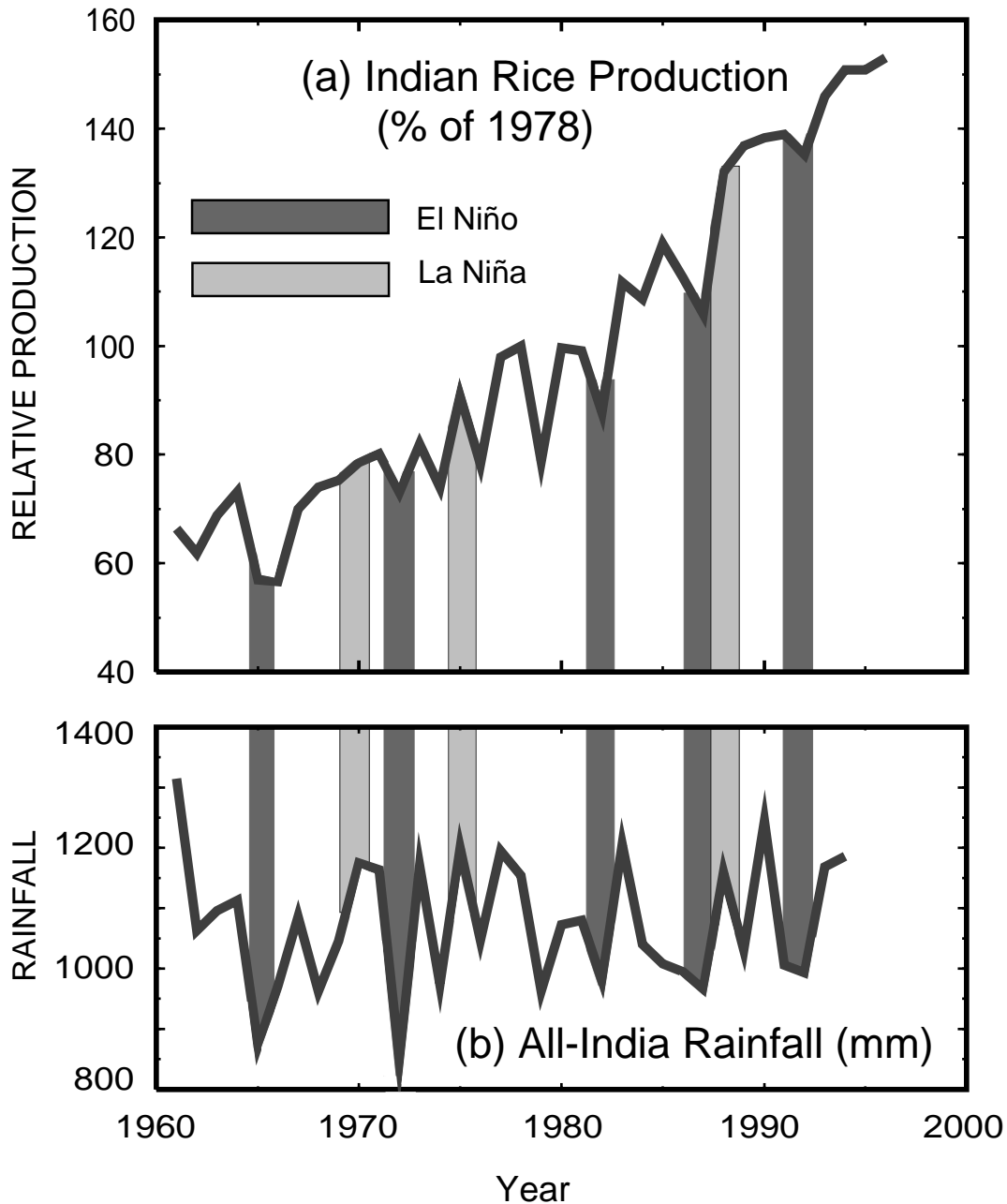


Fig. 2.1: Crop production vs. Indian monsoon rainfall. Notwithstanding the overall growth in rice production in India due to better farming practices and technological development, year-to-year fluctuations in production are determined largely by the success or failure of the summer monsoon which is in turn affected by the particular phase of the El Niño/Southern Oscillation phenomenon (from Webster et al. (1998), adapted from Gadgil, 1995).

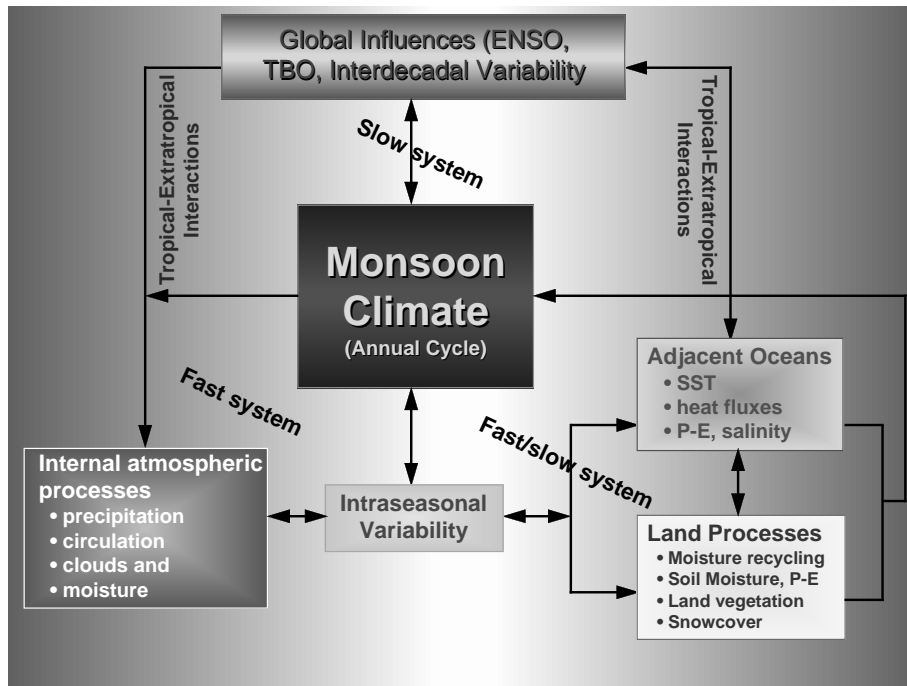


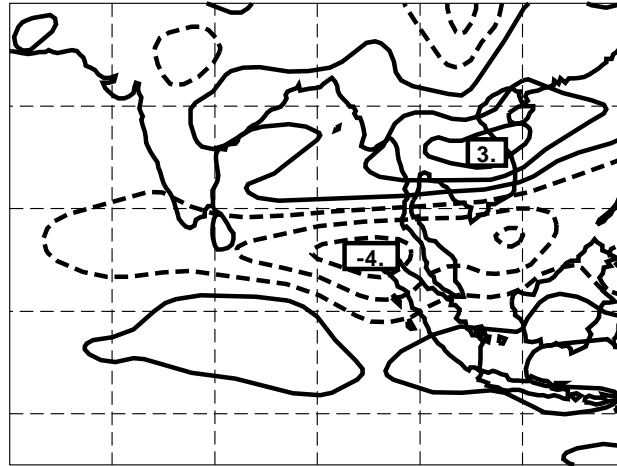
Fig. 2.2: Components of the AA-monsoon showing the interconnection between the various components discussed in the text (courtesy of K.M. Lau).

### 2.2.1 The annual cycle

First and foremost, the Panel recognises the need to better document and understand the mechanisms in the annual variations of the AA-monsoon. The annual variation of the monsoon is extremely complex, including sudden onset and breaks, abrupt transitions and strong interaction with SST in the adjacent and distant oceans and the surface hydrology of the Asian-Australian land masses (Meehl, 1987). The location of the maximum heat source during the Asian summer monsoon is far off the equator while that during the Australian summer monsoon is much closer to the equator, consequently, the fundamental dynamical regimes underlying these two monsoon components are quite different. For example, the response of the circulation to the Asian summer monsoon heating is mostly of the Rossby type where the rotational component of the wind and the  $\beta$ -effect (change of Coriolis parameter with latitude) are important. On the other hand, the near equatorial heat source during the Australian summer monsoon renders a stronger Kelvin type response, where gravity wave motions dominate. Moreover, the strong surface wind fluctuations over the maritime continent and the equatorial western Pacific associated with the Australian summer monsoon may exert a stronger influence on ENSO variability than its Asian counterpart. Recent studies suggest that the seasonal cycle can also influence the predictability of the ocean-atmosphere system (Torrence and Webster, 1998). For these reasons, both monsoon components need to be considered in studying the annual cycle of the overall monsoon system.



(a) Dominant EOF pattern (> annual cycle) based on **interannual** variability only



(b) Dominant EOF pattern based on **intraseasonal** variability only. The annual and semiannual cycles have been removed.

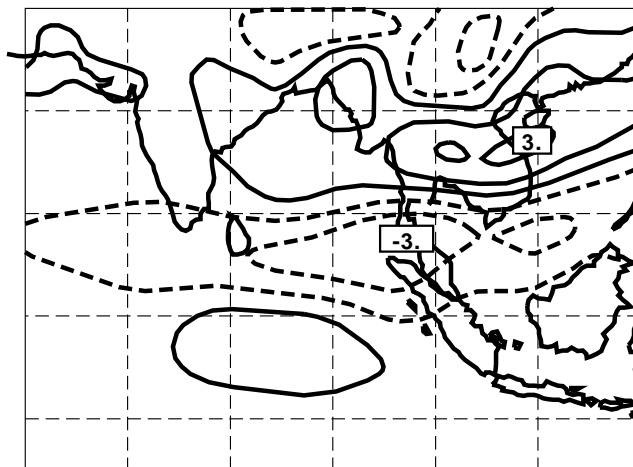


Fig. 2.3: Dominant spatial patterns of vorticity for (a) interannual and (b) intraseasonal variability of the Asian summer monsoon (Webster et al., 1998).

### 2.2.2 Intraseasonal Oscillations (ISO)

While the AA-monsoon is characterised by a very pronounced annual variation, it also possesses a wide range of variability from the intraseasonal, interannual to interdecadal time scales. ISO represent the strongest signal, with time scales from weeks to months, that permeate the monsoon land regions from India, Southeast Asia, East Asia and the Indian and western Pacific Oceans. A remarkable feature that should be noted is the strong similarity between spatial patterns of the intraseasonal and interannual variability (Fig. 2.3). While the basic physics of ISO is believed to originate from internal atmospheric moist dynamics, their interactions with the ocean and land surface processes are not very well understood; such interactions

may be important in determining the characteristics of ISO over the monsoon region. Besides having a strong control on the monsoon active-break cycles, ISO may define a monsoon “attractor” that determines the evolution of the climate states of the monsoon. Considering the similarity between the ISO and interannual variability, it may be hypothesised that the monsoon attractor has multiple basic states and that it may be nudged to go from one state to the other under the influence of remote forcing induced by sea surface temperature anomalies, changes in snow cover or other external forcing functions (Palmer, 1994 and Webster et al., 1998). Moreover, it should be noted that the annual and the ISO time scales are arguably the most important time scales on which improved prediction will provide the greatest social and economic benefit. Hence, they warrant high priority for AA-monsoon studies.

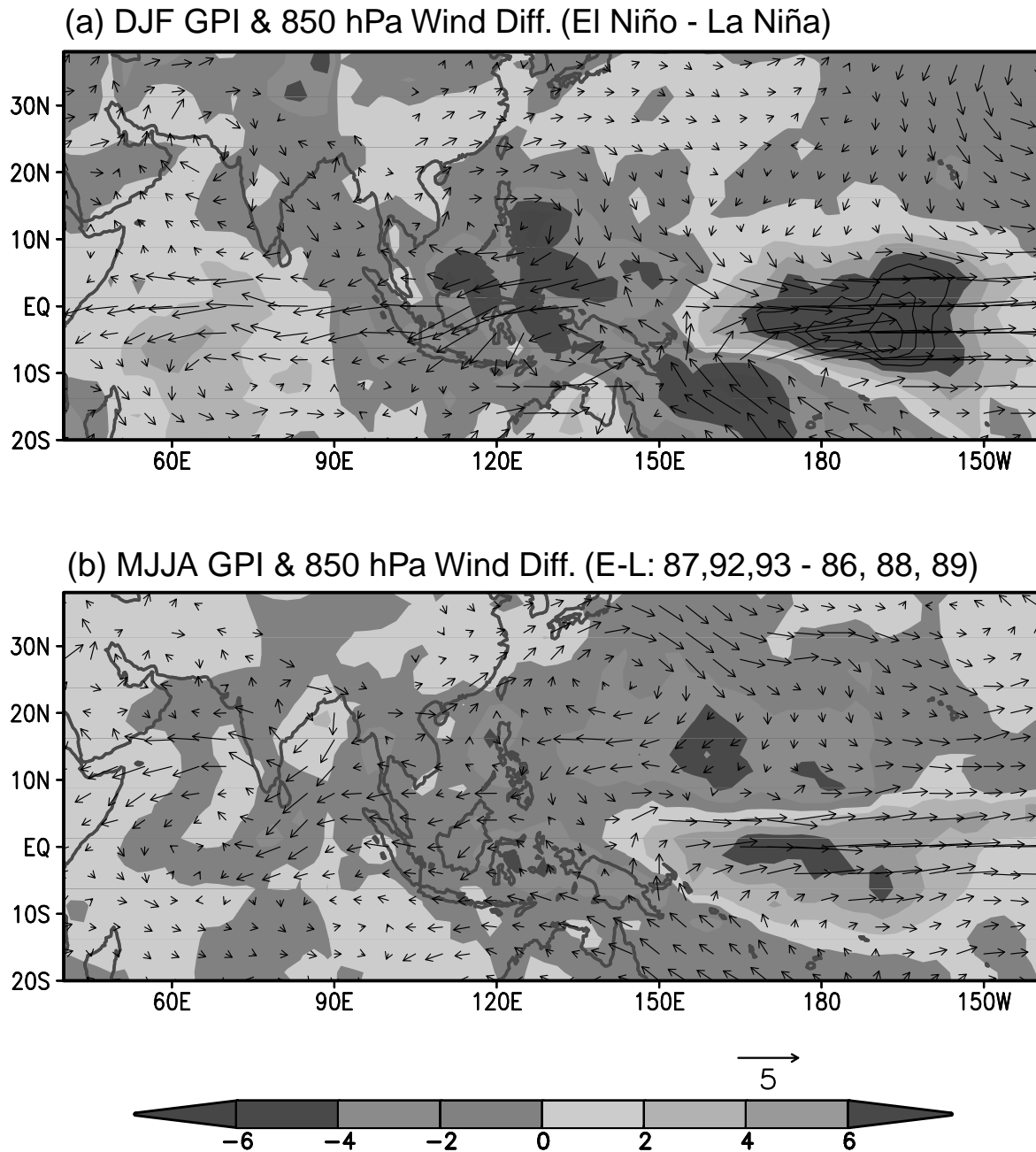


Fig. 2.4: Composites of warm-minus-cold 850 mb winds and GPI rainfall seasonal anomalies based on the NASA-GEOS reanalysis for December-January-February (upper panel) and for May through August (lower panel) (courtesy of K.M. Lau).

### 2.2.3 ENSO-monsoon coupling

Many studies have documented that both the summer and winter components of the AA-monsoon can be affected by ENSO. The warm phase of ENSO has been linked to a weakening of the AA-monsoon, with overall reduction of rainfall over Southern India, Southeast Asia during May through August and northern Australia and Indonesian regions from December to February, with anomalous surface easterlies over the Indian Ocean and anomalous surface westerlies over the equatorial central Pacific (Fig. 2.4). Yet, not more than 40% of the strong and weak monsoons can be associated with ENSO. At the very best, less than 10-15% of the monsoon rainfall variance can be explained by SST variation in the Pacific. Therefore the monsoon-ENSO relationship is tantalising but incomplete. Several reasons may exist. First, the monsoon-ENSO relationship is likely to be non-linear. It has been suggested that the monsoon interacts with the Pacific trade wind system much more strongly in the warm phase compared to the cold phase of ENSO. Second, the monsoon-ENSO coupling may be non-stationary since the correlation between long-term records of Indian rainfall and Pacific SST has varied from 0.4 to 0.8 for different decades from 1900 through the present (Mehta and Lau, 1997). Hence the ENSO-monsoon relationship is subject to modulation by long-term climate variations. Third, other factors such as snow cover or soil moisture may exert impacts on monsoon variability, either directly and/or indirectly through feedback processes with the ENSO. Finally, the ENSO-monsoon system itself may be part of a chaotic climate system, which can generate variability on long-time scales internally through mutual interaction, even in the absence of external forcings. Clearly, the understanding of the dynamical underpinnings of the coupling of the AA-monsoon and ENSO is a scientific problem which lies at the heart of CLIVAR.

### 2.2.4 The Tropospheric Biennial Oscillation (TBO)

The TBO is a quasi-periodic oscillation found in a wide range of monsoon variables including rainfall, surface pressure, wind, SST and subsurface water temperature. The origin of the TBO is a subject of debate. Several theories exist. One contends that the TBO arises from air-sea-land interaction with the monsoon regions. This theory requires the long-term memory in oceanic as well as land variables such as soil moisture and snow cover (Meehl, 1993). Another theory is that the monsoon is an integral part of a tropical coupled ocean-atmosphere-land system, including at least the Indian Ocean and the Pacific basins. The TBO then arises as a subharmonic of the annual forcing from the monsoons and interacts with the ENSO system. This may be the reason for the strong phase locking between the annual cycle, TBO and ENSO (Shen and Lau, 1995). Recent modelling results have indicated that it is also possible to generate variance at the TBO time scale in atmospheric GCMs from annual atmospheric forcing alone and that intermediate coupled ocean-atmosphere models can generate TBO-like events without generating ENSO events (Goswami, 1996). Thus the origin of the TBO and its strong connection with the monsoon presents one of the most intriguing scientific problems for CLIVAR. Understanding the origin of the TBO may help to explain the scale selection and irregularities in ENSO cycles and in ENSO-monsoon coupling.

### 2.2.5 Oceanic processes

Even in simplified coupled ocean-atmosphere models with no land processes, an extremely rich ENSO-like dynamical behaviour can be found. The atmospheric response to SST anomalies is very indirect. According to statistical and AGCM studies, SST anomalies that influence the monsoon are found in very disparate parts of the ocean. Notably, the northern Indian Ocean is not a strong region of influence. Positive SST anomalies in the east Pacific and negative ones in Indonesia during ENSO influence the monsoon through different mechanisms (e.g. Soman and Slingo, 1997). Nicholls (1989) found that the major pattern of non-ENSO related Australian winter rainfall correlated with a dipole of SST anomalies in the Indian Ocean.

Other regions whose SST anomalies are known to influence the AA-monsoon are the southern Indian Ocean, the western Pacific, the South China Sea and the Indian Ocean region, but more remains to be

learned regarding regions of SST influence on the monsoon. To predict the monsoon, these SST anomalies must be first predicted. This involves dealing with a range of oceanic processes, many still poorly known. Examples include the non-linear effects of currents in the western Pacific and the northern Indian Ocean (McCreary et al., 1993), the annual Rossby waves in the Southern Indian Ocean (Perigaud and Delecluse, 1992), tidal mixing and wind-driven upwelling in the waters of the Maritime Continent (Lukas et al., 1996 and Godfrey, 1996). Another critical issue confronting monsoon ocean research, and much of CLIVAR in general, is that the surface fluxes, which are key to the coupling of the atmosphere and the ocean and which are used to force ocean models, are all subject to large uncertainties (e.g. Weller and Taylor, 1993). Accurate estimate of surface fluxes are also critical to diagnostic and intercomparison studies of air-sea interaction in the Bay of Bengal, South China Sea and western Pacific. Two initial objectives of the ocean components of the AA-Monsoon programme have been identified (a) to understand the effects of SST anomalies in different regions on monsoon circulation, and (b) to determine the physical mechanisms governing SST changes in different geographic locations. A third objective is to improve the estimates of surface fluxes in the region, from both *in situ* and remote sensing methods, and from AGCMs and OGCMs when each is forced towards observed SSTs.

### 2.2.6 Land surface processes

Observational studies have suggested that the interannual variability of the Asian monsoon may be strongly affected by anomalous land surface conditions over the Eurasian continent (Shukla and Mintz, (1982)). The land surface anomalies may be due to snow cover, soil moisture or vegetation changes. It is believed that these land surface anomalies contribute to anomalies in the monsoons by modulating the surface heat budgets and therefore temperature and moisture contrasts between the continent and the adjacent oceans. For example, excessive snow during the antecedent winter and spring may lead to late melting thus keeping the ground temperature below normal and the mid-latitude westerly flow strong and persistent over the subtropics through early summer (Yasunari, 1991). These conditions reduce land-ocean contrast in early summer and prevent the northward migration of the monsoon westerlies and therefore favour a late onset and a weak monsoon (Webster and Yang, 1992). In this regard, the effect of the sensible heat flux in the elevated heat source over Tibet may be especially important in regulating the strength of the summer monsoon (Yanai and Li, 1994). Land surface processes may also impact intraseasonal variability, as evidenced in recent modelling results, suggesting that the feedback processes involving soil moisture, evaporation and convection over land may be important in the observed inverse relationship between the oceanic and land ITCZ (Lau and Bua, 1998). Possible feedback mechanisms involving the coupling of the land-atmosphere hydrologic and energy cycles under the influence of large-scale forcings are shown in Fig. 2.5.

### 2.2.7 Tropical-extratropical interaction

The importance of tropical-extratropical interaction in influencing AA-monsoon processes is well known. The onsets and breaks of the Indian monsoon are known to depend on the degree of meridional penetration of extratropical eastward moving troughs where the westerlies extend southward, and the position of the mid-tropospheric ridge over India during the boreal spring (Mooley and Shukla, 1987). These same ridge and trough systems are also responsible for the multiple onset and the discontinuous northward migration of the Mei-yu and Baiu fronts over East Asia. In particular, during the latter stages (July to August) of the East Asian monsoon, the influence of midlatitude baroclinic disturbances on the monsoon trough development is well known. Also documented are significant correlation of monsoon rainfall with the stratospheric circulation and in some cases the stratospheric QBO. Whether or not the latter is distinct or related to the TBO is an intriguing scientific problem that may have practical forecasting value. Strong extratropical influences associated with the winter monsoon cold surges from East Asia on near equatorial convection and possibly the austral summer monsoon have also been reported (Lau, 1982). The interaction of the winter monsoon over East Asia with convection over the South China Sea appears to be also important (Tomita and Yasunari, 1996). Because of their high frequency characteristics, extratropical influences may further limit the predictability of the AA-monsoon. An important scientific question is to determine in what ways

the distribution of these high frequency signals interact with the large-scale stationary patterns induced by the slowly changing boundary conditions.

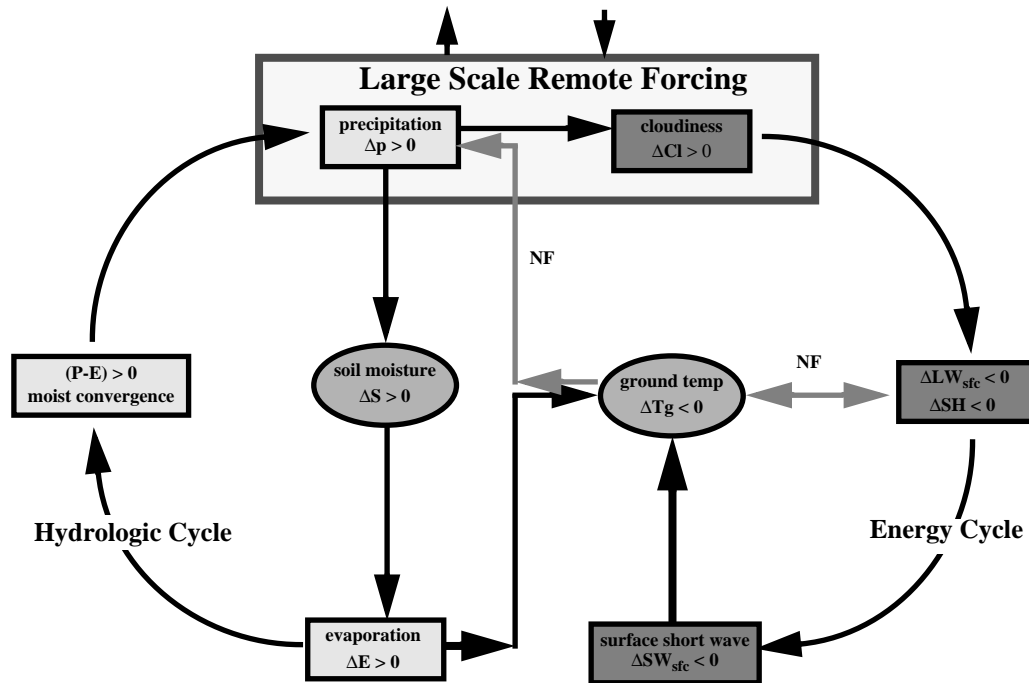


Fig. 2.5: Possible land-atmosphere feedback mechanisms under the influence of large-scale remote forcings in the AA-monsoon region (from Lau and Bua, 1998).

## 2.3 PROGRAMME OBJECTIVES

Under the guidance of the scientific rationale for an Asian-Australian monsoon programme outlined above and in pursuit of the goals of such a programme, CLIVAR will:

- Document the spatial structure and temporal variability of the AA-monsoon system from intra-seasonal, annual, interannual to interdecadal time scales.
- Identify specific mechanisms for the complex evolution of the annual cycle in the coupled ocean-atmosphere-land system in the monsoon regions.
- Unravel the mechanisms of the intraseasonal oscillations (ISO) and the role of ISO in the interaction between monsoon and ENSO.
- Determine the fundamental modes and mechanisms in ENSO-monsoon coupling, including the tropospheric biennial oscillation (TBO) and interdecadal modulations.
- Identify regions where land surface and SST anomalies influence the monsoons, and quantify the underlying meteorological causes of these influences.
- Determine the relative contribution by internal dynamics vs. boundary forcing, as well as remote vs. local forcing to monsoon predictability.

- Quantify the physical mechanisms responsible for generating SST anomalies, emphasising ocean regions known to influence the AA-monsoon.
- Identify external influences including tropical-extratropical and tropospheric - stratospheric interactions affecting monsoon variations.

Numerical modelling activities now, and will continue to be, a major tool in addressing these objectives. However, there are a number of aspects of the monsoon where present models are known to be inadequate; and process studies are needed to tackle these issues. Furthermore, for practical real-time prediction the observing system will need to be addressed. These aspects are addressed in the following sections.

## 2.4 MODELLING AND PREDICTION

To meet the stated goals and objectives, the modelling component of the CLIVAR AA-monsoon programme effort will utilise a hierarchy of models, from simple through intermediate to fully fledged AGCMs and CGCMs (coupled global circulation models). Simple and intermediate models are important for providing a basic understanding of physical processes and a dynamical interpretation of observations and results from GCMs. In the initial phase of the CLIVAR AA-monsoon programme, modelling work will be guided by statistical studies of observed monsoon climate variability and its sensitivity to changing lower boundary conditions.

As monsoon climates are determined largely through processes coupling the ocean, atmosphere and land, coupled GCMs will ultimately be used to address the problems of monsoon predictability. However, fully coupled modelling studies aimed at predicting the AA-monsoon are premature at this stage. Nonetheless, it is encouraging that several state-of-the-art high resolution AGCMs and regional climate models nested in AGCMs have shown promise in realistically simulating the regional features of the monsoon. Much of the success is due to better parameterisation of physical processes such as cumulus heating, water vapour and cloud radiative processes and land surface processes. Submodel developments to better simulate the mean monsoon will be strongly encouraged. In particular, such efforts will be co-ordinated with the process studies discussed in Section 2.5 and with other WCRP programmes e.g. GCSS (GEWEX Cloud System Studies).

Ocean models can now reproduce the observed mean seasonal cycle of SST quite well in most of the tropical ocean (e.g. McCreary et al., 1993; Chen et al., 1994), although in the Indonesian region they do not perform very well. These models are now being used to simulate interannual variability. However, their ability to reproduce interannual SST anomalies when driven by observed fluxes is as yet unknown, due at least as much to problems with uncertainties in the fluxes as to model deficiencies.

In view of the above considerations, there is an urgent need to develop and assess the ability of state-of-the-art AGCMs driven by observed SSTs to simulate the seasonal mean, interannual variability and intraseasonal variability of the monsoon, and conversely, to assess the ability of OGCMs to simulate the observed SST anomalies, given interannually-varying surface flux estimates. These steps are prerequisites for making quantitative estimates of the predictability contributions from slowly varying boundary conditions versus those estimated from internal dynamics. Experiments with stand-alone AGCM and OGCM experiments will be carried out first, to be followed by coupled GCM (CGCM) experiments. Discussions and proposals of AGCM, OGCM and CGCM experiments are presented in the following subsections.

## 2.4.1 Experiments with AGCMs

### 2.4.1.1 Atmosphere Model Intercomparison Projects

This modelling activity aims at assessing the ability of AGCMs to simulate the seasonal cycle, inter-annual variability and intraseasonal variability of the monsoon. The model results will be validated against re-analysis products and *in situ* observations in the region, including satellite data. For re-analysis, the current efforts by the major centres have to be continued. For in-situ observations, data on daily precipitation, circulation over the South Asian, East Asia and Southeast Asian monsoon regions will be required. For satellite data, estimates of cloudiness, convective strength, water vapour and surface fluxes and derived precipitation data are needed (see discussion in Section 2.7.1).

#### *Proposals:*

In conjunction with AMIP-II (Geckler, 1996), a 15 year period of monsoon simulations from 1979 to 1994 will be investigated. This period includes the strong 82/83 and 1987/88 ENSO events, along with persistent El Niño conditions during 1992 and 1994. For validating the simulation of the monsoon, several monsoon indices based on area-averaged precipitation (e.g. All-India, Central China, and South China Sea) as well as circulation anomalies (e.g. Webster and Yang, 1992) will be applied.

### 2.4.1.2 Monsoon predictability

The objective of these experiments is to assess the predictability limit of the monsoon and to make quantitative estimates of contributions from slowly varying boundary forcings and internal dynamics.

#### *Proposals:*

Three sets of experiments are proposed.

- Ensemble of AMIP simulations (5 or 9 members of 15 years each) which will give an estimate of contributions from slow boundary conditions and internal dynamics. Ensemble runs are started from different initial conditions but use identical boundary conditions of observed SST. AMIP simulations typically cover a 15 year period. If the experiments are done for the period 1979 to 1994 as in (2.4.1.1) the control simulation can represent one member of the ensemble. The uncertainty due to the chaotic nature of the atmosphere (noise) is determined from the range of the variability among the members of the ensemble in terms of rms values. The predictable part (signal) is estimated from the interannual variability of the ensemble mean. The signal to noise ratio determines the level of predictability.
- Dynamical seasonal prediction of the monsoon (again requiring ensemble of forecasts) for the summer seasons will provide measures of the influence from the initial conditions and the present skill of prediction.
- Sensitivity and predictability experiments to see the impacts of land surface processes on the Asian monsoon with the use of the global soil moisture dataset during 1986-1995 which will be prepared in the 2nd phase of the ISLSCP.

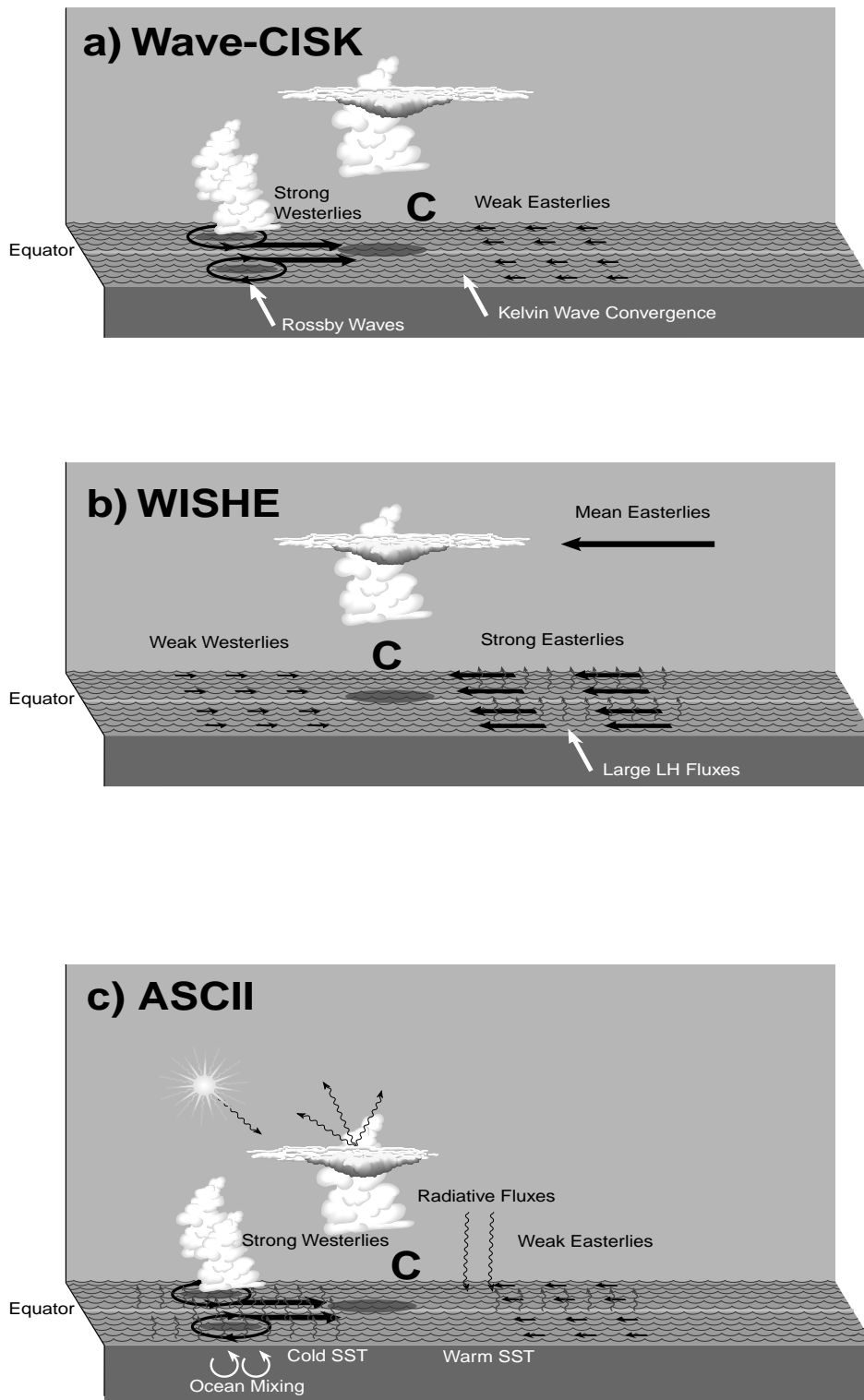


Fig. 2.6: Illustration of three conceptual models of intraseasonal oscillation: a) Wave CISK, b) wind-induced surface heat exchange (WISHE), c) air-sea convective intraseasonal interaction (ASCII) (Flatau et al., 1997).



### 2.4.1.3 Intraseasonal variability

Some evidence is beginning to emerge that the intraseasonal oscillations of the monsoon play an important role in determining the seasonal mean and interannual variability. There is also evidence that there are similar intraseasonal oscillations in the upper ocean on a basin-wide scale. However, it is not clear whether coupling with the ocean is essential for the atmospheric ISO or they could be sustained purely by the atmosphere. Idealised AGCM studies have suggested that the coupling may be important. Fig. 2.6 (Flatau, 1997) shows a summary of the possible mechanisms of the ISO involving air-sea interaction and atmospheric dynamics and radiation. It is also possible that land processes also play a significant role in modulating the intraseasonal variability.

#### *Proposals:*

To establish the roles of the oceans and the land in monsoon intraseasonal variability, the outputs of model runs from (2.4.1.1) and (2.4.1.2) will be examined in detail to diagnose the structure and propagation of ISO in the models. Additionally, the following AGCM integrations for 5-10 simulated years are proposed:

1. AGCM experiments with observed daily or weekly  $1^\circ \times 1^\circ$  gridpoint SST versus monthly mean SST
2. AGCM experiments with prescribed soil wetness vs. variable soil wetness

These experiments are to be carried out with selected AGCMs whose monsoon climatologies are reasonably realistic.

### 2.4.1.4 Role of SST anomalies in influencing the monsoon

SST anomalies in different regions of the ocean influence the monsoon in different ways and through a variety of mechanisms. Thus ENSO-related SST anomalies in the east Pacific affect monsoon westerlies, while Pacific SST anomalies directly influence convection (Soman and Slingo, 1997). Positive SST anomalies in the south Indian Ocean and Arabian Sea are expected to enhance continental precipitation through enhanced moisture flux, whereas a positive SSTA over the equatorial Indian Ocean (Bay of Bengal) may cause a decrease (increase) in continental precipitation by favouring the oceanic ITCZ over the continental one. Up to now, very little modelling work has been done to delineate the dynamical underpinnings of these differences. To test mechanisms, AGCMs with realistic monsoon mean climatology should be used, and the experiments guided by statistical climate studies.

#### *Proposals:*

To meet these objectives, the following set of experiments will be carried out:

1. Observed SST anomalies over the global ocean will be used as control.
2. Observed SST anomalies will be prescribed over different portions of the Indian Ocean and western Pacific, while the rest of the ocean regions are kept at climatological SST.

Attention will be focused on regions where the SST anomalies are likely to produce different impacts, e.g. east Pacific, southern Indian Ocean, Bay of Bengal, equatorial Indian Ocean and the western Pacific/South China Sea region. To be effective, these experiments will be co-ordinated with a series of experiments with AGCMs proposed by CLIVAR NEG-1 to understand the dynamics of interannual variability of the monsoon.

## 2.4.2 Experiments with OGCMs

### 2.4.2.1 Ocean process modelling and intercomparison

The SST accuracy needed for monsoon studies may be as small as 0.2°C; but presently, when OGCMs are run with realistic atmospheric boundary layer response to SST, they display SST simulation errors of order 2°C or more though the errors in SST anomalies will not be as large as those in absolute SST. The uncertainties in modelled SSTs are probably due to two major problems. First, most OGCMs have a significant thermocline drift in the tropics, especially the east Pacific. The development of OGCMs without such thermocline drift is thus a first priority. The other problem is related to the uncertainty in the net heat flux. Secondly, observed climatological net heat fluxes are uncertain to several tens of Watts/m<sup>2</sup> (which can generate SST changes of several degrees in a few months). However, ocean models also have problems and flux estimates obtained by forcing OGCMs towards observed SST often lie outside these large error limits. Details of mixed layer dynamics are essential for improving the OGCM estimates of surface heat flux. Also, the roles of salinity and solar radiation penetration are likely to be important for SST change throughout most of the monsoon region, and nesting of high resolution submodels may be needed, e.g. in the Indonesian region. The ocean modelling component of Asian-Australian Monsoon Implementation Plan will aim within the first five years to:

- Evaluate the performance of ocean models, driven by “state-of-the-art” observed fluxes, for simulating observed SST anomalies;
- Assimilate ocean subsurface data - and altimeter and SST data - into ocean models;
- Evaluate the performance of data-assimilating ocean models to reproduce observed high-quality surface flux measurements wherever these are available;
- Examine SST error growth rates when data assimilation is removed; and couple the resulting ocean models to atmospheric models for forecasting the monsoon.

#### *Proposals:*

To assess the performance of OGCMs in oceans in monsoon regions, the following four sets of experiments will be conducted:

1. OGCM simulations of the Pacific and Indian Ocean response to given surface stress products, and formulations of heat and freshwater flux boundary conditions (“OMIP” model intercomparison). These experiments will examine the mean seasonal cycle and anomalies of SST, ocean circulation and implied surface heat fluxes in several models, and will compare each with observations.
2. Studies of the sensitivity of OGCM simulations to different surface stress products, and formulations of heat and freshwater flux boundary conditions.
3. “Reanalysis” runs with data assimilating ocean models, forced towards observed SST. The surface flux data from these runs will be compared with high-quality surface heat flux observations, wherever these are available.
4. Studies of the “decay time” of model skill in simulating SST, following removal of data assimilation.

These experiments will be designed to complement AGCM experiments under Section 2.4.1.1 as closely as possible.

### 2.4.2.2 Evaluation of observed surface fluxes

To improve flux estimates for understanding monsoon mechanisms and for use in forcing ocean models, surface fluxes from AGCM reanalysis runs and operational models will be validated against all available high-quality, directly-observed flux data sets. Examples include the TOGA-COARE data, data obtained in recent process studies in the Arabian Sea, data to be collected in GAME, SCSMEX, PACS/VAMOS, satellite products from scatterometers (e.g. NSCAT, ERS-1) and radiation data collected in the equatorial central Pacific by the Atmospheric Radiation Measurement program (ARM). A comparison study by Weller and Anderson (1996) has suggested that the model fluxes may be seriously in error for the purpose of predicting short-term SST anomalies (Fig. 2.7).

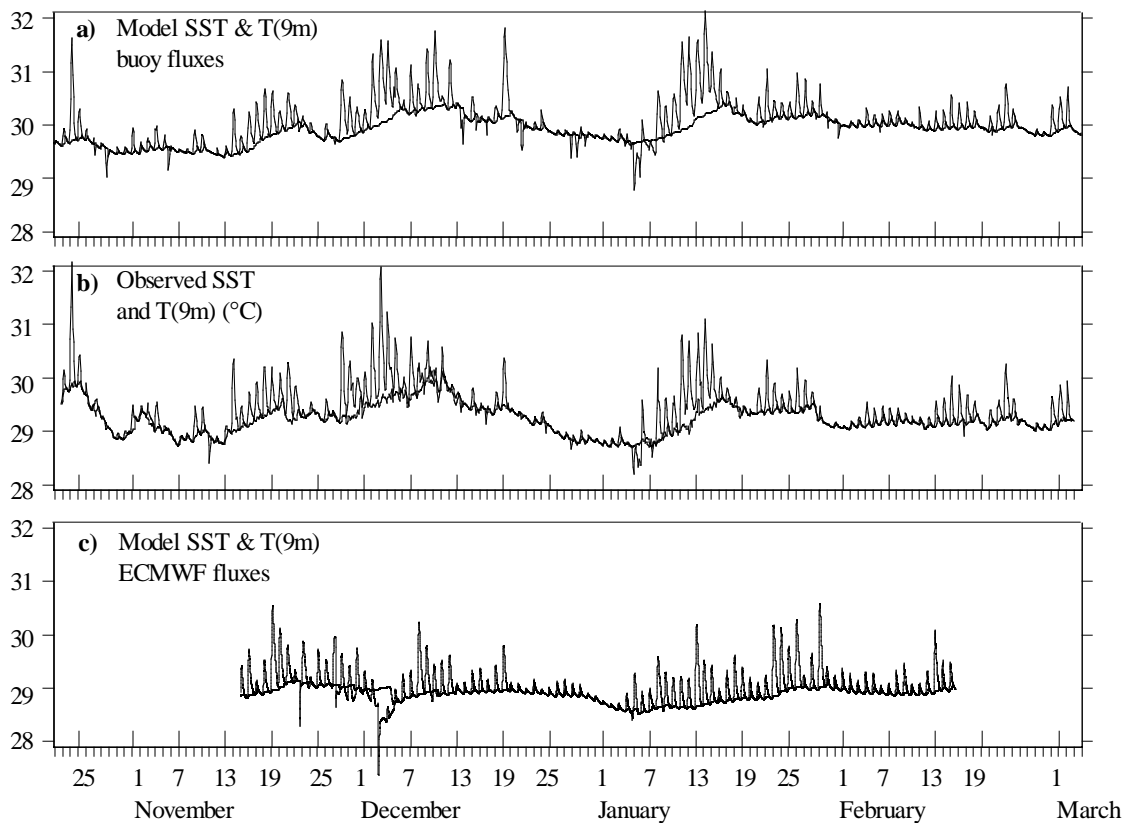


Fig. 2.7: SST and flux variations over the TOGA-COARE region (Weller and Anderson, 1996).

*Proposals:*

1. In order to reduce the presently large errors in the model fluxes, modellers will employ the TOGA-COARE data set and those obtained from other suitable field programmes and satellite missions to pursue improvements to flux codes and parameterisations,
2. Special flux datasets will be compiled from field programmes, e.g. GAME and SCSMEX that can be used directly for monsoon diagnostic studies and/or the validation of model parameterisations (see discussion in Section 2.5.2).

### 2.4.3 Experiments with CGCMs

As coupled GCMs become more generally available to the monsoon research community and their capabilities over monsoon regions are proven, activities along the following lines will be considered:

- Intercomparison of CGCMs simulations of the monsoon ocean-atmosphere-land system;
- Sensitivity experiments with CGCMs to investigate ENSO - monsoon connections;
- Assimilation of subsurface ocean data to improve the initialisation of ocean models for prediction with coupled models.

For sensitivity experiments, a multi-year control integration would first be carried out. The monsoon would then be perturbed (e.g. by increasing snow over Eurasia or by drying the land) and the impact on ENSO examined. Similarly, ENSO conditions could be perturbed, based on a knowledge of the interdecadal signals of the oceanic thermocline, and the impact on the monsoon examined. The ultimate objective is to couple data-assimilating ocean models to AGCMs, after it has been verified that both models generate realistic fluxes when each is forced by, or towards, realistic SSTs.

As discussed earlier, the modelling efforts will be closely co-ordinated with process studies (see Section 2.5) and future field campaigns. High resolution daily rainfall from both station data and satellite estimates will be needed for validation (see Section 2.7.1). Once such data sets become available, a “regional reanalysis” project will be launched that will use a good regional climate model nested in an AGCM or CGCM. This will establish a data set for detailed three dimensional studies of various processes related to monsoon variability. This work will be performed in close association with NEG-1 and the WOCE Modelling and Synthesis Group.

## 2.5 PROCESS STUDIES INCLUDING FIELD CAMPAIGNS

Process studies are focused research efforts, that may include field campaigns conducted over limited areas and duration. Such studies will be carried out within this initiative for the specific purpose of improving understanding of physical processes in the monsoon region. Process studies are an indispensable component of the CLIVAR AA-monsoon programme and will be carried out in close co-ordination with the modelling activities. Our understanding of the monsoon is developing rapidly, and we expect new proposals for process studies to emerge, and the present ones to evolve in the coming years.

### 2.5.1 Diagnostic studies

CLIVAR proposes five thrusts for conducting diagnostic studies. These are directed at elucidating the following:

#### 2.5.1.1 Seasonal variations

- Mechanisms of the complex seasonal evolution (e.g. abrupt changes, onset and break) of the entire AA-monsoon.
- Role of air-sea interaction processes for different phases of the seasonal cycle over the western Pacific and the Indian Ocean.
- Processes associated with heating over Tibet, and large-scale land surface processes such as

### III. The CLIVAR Principal Research Areas

snow cover and soil moisture.

- Impact of winter monsoon on near equatorial convection and surface wind fields and SST.
- Maintenance and evolution of the maritime heat source over the Indonesian subcontinent preceding and during the austral summer monsoon.

#### 2.5.1.2 Intraseasonal variations

- Relative importance of atmosphere/ocean interaction vs. land processes for the origin and propagation.
- Factors that govern the transition between active and break phases of the monsoon.
- Impact of intraseasonal variations on genesis of cyclones and monsoon depressions over the Indian Ocean and the western Pacific.
- Organisation of convection and interaction between convection and the large-scale environment over the Bay of Bengal and the South China Sea.
- Relationship with ENSO and the influence of ISO on interaction between the monsoon and ENSO.

*Proposals for (2.5.1.1) and (2.5.1.2):*

1. Support planned monsoon process studies and field campaigns in the western Pacific and East Asian regions i.e. GAME, SCSMEX, and other regional process experiments (e.g. KORMEX, Korea Monsoon Experiment).
2. Expand GEWEX/GAME regional experiment to the Indian subcontinent by the active involvement of Indian scientists, in particular, enhancement of radiosonde network over India for 1998 in conjunction with SCSMEX and GAME field experiments.
3. Initiate a pilot study of monsoon intraseasonal variability in the Bay of Bengal region, capitalising on the various observation platforms available from INDOEX in 1999 and activities planned under the National Indian Climate Research Programme.
4. Carry out feasibility and pilot studies for a focused field experiment on the Indian subcontinent and the surrounding oceans, which will provide data for the process studies of the seasonal march of the monsoon, including active and break periods associated with the intraseasonal variation of the South Asia monsoon and heat budget over the Indian Ocean (see Section 2.5.3 for specific proposals).
5. Expand the effort to process rainfall data to document the evolution of Indonesia rainfall on various time scales in conjunction with Indonesian scientists and research institutions.

#### 2.5.1.3 Monsoon-ENSO coupling

Process studies addressing this issue will:

- Examine poorly understood ocean processes that may contribute to SST anomalies of importance for monsoon-ENSO coupling.

- Delineate the relative importance of land processes such as soil moisture, snow cover and continental ground temperature in amplifying or damping monsoon-SST coupling.

#### **2.5.1.4 Tropospheric biennial oscillation**

Process studies addressing this issue will:

- Identify the physical origin(s) of the TBO in monsoon regions, including local air-sea-land interaction, global-scale influence as well as internal dynamics.
- Identify the role of active convection during the boreal spring through summer, where interannual monsoon anomalies switch sign.
- Provide better understanding of the mechanism for interaction between processes with various time scales, i.e. 4-5 years, 2-3 years and others associated with the irregularity of ENSO-monsoon coupling.

*Proposals for (2.5.1.3) and (2.5.1.4):*

1. Conduct ocean process studies to illuminate the following subgrid scale processes in monsoon-affected oceans and marginal seas: diapycnal mixing near boundaries, especially the impact of baroclinic tides; epipycnal mixing in boundary regions (eddy statistics); topographic influences (marginal seas, sills and straits); entrainment from the top of the thermocline and subtropical subduction.
2. Analyse outputs of high-resolution ocean models and observations to clarify large-scale oceanic processes: non-linear modifications of the reflection of Rossby waves from the irregular western Pacific boundary; bifurcation of the North and South Equatorial Currents and their variable impacts on low-latitude western boundary currents and effects of wind-driven upwelling on SST variations within the Warm Pool.
3. Analyse changes in land surface processes during warm and cold phases of ENSO to delineate possible impact of land surface processes in fostering or inhibiting the ENSO-monsoons coupling mechanisms, based on long-term integrations of CGCM (Section 2.4.1.4), satellite and reanalysis data.
4. Carry out process studies in conjunction with the development of special datasets and reanalysis projects for the monsoon regions (see discussion in Section 2.7).

#### **2.5.1.5 Heat balance of the Indian Ocean**

Process studies in this group will address the following issues:

- Understanding how the ocean dynamics can accommodate the anomalous heat flux into the North Indian Ocean.
- Identifying factors that inhibit organisation of deep convection over the Indian Ocean and unravelling causes for the small interannual variability in the Indian Ocean in contrast to the western and central equatorial Pacific.

### III. The CLIVAR Principal Research Areas

#### *Proposals:*

1. Carry out diagnostic studies using satellite, reanalysis data and outputs from OGCM and CGCM as proposed in (2.4.2) and (2.4.3).
2. Investigate the feasibility of special observation platforms for the Indian Ocean (see Section 2.5.3).

#### **2.5.2 Parameterisation of physical processes**

Several sub-grid scale processes are considered most important for understanding the AA-monsoon. CLIVAR will work closely with the relevant GEWEX subprogrammes to make improvements in parameterizing the following:

- Cumulus convection, including prognostic cloud water to better represent the monsoon moisture re-cycling and transport in the monsoon regions.
- Cloud-radiative processes associated with deep convection and cirrus shields that affect the water and heat budgets of the monsoon region.
- Coupling between vertical motions in deep convection and the boundary layer that modify surface fluxes at the air-sea and air-land interfaces.
- Improvement of land and ocean surface fluxes estimates based on information gained from prior and planned field campaigns and satellite missions. In addition, oceanic processes discussed in (2.5.1.3) need to be considered.

#### *Proposals:*

1. Exploit TOGA-COARE data fully to improve parameterisations of cumulus convection, heat and moisture surface fluxes, ocean surface layer and planetary boundary layer processes. CLIVAR monsoon scientists interested in this work will work within the TOGA-COARE research effort, which expects to yield its main results soon after the year 2000.
2. Develop, in association with relevant GEWEX subprogrammes, better techniques for representing in computer models, land and ocean surface processes and atmospheric mesoscale convection, employing data from planned field campaigns such as GAME, SCSMEX.
3. Utilise regional climate models nested in GCMs to provide better and more detailed description of physical processes so as to improve parameterisation and the development of physical submodels in the monsoon regions.

#### **2.5.3 Special observations and enhanced monitoring**

Special observations over the eastern tropical Indian Ocean and western Pacific are required to understand better both the relationship between the seasonal variation of warm pool over the eastern tropical Indian ocean and the western Pacific, and the onset and variability of monsoon rainfall over South Asia, and also to improve model physics. The last international large-scale field campaign of the summer monsoon dates back to MONEX, 1979. Since then our knowledge of the regional monsoon has increased greatly, but knowledge of the monsoon as a climate subsystem is still lacking. Currently two major international monsoon field campaigns, i.e. GAME and SCSMEX are pending in 1998. GAME and SCSMEX will greatly enhance our understanding of the East Asian monsoon climate. Yet even with these special observations, knowledge of the structure of deep convection over interior India and Asia (morphology, heating distribu-

tions, etc.) and adjacent oceans and their role in the active and break of the monsoon is woefully lacking. CLIVAR will explore opportunities for continued special observations and enhanced monitoring over the South Asia and adjacent oceans. In this regard, three of the process studies described above are of particular relevance:

- Role of intraseasonal transitions (2.5.1.2);
- Monsoon-ENSO interactions (2.5.1.3);
- Heat balance of the Indian Ocean (2.5.1.5).

The use of existing observing platforms such as XBTs and drifting buoys must at least be continued at their present levels, and if possible enhanced. The use of well-instrumented oceanographic moorings is also essential. These are the only reliable means of obtaining *in situ* surface meteorology for accurate flux estimates. Mooring data will be intercalibrated with data obtained from other measurement platforms such as aerosondes and airborne remote sensors to provide estimates of near surface quantities and humidity profiles. Moorings also provide platforms for the deployment of emerging technologies such as acoustic tomography. Other activities including field programs and observations are being planned as national efforts and these are expected to contribute to project G2.

## 2.6 OBSERVATION SYSTEM REQUIREMENTS

### 2.6.1 Meteorological variables

Routine meteorological observations are the largest contributor to the observation systems for monsoon. Much of the detailed data derived from radiosonde and surface observations are either unavailable or are not digitalised for research use. For monitoring purposes, satellite data will play a critical role in the monsoon observing system. However, the moist and cloudy nature of the monsoon atmosphere may introduce large uncertainties in operational satellite retrieval algorithms. For example, various satellite-based rainfall estimates show major inconsistencies over the monsoon region, both in the mean and in the variance. Satellite-based surface winds fail during rainy periods, when it is critical to assess the impact of air-sea interaction on monsoon variability. While present satellite products provide good information on total water vapour content, they do not provide information on the vertical profile - of great importance for determining atmospheric stability and horizontal moisture fluxes. For all these variables, the failure during rain introduces the potential for aliasing - e.g. satellite estimates of SST may be systematically incorrect during the convective phase of ISO.

*Proposals:*

1. Make historical data and real-time satellite data (e.g. GMS, INSAT and others) available to the CLIVAR monsoon research community to enable effective coverage of the South Asian and Southeast Asian region.
2. Utilise rainfall products from TRMM and work closely with satellite algorithm developers to devise methods for improving satellite rainfall estimates and vertical profiling of water vapour.
3. Deploy rain gauges, incoming short-wave and long-wave radiation sensors and humidity sensors on ocean moorings; upgrade and install meteorological sensors on VOS (Volunteer Observing Ships); and instrument commercial aircraft for soundings during take-off and at flight-level.
4. Continue the development of new technology, such as aerosondes, i.e. autonomous atmospheric sounders (Holland et al., 1992), and explore its use strategically in monsoon-affected regions.
5. Maintain and expand on the existing network wind profilers in the monsoon region, e.g. in Indone-



sia, to provide continuous monitoring of boundary layer and upper wind conditions of the equatorial Pacific.

## 2.6.2 Oceanic variables

For monsoon oceanography, a serious difficulty arises from the fact that outside the equatorial Pacific, our understanding of the mechanisms that produce SST anomalies is quite limited. In much of the Indian Ocean, these mechanisms are complex and unique. Fluxes derived from models or from satellites contain serious errors. Salinity and other subsurface data in the monsoon oceans are almost non-existent.

Present routine SST products are based on satellite infrared estimates (AVHRR), which cannot see through clouds, and have to be corrected for vertical details of the water vapour profile to achieve the required 0.2°C accuracy. As a result, SST estimates over the Bay of Bengal and the Indian Ocean ITCZ may be significantly in error during the monsoon season.

### *Proposals:*

1. Maintain the current VOS XBT network, which was designed to meet WOCE/TOGA requirements, and expand it into the monsoon oceans (western Pacific and Indian Ocean) during the CLIVAR era and promote the continuation of the planned extension of TRITON (TRIangle Trans Ocean buoy Network) ocean moorings into the Indian Ocean (see 2.6.2.1).
2. Conduct or commission Observing System Sensitivity Experiments (OSSEs) to estimate the best use of existing resources, for purposes of understanding and predicting SST anomalies of relevance to the monsoon forecasting. Ideally these should be done with coupled models, but until these reach sufficient skill ocean-only models will be adequate. Based on the results of these OSSEs, it is further proposed to:
3. Vigorously pursue all opportunities for deploying TAO-type moorings, drifting buoys and profiling ALACE floats in the Indian Ocean in a fashion consistent results of the OSSEs and with effectively enhancing CLIVAR sustained observations and the initial observing system of GOOS/GCOS in the region. Although TAO-type moorings have yet to be justified as a requirement for operational monsoon prediction and inclusion in the GOOS/GCOS initial observing system, the research of G2 may easily do so.
4. Encourage the optimal use of the currently costly salinity sensors.
5. Utilise satellite data for SST and surface flux estimates, e.g. ADEOS/NSCAT, MODIS from EOS AM/PM Platforms.

### 2.6.2.1 The TRITON array

A new moored-buoy network named TRITON (TRIangle Trans Ocean buoy Network) has been developing at JAMSTEC for observing oceanic and atmospheric variabilities in the western tropical Pacific ocean and its adjacent seas as a part of CLIVAR observing system.

The principal scientific objective is to understand basin scale heat transports with emphasis on ENSO, Asian-Australian Monsoon showing large seasonal to interannual scale variations, and decadal scale variability that influence global climate change.

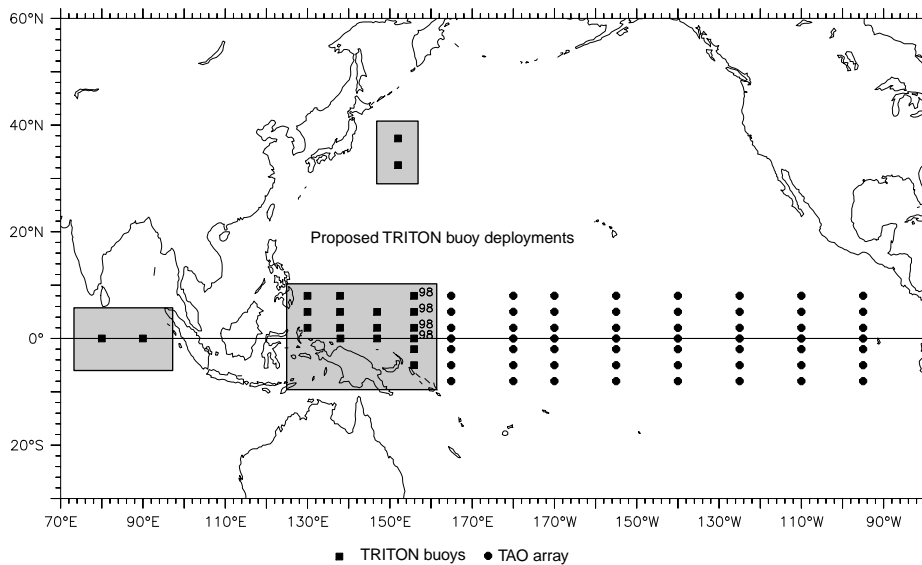


Fig. 2.8: The proposed TRITON buoy deployments (grey areas) and the TAO array.

The deployment will be started at four locations in the western tropical Pacific at TAO locations (Fig. 2.8). Subsurface ADCPs will be continually deployed along the equator as part of the Tropical Ocean Climate Study in conjunction with the TRITON buoy array. After establishing the network in the western tropical Pacific, two of buoys are planned to be extended in the eastern Indian ocean for the better understanding of heat and water budgets in the key area of Asian-Australian monsoon. Basically the sensors and those depths on the buoy are designed to be compatible with a standard TAO buoy in the western tropical Pacific. The TRITON buoys are also designed to measure the temperature and salinity in the full depth down to 750 m, and full surface meteorological parameters as wind speed/direction, temperature, relative humidity, atmospheric pressure, precipitation and short wave radiation. The buoy data are transmitted in real-time via GTS.

### 2.6.3 Land variables

In order to understand the predictability of the monsoon and the mechanisms of boundary forcing and internal dynamics, the continuous monitoring of land surface processes is necessary. Key land variables include soil moisture, river run-off, snow cover, surface heat budgets, including latent heat flux, sensible heat flux, long-wave and short-wave radiation. Currently, observations for these variables are mostly lacking. Many of the limited observations are being carried out under national or bilateral efforts within monsoon countries and regions.

#### *Proposals:*

1. Work closely with GEWEX, which has planned land surface programmes, e.g. GAME, GCIP to develop and share mutual needs for land surface atmospheric monitoring.
2. Create, in collaboration with GEWEX, an international framework to promote existing national and bilateral programmes for land surface monitoring.
3. The AAN/AWS network for GAME will be harnessed for long-term monitoring of surface heat budget and soil moisture to meet the CLIVAR AA-monsoon needs.

4. Make use of satellite estimate of land surface characteristics from land imaging sensors from ADEOS, EOS AM/PM and ENVISAT.

## 2.7 DATA SET AND PREDICTION SYSTEM DEVELOPMENT

### 2.7.1 Data set development and related studies

The most important parameter for describing the monsoon is rainfall. Yet the lack of rainfall data is very severe over the monsoon regions, in particular for the Southeast Asian region. Part of this is due to lack of observing stations and part due to data in local archives that is difficult to access. The lack of long-term rainfall and other critical datasets is a major impediment to progress in monsoon research. The following is a list of priority datasets that need to be developed:

- Long time-series (going back in time as far as possible) of daily rainfall data over the entire monsoon region.
- $1^{\circ} \times 1^{\circ}$  daily precipitation data derived from INSAT, GMS and TRMM in the monsoon oceanic region.
- $1^{\circ} \times 1^{\circ}$ , weekly SST over the Indian Ocean and Western Pacific for the present and past decades.
- Daily surface temperature and soil moisture data from historical archives.
- Surface flux data over the monsoon oceans, including data from historical archives, satellites and *in situ* measurements.
- Upper air data from routine, operational radiosonde observations in monsoon regions.
- Datasets of dynamics, thermodynamics and physics fields from ongoing reanalysis efforts.

#### *Proposals:*

CLIVAR recognises that the development of historical datasets will entail major efforts and the full co-operation of many countries in the monsoon region. CLIVAR will collaborate with the data rescue projects of the World Climate Data and Monitoring Programme and other data rescue efforts to maximise the recovery and digitalisation of archived data sets in the monsoon region. Empirical studies will be conducted in parallel with the dataset development effort to ascertain the validity of the datasets. The following dataset development effort and related empirical studies will be carried out:

1. Establish and fund international programmes to retrieve, digitalise and archive historical daily rainfall data for the entire monsoon region.
2. Combine *in situ* and satellite data to develop gridded daily rainfall over the entire monsoon ocean and land region.
3. Develop appropriate monsoon indices based on rainfall and dynamical variables.
4. Construct high resolution maps of simultaneous and lagged correlation of monsoon rainfall and SOI or Niño area SST indices to quantify monsoon-ENSO relationships.
5. Identify SST regions in the Indian Ocean and western Pacific for which monsoon activities (as measured by the monsoon indices) are most sensitive to.

6. Conduct focused reanalysis effort in the monsoon regions in conjunction with special observations and field programmes for the validation of nested climate models.

### **2.7.2 Monsoon prediction system**

A new thrust of the CLIVAR monsoon programme will be to take into account the applications and human dimensions of the predictability of the monsoon. Efforts towards the development of an end-to-end monsoon prediction system will be taken. These efforts will involve physical scientists, users and social scientists from the outset. This group will continue to work together throughout the process. Such an involvement promotes “ownership” of the products and optimises their usage. In this regard, CLIVAR will aid in the development of capacity building efforts in monsoon countries, with an eye towards the development of an end-to-end monsoon prediction system.

*Proposals:*

1. Establish a data network (internet based) to support users of monsoon data for the entire scientific community.
2. Develop capacity building programmes in monsoon countries for research and utilisation of research results for prediction in conjunction with APN/START (System for Analysis Research and Training) programme.
3. Expand activities of the IRI and related efforts, e.g. CLIPS, within national meteorological services to include a substantive monsoon component, with end-to-end prediction capabilities.

## **2.8 PROGRAMME LINKAGES**

Because of the complexity of the monsoon problem and its linkages to many different subsystems of the earth's climate, the CLIVAR monsoon research programme must be carried out in co-ordination with other WCRP programmes. The major linkages are:

### **Linkages with other CLIVAR components**

- CLIVAR GOALS NEG-1 Panel: monsoon modelling and prediction experiments; development of coupled ocean-atmosphere model in monsoon regions.
- CLIVAR Upper Ocean Panel: studies of oceanic processes and response to monsoon forcings.
- CLIVAR/GCOS/GOOS TAO Implementation Panel (TIP): strategies of deployment of oceanic measurement platforms in the Indian Ocean for monsoon special observations.

### **Linkages within WCRP**

- GEWEX/GCSS: GEWEX Cloud System Studies for cloud ensemble and mesoscale models for development of nested regional climate models and improvement of physical parameterisation in AGCMs.
- International field campaigns: GEWEX/GAME, SCSMEX and other regional campaigns.
- COARE: model validation, flux estimation and description of atmosphere-ocean processes over the western Pacific warm pool that are related to the Asian-Australian-monsoons.

### III. The CLIVAR Principal Research Areas

- WCRP/AMIP: Atmospheric model intercomparison over monsoon regions.
- WOCE (World Ocean Circulation Experiment): ocean circulation data from the WOCE Indian Ocean Expedition.

#### Other Linkages

- International Pacific Research Center (IPRC): focused on basic research on Asian-Pacific climate, hydrologic cycle and related global changes issues.
- International Research Institute (IRI) & Climate Information and Prediction Service (CLIPS): end-to-end ENSO forecast system development and regional social and economic applications.
- International satellite missions: NASA/NASDA TRMM (rainfall); EOS (land surface characteristics and SST, clouds) ADEOS-1 and -2 and ERS-1 and -2 (atmospheric humidity and surface wind).

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### **3. VARIABILITY OF AMERICAN MONSOON SYSTEMS (VAMOS) (G3)**

#### **3.1 SCIENTIFIC RATIONALE**

The word monsoon is derived from an Arabian word referring to season: it was the term used by sailors to describe the seasonal reversal of the winds over the Arabian Sea. It is now applied to low latitude regions that experience pronounced changes in the low-level circulation and precipitation regimes that result from the seasonal cycle of heating associated with the reversal of the temperature gradient between continents and oceans.

##### **3.1.1 The American monsoon systems**

The Asian-Australian and American monsoon systems are the two dominant monsoon systems of the world. Viewed in a global context, these two systems constitute major components of the low-latitude atmospheric heating field and the seasonally-varying, zonally-averaged Hadley Circulation. During most of the year, the dominant feature of the low-latitude Hadley Circulation is a single direct cell which links the two hemispheres (descending motion in the winter hemisphere; ascending motion in the summer hemisphere). Similarly, the regional monsoonal components of the Hadley Circulation link the winter monsoon circulation of one hemisphere with its summer monsoon counterpart.

The configurations (size, shape and location) of the land masses and surrounding ocean features involved in the Asian-Australian and American monsoon systems have important differences:

- The distribution of land and ocean in the Asian-Australian sector is largely north-south oriented, with land (ocean) primarily to the north and ocean (land) primarily to the south in Asia and vice versa in Australia. Over the Americas, the orientation of the land masses is primarily north-south, with oceans to the east and west.
- The major mountain complex of southern Asia has an east-west orientation, while the major western continental mountain ranges over the Americas extend north and south for the entire length of both continents.
- The continents of the Americas are more similar in size than Asia and Australia, but exhibit different asymmetries. Most of the land mass of South America is at low latitudes, and in fact extends into the northern hemisphere, while North America resides in the middle and high latitudes.
- The Intertropical Convergence Zone (ITCZ) in the Asian-west Pacific sector executes a pronounced inter-hemispheric seasonal migration, while its counterpart in the eastern Pacific and eastern Atlantic executes a much smaller seasonal migration and remains north of the Equator (except for a weak secondary ITCZ that sometimes develops west of south America during the height of the warm season). Associated with this asymmetry is the great contrast between the relatively warm waters of the North Atlantic and Pacific and the colder waters of the South Atlantic and Pacific.

Turning to the individual continental scale features, the definition of a monsoon region has centred on the requirement of a reversal in the low-level flow and the steadiness of this flow (Fein and Stephens, 1987). One can also describe a three dimensional, continental scale “monsoon circulation system”, which includes both an upward branch associated with the region of enhanced precipitation (e.g. the Indian “monsoon”) and a downward branch associated with regions of suppressed precipitation (e.g. the compensating subsidence over the arid regions of the Middle East). The monsoon system perspective provides a useful



framework for describing, understanding and modelling the annual cycle and interannual variability of the low and middle latitude continental precipitation and associated temperature regimes.

Fig. 3.1 shows the Northern Hemisphere wet season (June-July-August) and Southern Hemisphere wet season (December-January-February) rainfall. The continental monsoons and the oceanic ITCZs are clearly seen in this figure. During the Northern Hemisphere wet season, the northern branch of the Pacific ITCZ extends across much of the basin and merges with the continental monsoons of Mexico, central America and northern South America. In the Atlantic the ITCZ is at its most northern position and also merges with the monsoon over northern South America. During the Southern Hemisphere wet season, the ITCZ in both oceans weakens and the monsoon over Amazonia dominates and merges with the South Atlantic Convergence Zone (SACZ). In this context, the rainfall climatology of the low and middle latitude continental regions of the Americas is dominated by the eastern Pacific and western Atlantic ITCZs and the seasonal continental monsoons.

### 3.1.1.1 The monsoon system in the Northern Hemisphere

Climatologists and meteorologists have long referred to a “southwest monsoon” over Arizona and New Mexico, which begins in early July (Carleton, 1985, 1986, 1987; Adang and Gall, 1989; Hales, 1974). It is now apparent that this southwest monsoon is simply the northernmost portion of a more extensive region of heavy precipitation that first develops over southern Mexico and then spreads northward along the western slopes of the Sierra Madre Occidental (see Fig. 3.2).

The development phase of the North American monsoon system (May-June) is characterised by a decrease in synoptic-scale transient activity over northern Mexico and the U.S., as the mid-latitude storm track weakens and migrates poleward. Heavy rainfall starts over southern Mexico and quickly spreads northward along the western slopes of the Sierra Madre Occidental into Arizona and New Mexico by early July. Early in the mature phase (July-August), a “monsoon high” becomes established in the upper-troposphere near the U.S.-Mexican border. This feature is analogous to the Tibetan High over Asia (Tang and Reiter, 1984; Carleton et al., 1990). The region of enhanced upper tropospheric divergence in the vicinity and to the south of the upper troposphere high coincides with enhanced upper tropospheric easterlies or weaker westerlies and enhanced Mexican monsoon rainfall. In contrast, the flow is more convergent and rainfall diminishes in the increasingly anticyclonic westerly flow to the north and east of the monsoon high. There is some indication of increased divergence and precipitation in the vicinity of the “induced” trough over the eastern U.S. The decay phase of the system (September-October) is generally the reverse of the development phase, but proceeds at a slower pace. The ridge over the western U.S. weakens, as the monsoon high and Mexican monsoon precipitation retreat southward into the deep tropics.

The North American monsoon system, therefore, affects much of Mexico and the U.S. (Douglas et al., 1993). Major drought episodes in the midwestern U.S. are associated with what may be broadly characterised as an amplification of the upper tropospheric monsoon ridge. Associated changes in the lower troposphere include a weakening of the western end of the “Bermuda High” and the low-level jet over the Great Plains, which in turn is associated with a weakened inflow of moisture to the central U.S (McCorcle, 1988; Higgins et al., 1997a). A more or less reverse series of anomalies tends to develop during wet periods over the Midwest. Recent empirical studies provide evidence of a negative correlation between precipitation over the southwest U.S. monsoon region and over the northwestern U.S.-Mississippi Basin (Higgins et al., 1997b; Higgins et al., 1998a). The teleconnection may be one that develops over a time span of just a few days, with the arrival of a strong monsoon linked to atmospheric descent and drying over the Great Plains as a response to outflow from the monsoon (Higgins et al., 1998b). The primary mode of precipitation in July shows strong correlation with a mid-latitude circulation type termed the Pacific Transition Pattern. This suggests that mid-latitude circulation anomalies may play a part in the development of the monsoon system in Mexico.

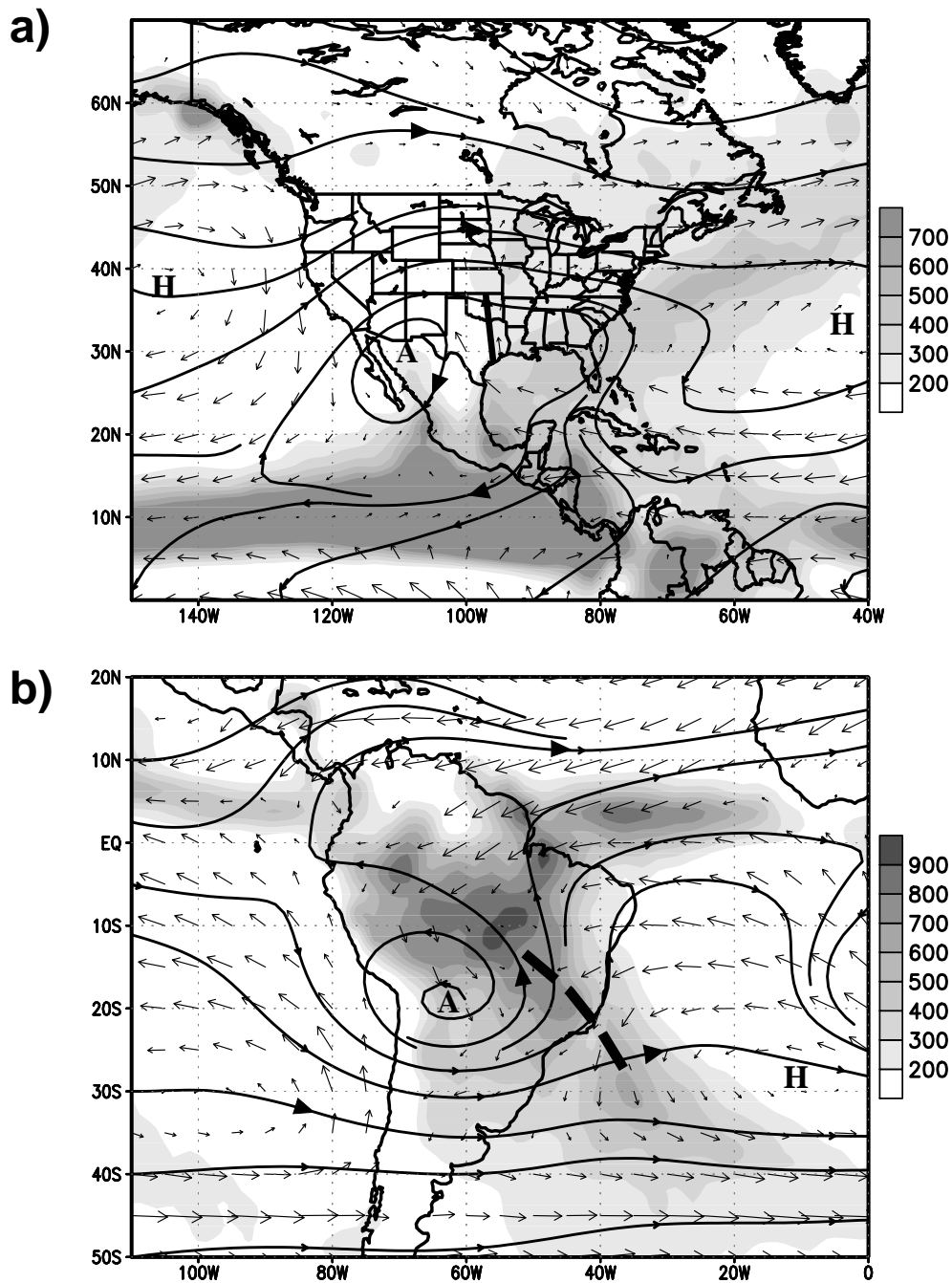


Fig. 3.1: Mean (1979-1995) 925 hPa vector wind and 200 hPa streamlines from the NCEP/NCAR reanalysis archive, and merged satellite estimates and station observations of precipitation (mm, shading): a) July-September. The position of the American North-Monsoon High is indicated by “A”. The Bermuda and North Pacific subtropical high pressure centres are indicated by “H”. The approximate location of the Great Plains low-level jet is indicated by the heavy solid line. b) December-February. The position of the Bolivian High is indicated by “A”. The South Atlantic subtropical surface high pressure centre is indicated by “H”. The approximate axis of the South Atlantic Convergence Zone is indicated by the heavy dashed line (courtesy of W. Higgins and M. Halpert (upper panel), resp. V. Kousky and M. Halpert (lower panel)).

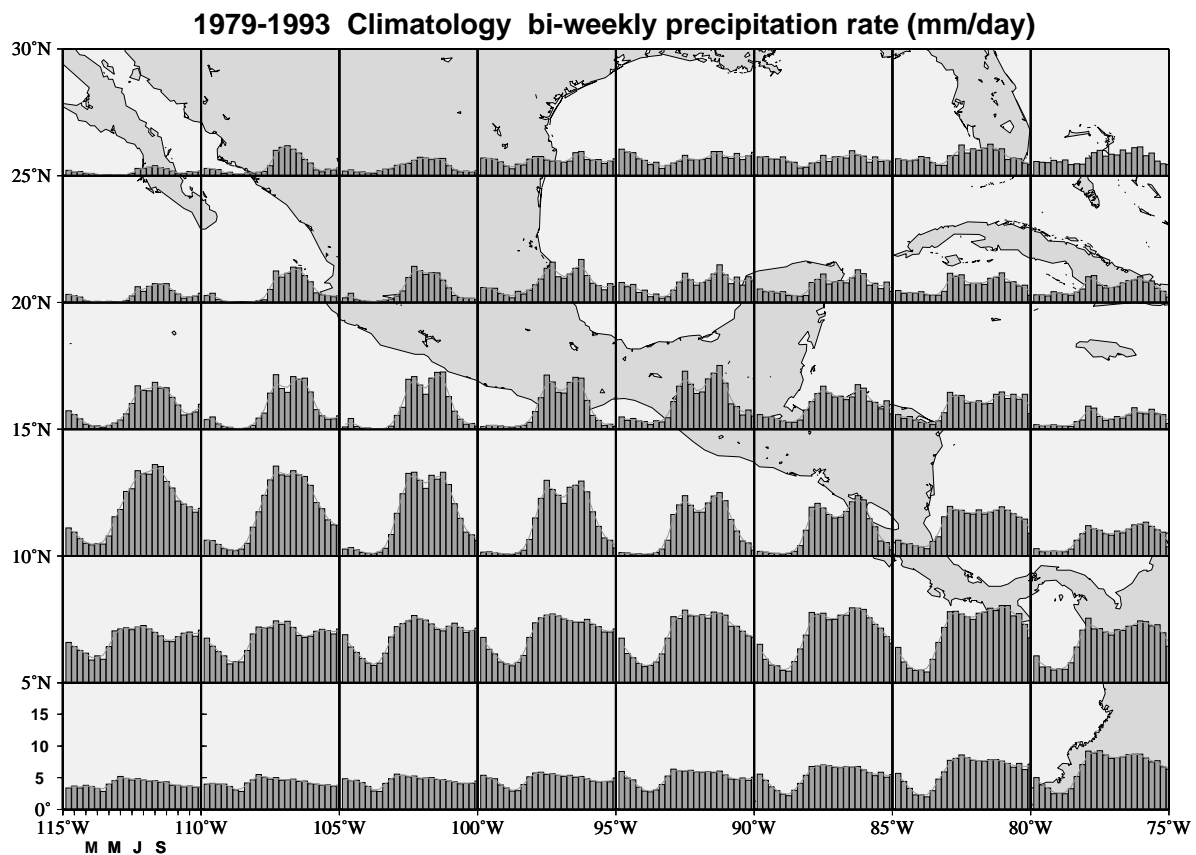


Fig. 3.2: Mean by-weekly precipitation (mm/day) during the period 1979-1993 in different regions of the Americas (Magaña et al., 1998).

The contribution of ocean processes to the interannual variability of rainfall over the Americas is discussed in Section 3.1.2. There is also evidence of links between tropical storm activity and the North American monsoon. The long rainfall record for Mexico City demonstrates that the summer monsoon was weak during the early 1900s and again in the late 1940s through the early 1960s, and was noticeably higher from the late 1920s to 1940 and again from the late 1960s to 1980. The eastern North Pacific had enhanced tropical storm activity in the 1920s, while the Gulf of Mexico was active in the 1930s (Díaz and Pulwarty, 1997). Thus, the wet 1920s and 1930s were associated with enhanced storm activity in one of the adjacent oceans. In contrast, the poor monsoon seasons of the 1940s were associated with reduced storm activity in the eastern North Pacific. This dry period extended into the 1950s when storm activity was greatly reduced in the Gulf of Mexico. The wet regimes of the late 1960s and 1970s were associated with a weakened Atlantic trade wind regime, decreased atmospheric stability and weak vertical shear. Tropical storm activity in the Gulf of Mexico and eastern North Pacific may not show strong year to year correlation, but decadal variability in storm activity between the two ocean regions appears to play an important part in the modulation of rainfall across much of Mexico.

The wintertime circulation over North America does not exhibit the pronounced reversal observed over portions of southern and eastern Asia. It does exhibit some similarities, however, such as the transient cold surges that spread southward east of the Rockies. These cold surges sometimes penetrate deep into the southern Gulf of Mexico and the Caribbean Sea, and trigger wind surges through low-altitude Mexican and Central American passes that affect SSTs in the eastern Pacific (DiMego et al., 1976; Schultz et al., 1997).

### 3.1.1.2 The monsoon system in the Southern Hemisphere

The characterisation of the seasonal cycle in the southern hemisphere as monsoonal in nature is more problematical. There is a seasonal shift in the inflow on the eastern side of the continent, which includes a distinct seasonal reversal in the cross equatorial flow, but the wind shifts are generally far from a complete reversal in the flow. Nevertheless, the elevated terrain of the Andes and the latent heating during the warm season give rise to an upper troposphere anticyclone (“the Bolivian High”) that seems to be analogous to the Tibetan High. Furthermore, there is a marked seasonal cycle in the precipitation regime and associated continental-scale vertical motion field over the continent (Tanajura, 1996; Kousky and Ropelewski, 1997).

The development of the monsoon system in the southern hemisphere during the austral spring is characterised by a rapid southward shift of the region of intense convection from northwestern South America to the highland region of the central Andes (South American altiplano) and to the southern Amazon basin (Schwerdtfeger, 1976). In contrast to its counterpart in the northern hemisphere, transient synoptic systems at higher latitudes play an important role in modulating the southward shift in convection. Cold fronts that enter northern Argentina and southern Brazil are frequently accompanied by enhanced deep convection over the western and southern Amazonia (Kousky and Ferreira, 1981; Kousky, 1985) and by increased southward moisture flux from lower latitudes. It has been suggested that this moisture flux is enhanced by a strong low-level jet east of the Andes (Virji, 1981, 1982; Stensrud, 1996). The low-level jet over South America is not as well-documented as its counterpart over the Great Plains of North America. As the austral spring progresses, precipitation increases over the Brazilian altiplano and southeast Brazil, as the SACZ develops (Kousky, 1988). The Bolivian High becomes established near 15°S, 65°W, as the monsoon system achieves mature phase characteristics. Intraseasonal and interannual rainfall variability in the region of the South American altiplano is closely linked to changes in intensity and position of this high pressure system. To the east of the Bolivian High and off the east coast of Brazil there is an upper-level cold trough, where rainfall is very low (Kousky and Ropelewski, 1997). The decay phase of the monsoon begins in late summer as convection shifts gradually northward toward the equator. During April and May, the low-level southward flow of moisture from the western Amazonia weakens, as more frequent incursions of drier and cooler air from the mid-latitudes begin to occur over the interior of subtropical South America.

Diagnostic studies of the diabatic heat source over the South American continent reveal a predominant role of the surface sensible heating in warming up the mid-troposphere over the central Andes during the pre-monsoon period. After the monsoon onset, strong latent heat release, accompanying deep convection over the subtropical highlands and the southern portion of the Amazon basin, maintains the thermal structure of the troposphere. The heating is largest in the mature phase, while the warm air spans the widest subtropical domain from the eastern south Pacific to the western south Atlantic.

Analysis of persistent wet and dry conditions over tropical and subtropical eastern South America during the austral summer reveals a dipole pattern of rainfall anomalies, with one centre over southeastern Brazil in the vicinity of the SACZ and another centre over southern Brazil, Uruguay and northeastern Argentina (Casarin and Kousky, 1986; Nogues-Paegle and Mo, 1996). This seesaw pattern, which reflects changes in the position and intensity of the SACZ on intraseasonal and interannual time scales, appears to be a regional component of a larger scale system. The southward extension and strengthening of the SACZ is associated with enhanced convection over the central and eastern tropical Pacific and dry conditions over the western Pacific and the maritime continent. Convection is simultaneously suppressed in the region of the SPCZ, over the Gulf of Mexico, and in the ITCZ over the north Atlantic (Grimm and Silva Dias, 1995a, b). In the opposite phase, there is a strong influx of moisture from the tropics into central Argentina and southern Brazil.

The contribution of ocean processes to the interannual variability of rainfall over the Americas is discussed in the following subsection. There is also evidence that inter-hemispheric teleconnections contribute to that variability. The North Atlantic Oscillation (NAO) is an example of such connections: blocking conditions over the North Atlantic are normally associated with negative rainfall anomalies over the eastern Amazonia and northeast Brazil (Namias, 1972).

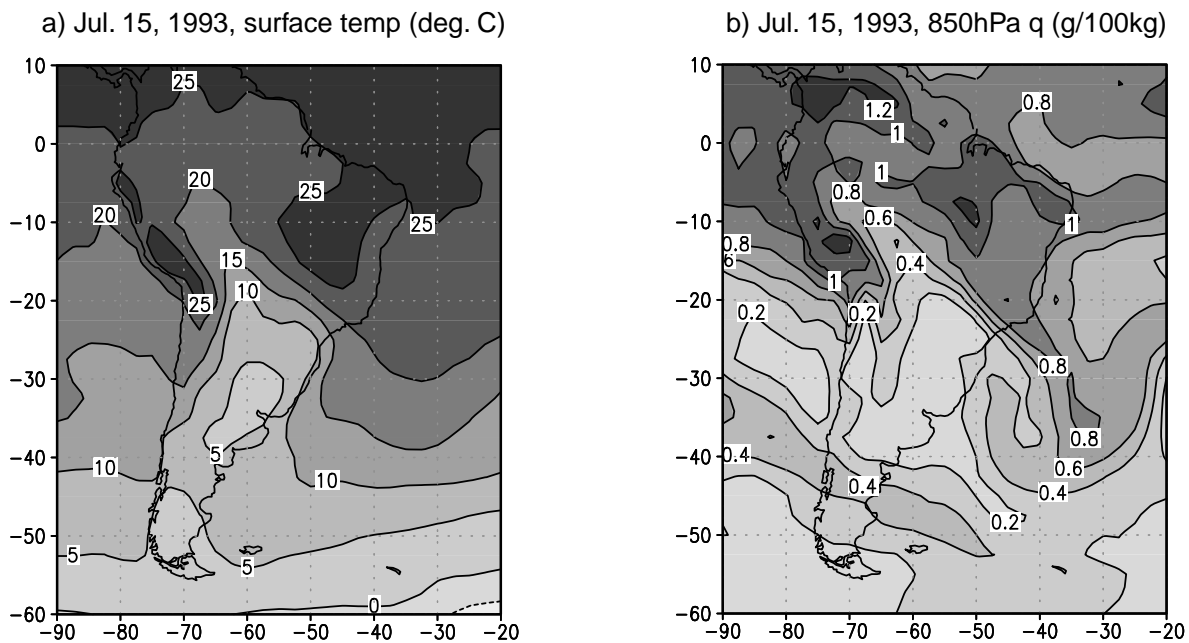


Fig. 3.3: Two features of a typical cold surge over South America during the Southern Hemisphere winter:  
 a) equatorward penetration of cold air at the surface (contour interval 5K),  
 b) decrease in specific humidity at 850hPa (contour interval  $0.2 \times 10^{-2} \text{g kg}^{-1}$ )  
 (courtesy of C. Vera).

Large-scale features, such as the ITCZ and SACZ, are frequently composed of organised mesoscale systems that are important in understanding the local climate and in weather forecasting. Some of these mesoscale systems are strongly tied to the local surface characteristics and are strongly modulated by the diurnal cycle. Satellite studies reveal the complexity of the diurnal variation of convection over the South American monsoon region (Kousky, 1980). There are clear indications of precipitation maxima associated with the inland penetration (sometimes up to several hundred kilometres) of convective activity initiated by the sea breeze along coastal sections of tropical South America. The large rivers and flooded areas in the equatorial region also provide the necessary forcing for the establishment of local circulation systems that can be clearly identified in satellite data and precipitation observations. The development and intensity of mesoscale convective systems, such as mesoscale convective complexes, squall lines and diurnal convection are strongly modulated by transient synoptic systems. At times, this scale interaction leads to excessive rainfall and flooding.

During the austral winter, precipitation is larger over northwestern South America north of the equator. The upper level subtropical jet stream is strongest at this time and is displaced equatorward over South America in agreement with the descending branch of a Hadley-type circulation over that area. Frontal systems move fast above regions of low specific humidity and high loss of heat by radiation, and are not associated with strong convective activity, but introduce cold surges, known as “friagens”, in central and north Brazil (Fig. 3.3) (Parmenter, 1976; Hamilton and Tarifa, 1978; Fortune and Kousky, 1983; Marengo et al., 1997).

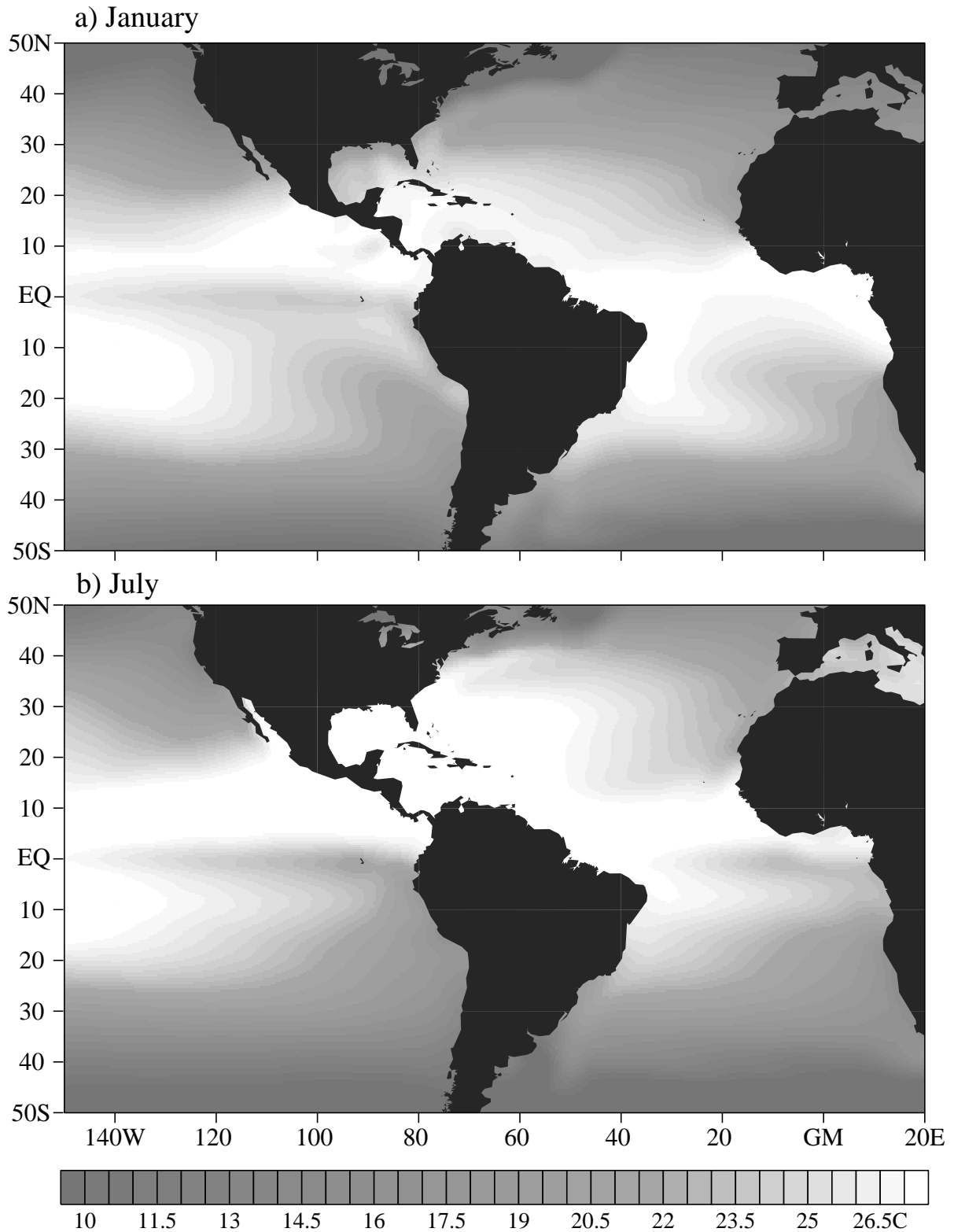


Fig. 3.4: Mean sea surface temperature distributions for a) January, and b) July. The northern hemisphere wet season shows a well defined “warm pool” extending from the eastern Pacific across central America and through the Caribbean Sea. In contrast, the southern hemisphere wet season shows warm pool temperatures weakening substantially and shifting southward. SST climatology for 1984-95 from Reynolds and Smith (1994) (courtesy of T. Mitchell).

### 3.1.2 The importance of ocean processes

For the American Monsoon System, the most important ocean-atmosphere-land interactions involve the eastern tropical Pacific and tropical Atlantic, as well as the Caribbean Sea and the Gulf of Mexico. Fig. 3.4 shows the sea surface temperature field (SST) in the Northern and Southern Hemisphere wet seasons, respectively. During the northern hemisphere wet season there is a well defined “warm pool” that extends from the eastern Pacific across central America and through the Caribbean Sea. For the most part, the oceanic rainfall is coincident with the warmest SST, and the large-scale continental precipitation can be viewed as an extension of the ITCZs over the continents. In contrast, during the southern hemisphere wet season the warm pool temperatures weaken substantially and shift southward. Moreover, the direct connection between the continental precipitation and the oceanic ITCZs fades.

The eastern equatorial Pacific and Atlantic Oceans are characterised by cold tongue/ITCZ complexes with marked hemispheric asymmetry and strong seasonality. Southeasterly tradewinds drive equatorial and coastal upwelling, leading to cooler surface waters along and to the south of the equator. In contrast, north of the equator in the eastern Pacific and Atlantic, surface temperatures are warmer in the vicinity of the ITCZ. At comparable latitudes in the Southern Hemisphere, large-scale subsidence over cool surface waters leads to the formation of low level stratus decks and minimal precipitation (Mitchell and Wallace, 1992). The reasons for these inter-hemispheric asymmetries are not fully understood at present (Li and Philander, 1996; Philander et al., 1996).

The hemispheric asymmetries in the eastern Pacific and Atlantic Oceans are most marked near the coasts. In the eastern Pacific, for example, the coolest surface waters are found in the coastal upwelling regime off the west coast of South America, where the climate is of the “humid desert” type. North of the equator, on the other hand, the warmest waters in the ITCZ region are located off the west coast of Central America. This eastern Pacific “warm pool” develops in a region of convergent wind driven ocean currents, and is marked by extreme rainfall over both the ocean and neighbouring land mass. The intensity of these features decreases from east to west in and over the ocean, as upstream continental influences wane and as the trade winds become more zonally oriented. In the tropical Atlantic there is a deep warm pool along the coast of South America, with extensions into the Caribbean Sea and Gulf of Mexico. This warm pool, and the corresponding warm pool in the northeastern equatorial Pacific separated by the relatively narrow continental land mass of Central America, are noteworthy in that so little is known about the processes that contribute to their maintenance.

The wind driven oceanic circulation in the eastern equatorial Pacific and Atlantic is important in determining the patterns of SST variability (Wallace et al., 1989). Major zonal flows of the equatorial current system include the westward flowing North and South Equatorial Currents, between which flows the eastward North Equatorial Countercurrent north of the equator in the vicinity of the ITCZ. A meridional ridge/trough system in surface topography and thermocline depth delimits the latitudinal boundaries of these currents. The Equatorial Undercurrent flows eastward below the surface along the equator, providing a source for upwelled water from the thermocline. Superimposed on these zonal flows is a meridional circulation involving poleward Ekman divergence and upwelling near the equator, meridional convergence and downwelling at higher latitudes, and geostrophic inflow towards the equator from higher latitudes at thermocline depth.

Surface winds in the South Atlantic force a gyre-scale interior ocean circulation, which is closed along the western boundary by the strong, southward-flowing Brazil Current. The southwestern tropical Atlantic is also characterised by the SACZ (Casarin and Kousky, 1986; Kousky 1988; Kodama, 1992), which is in some ways analogous to the South Pacific Convergence Zone (SPCZ) in the southwestern Pacific. The SACZ is not as well documented and explored in terms of oceanographic consequences as its Pacific counterpart. It is unclear, for example, whether the SACZ is associated with a South Equatorial Countercurrent in the south Atlantic to the same extent to which the SPCZ is associated with a similar current in the south Pacific.

The seasonally varying climate of the Americas is governed in part by pronounced seasonal variations in the surrounding tropical oceans. In boreal summer, for example, coastal and equatorial upwelling

circulations intensify in response to intensified southeasterly trade winds, and the cold tongues of the equatorial eastern Pacific and Atlantic intensify and expand poleward. The ITCZ, and the warm surface waters underlying it, are displaced northward. The northern branch of the South Equatorial Current and the North Equatorial Countercurrent intensify in both the Atlantic and Pacific. Associated with these zonal current variations are changes in thermocline topography and meridional mass fluxes, which result in an increased heat flux from the Northern to Southern Hemisphere.

Boreal summer monsoon circulations also develop in the atmosphere with onshore flow of moisture laden air in Central America and in the southwest U.S. Convergence of this moisture flux over land leads to convection and marked increases in continental precipitation. In northeast Brazil on the other hand, boreal spring is the wet season, corresponding to the time when the equatorial oceans are warmest, and the ITCZ in the western Atlantic is at its southernmost position south of the equator. In the southwestern Atlantic, the SACZ is best developed in austral summer, whereas in austral winter, migratory cyclones and associated cold fronts coming from the Pacific affect this region.

The intensity of the American monsoon systems is significantly modulated on intraseasonal, interannual and decadal time scales. The impacts of El Niño-Southern Oscillation (ENSO) phenomenon in the tropical Pacific are global, with specific regional imprints on precipitation patterns over the Americas (Ropelewski and Halpert, 1987, 1989; Aceituno, 1988, 1989; Pisciottano et al., 1994). There is evidence that the monsoon in Mexico is modulated by ENSO (Cavazos and Hastenrath, 1990). Specifically, a wet equatorial central Pacific (warm ENSO) is associated with dryness along the Pacific coast of southern and western Mexico (Magaña and Quintanar, 1997). Several studies suggest that in late-spring/early-summer ENSO establishes a teleconnection pattern with an anomalous trough over North America, and the jet stream and storm track displaced southward of their average locations. (e.g., Kalnay et al., 1990; Trenberth and Branstator, 1992; Trenberth and Guillemot, 1996; Bell and Janowiak, 1995; Janowiak, 1988). This results in increased frequency of storms and higher precipitation. Conversely, anomalously cold SSTs in the central equatorial Pacific are associated with a decreased frequency of storms and lower precipitation over North America. The modulation of monsoonal rainfall over South America SST variations in the tropical Atlantic is suggested by other studies (Namias, 1972; Hastenrath and Heller, 1977; Enfield, 1996). Through atmospheric teleconnections, ENSO events also affect the winds and therefore the oceanographic conditions in the Atlantic basin (Enfield and Mayer, 1997). In particular, the equatorial Atlantic is often characterised by unusually warm SSTs in the year following major ENSO warm events in the Pacific. Ocean-atmosphere interactions internal to the Atlantic are also an important source of interannual climate variability in that basin, in addition to that generated externally via teleconnections to the Pacific (Philander, 1986; Zebiak, 1993; Carton and Huang, 1994; Latif and Barnett, 1995).

Notable decadal time scale oceanic variations have also been reported in the Atlantic (Deser and Blackmon, 1993; Kushnir, 1994; Mehta and Delworth, 1995; Chang et al., 1997). Those variations include the so-called Atlantic dipole, which is characterised by inter-hemispheric variations in SST, surface winds and surface heat fluxes. The dipole influences the latitudinal position of the ITCZ and associated rainfall fields, and therefore has significant socio-economic impacts on countries bordering the region. The dipole also exhibits fluctuations on shorter seasonal and interannual time scales, which are important to describe and understand for the purposes of predicting short-term climate variability (Weiner and Soares, 1997). Decadal time scale variations have also been recently documented in the tropical Pacific (Trenberth and Hurrell, 1994; Graham, 1994; Deser et al., 1996). These low frequency variations manifest themselves in terms of SSTs with a spatial structure different from that associated with ENSO. Whether these variations represent a decadal modulation of the ENSO cycle, or arise from ocean-atmosphere interactions distinct from those associated with ENSO, is unknown at the present time. It is also unknown to what extent these decadal fluctuations are linked to decadal fluctuations in the North Pacific, and/or to anthropogenic climate change.

In addition to these long-term climate fluctuations, significant intraseasonal variations occur in the tropical Atlantic and Pacific which affect the detailed evolution of the seasonal cycle. Common to both basins are tropical instability waves with periods of about one month and horizontal scales of several hundred kilometres (Philander et al., 1985). These waves are important in regulating temperatures and large-scale current variations in the equatorial cold tongue regions through horizontal turbulent transports of heat and



momentum. In the western Atlantic, ocean eddies are prominent in the strong western boundary current regime of the coast of South America, where they affect ocean circulation and heat transports. In the Pacific, intraseasonal (60-90 day) equatorial Kelvin waves forced by surface winds associated with the atmospheric Madden and Julian Oscillation (MJO) are a very pronounced mode of variability (Madden and Julian, 1994). Intraseasonal variations in SST, thermocline depth and ocean currents result from the passage of these waves along the equator, and poleward along the coasts of North, Central and South America. Enhancements of MJO and Kelvin wave energy at intraseasonal frequencies are, moreover, implicated in the development of ENSO warm events.

### 3.1.3 The importance of orography and land surface processes

Over the continents, the orography and coastal geometry have a profound role in modulating the continental monsoon circulations. For example, during the wet season in Mexico the rainfall along the western slopes of the Sierra Madre Occidental can exceed 65 cm, whereas less than 200 km directly to the west the wet season rainfall is over 40 cm less. This mesoscale structure is influenced by the complex surface characteristics from the gulf of California in the west to the Mexican highlands in the east. Over South America, the narrow Andes mountains strongly influence the character of the monsoon circulation. During the Southern Hemisphere wet season the western slopes of the Andes mountains are arid, but the eastern slopes exhibit a relative rainfall maximum. The surface characteristics of the Amazon basin also influence the local monsoon rainfall maxima at the southern edge of the basin and at the mouth of the Amazon River.

Land surface processes are particularly relevant to the American monsoonal circulations. Early warm season conditions, which are most likely related to global circulation, can provide the land surface with either an excess or a deficit of moisture relative to the long-term mean value. The hypothesis is that this anomaly influences subsequent moisture conditions, either locally or regionally, as larger-scale atmospheric circulation becomes less important and local convection (and perhaps moisture recycling) becomes dominant in the summer season (e.g. Rind, 1982; Mintz, 1984; Delworth and Manabe, 1989). Preliminary coupled terrestrial hydrologic-atmospheric modelling studies (Koster and Suarez, 1995) tend to support this hypothesis.

Dynamical processes controlled by the regional water and energy balance can influence water vapour flow and, in this way, contribute to the occurrence of extreme events. Land-surface processes also have substantial influence on elevated mixed layers, and on associated lids on atmospheric instability that act to determine the distribution of the regional precipitation in time and space (Benjamin and Carlson, 1986; Clark and Arritt, 1995). There is compelling evidence that meteorological prediction is sensitive to terrestrial hydrologic-atmospheric coupling processes, which argues for research aimed to identify the coupling processes that are most important for improved prediction, and the level of complexity that is worthwhile to include in sub-models describing those processes.

## 3.2 VAMOS: PROGRAMME DEFINITION

GOALS, one of the main streams of CLIVAR, deals with climate variability and predictability on seasonal-to-interannual time scales building upon the accomplishments and observing system of TOGA. GOALS, acting in collaboration with GEWEX, seeks to develop skilful prediction of global climate variability on seasonal-to-interannual time scales through exploitation of linkages with predictable variability of tropical heat sources and sinks associated with SST and other surface anomalies, or that predictability that may be inherent in the extratropical system. The overall strategy is to focus on the monsoon systems in order to capitalise on the known major heat sources that contribute to shape the global atmospheric circulation. The largest annually varying tropical heat source is associated with the switch from the Australian summer monsoon centred in January, to the Asian summer monsoon centred in July. The second largest monsoon occurs over the Americas as the large atmospheric heat source, associated with rainfall over the Amazon basin that peaks in January, migrates to the Northern Hemisphere in the northern summer. Two distinctive

characteristics of the American monsoon system differ from the Asian-Australian monsoon system.

First, tropical SST anomalies are particularly influential on climate variability in the American sector. Hence, a study of the American monsoons will address the predictability of tropical SST to a greater extent than the other GOALS components. Second, complex orography and coastal geometry imprint a mesoscale signature upon the American monsoon systems that is strong enough to qualitatively influence its planetary-scale structure and behaviour. Hence, a study focused on American monsoons will emphasise multi-scale studies ranging from the planetary to the regional.

Because many countries are affected by these monsoons systems, it is advantageous to co-ordinate research programmes that address the outstanding scientific issues. Therefore CLIVAR has established two panels dealing with the different aspects of the Asian-Australian and the American monsoons: Asian-Australian Monsoon Panel and Variability of the American Monsoon Systems (VAMOS) Panel.

VAMOS is a component of CLIVAR GOALS with three major objectives:

1. to describe, understand, and model the mean and seasonal aspects of the American monsoon systems,
2. to investigate their predictability and to make predictions to a feasible extent, and
3. to prepare products in view of meeting societal needs.

VAMOS will focus on rainfall and the probability of occurrence of significant weather events such as tropical storms and temperature extremes. The term “monsoon system” encompasses not only the summer monsoon rainfall in the tropical Americas, but also the perturbations in the planetary, synoptic and mesoscale flow patterns that occur in association with it, including those in the winter hemisphere. The region of interest covers both the tropical and the extratropical Americas and surrounding oceans. Like the other regional components of CLIVAR, VAMOS will also foster the development of the observing, modelling and data management capabilities required for climate prediction.

A number of regional and national research projects, such as the Pan-American Climate Study (PACS), the GEWEX Continental Scale International Project (GCIP), the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), and the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) contribute to VAMOS. The Inter-American Institute for Global Change Research (IAI) provides important linkages to the societal impact of climate research within the Americas. Finally, the International Research Institute for Climate Prediction (IRI) provides a framework for VAMOS to carry out climate predictions and the assessment of predictability of the American monsoon systems. More detailed descriptions about the linkages to these programmes is provided in Section 3.8.

### **3.3 MODELLING AND PREDICTION**

#### **3.3.1 Atmospheric general circulation models (AGCMs)**

Inference of causal relationships based on empirical evidence is often difficult because the anomalous surface wind field associated with the rainfall anomalies can induce SST anomalies of its own, and anomalous boundary conditions in a number of different regions are often interrelated by way of planetary-scale atmospheric teleconnections. In view of the complexity of these processes, AGCMs play key roles in establishing hypotheses on the atmospheric response to boundary forcing. Nevertheless, present AGCM simulations forced with climatological mean boundary conditions exhibit systematic biases in regions of the Americas and adjacent oceans. The models generally underestimate the wind stress in the equatorial belt, and the coverage of oceanic stratus clouds. These clouds play an important role in the energy balance of the PBL and the ocean mixed layer and are associated with the equatorial asymmetry of SST in the tropical Atlantic and eastern Pacific (Ma et al., 1996). Such well-defined biases highlight basic deficiencies in the at-

### III. The CLIVAR Principal Research Areas

mospheric models that need to be corrected in order to pave the way for the development of realistic coupled models.

VAMOS will encourage studies with AGCMs aimed at a better understanding of atmospheric sensitivity to anomalous boundary forcing. Results of several published AGCM studies suggest that tropical SST anomalies can influence warm season rainfall over the Americas (Moura and Shukla, 1981; Mechoso and Lyons, 1988; Mechoso et al., 1990; Díaz et al., 1998). AGCM experiments can explore the mechanisms by which monsoon rainfall anomalies over northeast Brazil are positively correlated with SST anomalies over the tropical South Atlantic and negatively correlated with SST anomalies over the tropical North Atlantic. Additional experiments may examine the hypothesis that SST anomalies associated with El Niño are capable of inducing rainfall anomalies over northeast Brazil and other regions of the Americas, independently of the anomalies in the Atlantic. Such experiments are needed to understand, and ultimately to predict, the way in which the slowly evolving planetary-scale atmospheric response to boundary forcing modulates the more intermittent, higher frequency synoptic and subsynoptic phenomena that are responsible for the individual episodes of heavy rainfall and significant weather.

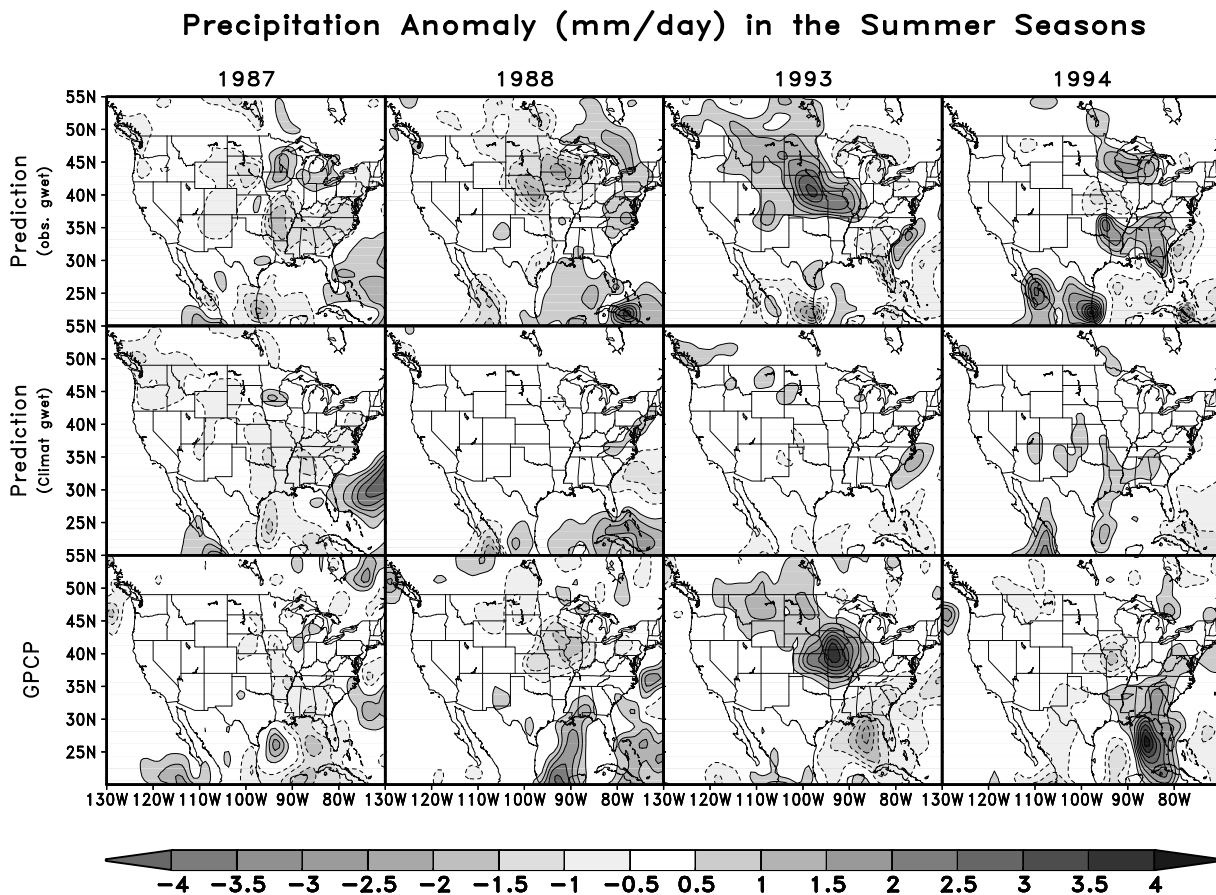


Fig. 3.5: Precipitation anomalies produced by AGCM forecasts for May-August 1987, 1988, 1993, and 1994. Soil wetness conditions were prescribed according to observational estimates for the corresponding periods (top row), or at climatological values for the northern summer season (middle row). In both forecasts, global sea-surface temperature anomalies for those years are included in the boundary forcing. The precipitation anomalies from the GPCP dataset are shown in the bottom row (courtesy of S. Schubert and M. J. Suarez).

AGCMs can also address the feedbacks involving land surface processes that can also play important roles in warm season rainfall over the Americas (Atlas et al., 1993, Betts et al., 1996). Fig. 3.5 shows results of controlled experiments using the Goddard Earth Observing System AGCM. Two ensemble forecasts were performed beginning in mid May of 1988, 1989, 1992, and 1993, and extending through the end of the following August. In the set of ensembles, soil wetness conditions were prescribed according to either observational estimates for the corresponding periods or at climatological values for the summer season. In both sets, the appropriate global SST anomalies were included in the boundary forcing. Fig. 3.5 also includes precipitation anomalies from the GPCP dataset.

Focusing on 1988 and 1993 summers that were quite anomalous over North America, Fig. 3.5 shows that when a realistic soil moisture anomaly is prescribed, the model reproduces precipitation anomalies similar to those observed; but when only climatological soil moisture is used, there is almost no anomalous precipitation over North America. These results are a dramatic demonstration of the importance of land surface processes in predicting summertime precipitation. In an actual forecast the soil moisture could not have been specified and the state of the entire hydrological system (land plus atmosphere) would have had to be predicted.

The principal issues to be addressed with AGCMs include:

- Are simulations by AGCMs realistically sensitive to slowly varying boundary forcing?
- What is the atmospheric response to SST anomalies in the Caribbean Sea and the Gulf of Mexico?
- In which way does the slowly evolving planetary-scale atmospheric response to boundary forcing modulate the more intermittent, higher-frequency synoptic and subsynoptic phenomena that are responsible for episodes of heavy rainfall and significant weather (e.g. flare-ups in the ITCZ and SACZ, migrating frontal systems, Atlantic and Caribbean hurricanes, and higher latitude blocking events associated with cold air outbreaks)?
- How can the simulations of the intensity of ITCZ rainfall and the diversity of convective heating profiles in the tropics be improved?
- How can the simulations of regional differences in the diurnal cycle of precipitation be improved?
- What vertical resolution is required for simulation of the different stratiform cloud regimes?
- Can AGCMs provide appropriate boundary (lateral) conditions to embedded mesoscale models?

### 3.3.2 Oceanic general circulation models (OGCMs)

OGCMs will address a number of important questions concerning the processes that contribute to SST variability in the tropical Pacific and Atlantic. The mechanisms that control the annual march of SST in the monsoon regime of the eastern tropical Pacific appear to be fundamentally different from those in the trade wind regime of the central Pacific, upon which much of the prior OGCM development effort has been focused. The lack of correspondence between fluctuations in SST and thermocline depth in the annual cycle of the eastern Pacific Ocean attests to the importance of other processes such as insolation and other surface fluxes, upwelling, horizontal advection and vertical mixing in the heat balance (Philander et al., 1987).

There are unresolved questions on the source of water upwelled in the equatorial cold tongue, the depth from which it originates, and the meridional extent of the upwelling cell. Also, it is unknown whether the upwelling water can be traced back to the surface in extratropical regions, as has been suggested in recent studies (Deser et al., 1996; Gu and Philander, 1997). As in the atmosphere, an issue that remains unre-

solved is the rectification of high-frequency forcing and internal instabilities into the low-frequency variability. Since mixing is an irreversible process, the net effect of high-frequency signals on the annual cycle might be quite different than would be deduced from low frequency averages alone. There also appears to be important smaller-scale regional variability that escapes the resolution of basin-scale OGCMs, but that may be significant for understanding the heat, mass, and momentum budgets over the eastern tropical Pacific. The region up to a few hundred kilometres of the Central American coast is generally very warm but can cool rapidly in response to winter northerlies blowing through gaps in the American cordillera.

The principal issues to be addressed with OGCMs include:

- What are, and how to model, the processes that contribute to the maintenance of the oceanic mixed layer in the presence of equatorial upwelling?
- What is the source of water upwelled in the equatorial cold tongue, the depth at which it originates, and the meridional extent of the upwelling cell?
- What is the relative importance of dynamical and thermodynamical processes associated with the seasonal variations of the meridional wind stress in the eastern tropical Pacific and Atlantic?
- What mechanisms control the seasonal cycle of SST in the monsoon regime of the eastern tropical Pacific and in the trade wind regime of the central Pacific?
- What role do tropical instability waves in and north of the cold tongue play in the transport of heat and momentum in the upper ocean?
- What is the role of small-scale regional variability in the heat, mass, and momentum budgets of coastal regions?

### 3.3.3 Coupled atmosphere-ocean-land GCMs (coupled GCMs)

Many of the challenges confronted in modelling the atmosphere, ocean and land surface are further heightened in a coupled context, as the interactions among the components can lead to strong internal feedbacks (Webster and Chou, 1980). A relevant case in point is the simulation of the coupled annual cycle in the eastern Pacific (Ma et al., 1994). The strong meridional gradients, and strong equatorially asymmetric character of the annual cycle evolution clearly involves coupling between land, atmosphere and ocean, and has proven a very difficult challenge for coupled models. At this time, many models are unable to simulate the evolution realistically, perhaps the most common errors being associated with the appearance of overlay warm waters and atmospheric convection to the south of the equator during the austral summer season (Mechoso et al., 1995). Such errors clearly impact the circulation over the Americas, and in particular, the simulation of the American monsoon systems. VAMOS will encourage studies that further elucidate the boundary layer, convective cloud interaction, and dynamical processes giving rise to seasonal-to-interannual variability in the American sector. It is only through improved understanding that better parameterisations and model simulations will be possible.

These issues to be addressed with coupled GCMs include:

- What mechanisms determine the variability of ENSO?
- Why do the simulated cold tongues in the equatorial Pacific and Atlantic Oceans tend to be so strong and persistent, to extend so far west, and to separate from continental coasts to the east?
- What are the atmospheric, oceanic, and coupled atmosphere-ocean processes that contribute to the existence of the persistent stratus clouds in the eastern Pacific and Atlantic Ocean?
- Why is it that coupled GCM simulations tend to show relatively warm water extending too far

east in the subtropical southern Pacific and Atlantic Oceans?

- How strong are the connections between the variability of the coupled atmosphere-ocean system in the Pacific and Atlantic Oceans?
- What would be the impact on the precipitation forecasts over the Americas of extending operational forecasts of the coupled atmosphere-ocean system for the Pacific to include the Atlantic Ocean?

### 3.3.4 Mesoscale atmospheric models

The richly textured distribution of rainfall over the continents and oceanic convergence zones presents a challenge and an opportunity for regional analyses and predictions. Along the coasts and over the mountainous terrain of the Americas, the coarse-resolution rainfall simulated by GCMs cannot be compared directly with station data. GCM simulations are particularly poor in the summer, when mesoscale convective systems play a dominant role in organizing the precipitation (Horel et al., 1989; Rao et al., 1996).

VAMOS will focus attention on mesoscale processes that affect the distribution of continental-scale precipitation and its variability on seasonal-to-interannual time scales. Mesoscale processes have long been considered to have both deterministic and probabilistic components. Characteristics of the underlying surface on the mesoscale help to control the development and organisation of mesoscale circulations (Figuerola et al., 1995). Mesoscale resolution of such factors as the slope of the terrain, land-sea temperature contrasts, or variations in soil moisture and vegetation will be necessary in order to understand better the American monsoon systems. On the other hand, mesoscale instabilities (e.g. tropical storms or mesoscale convective systems) contribute a significant fraction of the total seasonal precipitation in many areas of the Americas, and their occurrence (or absence) can lead to large year-to-year variations in precipitation. Thus, VAMOS will evaluate the aggregate effect of such mesoscale instabilities on the climate of the American monsoon systems.

Mesoscale models are expected to contribute to VAMOS in several ways, including the analysis and simulation of the mesoscale aspects of the mean state and spatial and temporal variations of the American monsoon systems. There is a need to evaluate specific physical processes that affect important components of the American monsoon systems. For example, cool season surges through the mountain gaps of Central America are known to rapidly lower the sea surface temperature downwind of the gaps and modify regional oceanic currents. In addition, the low-level jet to the east of the Andes Mountains contributes to the meridional moisture transport from the Amazon Basin into the subtropical regions of South America and modulates convective outbreaks in those regions. There is also a need to perform sensitivity and predictability experiments in which a model with mesoscale resolution is nested within an AGCM or coupled atmosphere-ocean GCM. The nesting strategy employed may be one-way (i.e. the mesoscale structures in the interior domain do not affect the GCM solution in the outer domain) or two-way (i.e. the mesoscale structures in the interior domain may affect the global solution).

The mesoscale modelling strategies will most likely evolve over the duration of the VAMOS programme. To effectively employ mesoscale models, a number of fundamental model design issues must be addressed. These issues focus on how to improve mesoscale models for climate analysis and prediction and include:

- How do mesoscale physical processes, such as convection, differ as a function of latitude and how do these differences affect model parameterisations?
- What is the sensitivity of the mesoscale simulations to the details of the underlying surface: e.g. sea surface temperature gradients or terrain? How important is the specification of soil moisture to the initialisation of mesoscale simulations as a function of soil type and seasonally evolving vegetation?

- How well can the seasonally varying climate be simulated as a function of horizontal and vertical resolution?
- How dependent are mesoscale simulations on specific physical parameterisations, such as surface exchange, and how do these dependencies differ for the various components of the American monsoon systems?
- What is required to develop an integrated approach to air/land/sea interactions on the mesoscale?
- What are the most appropriate nesting strategies and what are the sensitivities to the nesting methodology?
- To what extent does the skill of the GCM or coupled GCM in which a mesoscale model is embedded control the skill of regional predictions?

### 3.3.5 Predictability

The quality of deterministic atmospheric forecasts depends heavily on the quality of the initial data. The initial data cannot be created with absolute accuracy because of errors in observational data, lack of coverage and problems with representativeness. Forecasts starting from two slightly different initial data which are equally likely to represent the true atmospheric state, will deviate from each other after a few days. On average such forecast pairs deviate from each other as randomly chosen atmospheric states after 10 to 15 days. From that one can deduct that deterministic forecasts of the weather beyond 12 days are presently hardly possible.

There is also an interest in forecasts of the mean (weekly, monthly, or seasonally averaged) state of the atmosphere but then with a longer lead time. Experiments have been shown that the boundary forcing (SSTs, snow, soil moisture) become important for such forecasts. There are areas, especially in the tropics, which show a high sensitivity of e.g. mean precipitation to the phase of ENSO. An atmospheric model could be used to predict atmospheric mean states for such areas, if the oceanic temperatures could be forecasted. The latter has successfully been achieved with statistical models but for larger lead times (more than 6 months) only forecasts with coupled ocean-atmosphere models have the chance of success. The forecast of the 1997-98 strong El Niño with a lead time of one year is an example of the potential skill of such forecasts with coupled models especially for the Americas. Comparisons between forecasts by different schemes may contribute to enhance progress in coupled modelling

Simulations-predictability issues arise in the context of regional scale models. At the present time, very little work has been done regarding sensitivity of mesoscale models to initial and boundary conditions. These studies are a necessary prerequisite to the prediction of regional scale climate over the Americas.

### 3.3.6 Prediction

At present, ENSO SST predictions are being done routinely with an array of coupled dynamical models, as well as statistical-dynamical and purely statistical models (Cane et al., 1986; Barnett et al., 1993; Penland and Magorian, 1993; Balmaseda et al., 1994; Ji et al., 1996). Nonetheless, dynamical climate prediction is in its infancy. For example, many systems do not utilise much of the observational information available, and are thus obviously limited. Almost none of the climate assimilation systems acknowledge atmosphere-ocean coupling, even though a coupled system is more natural and undoubtedly optimal for coupled models. Forecasting methodologies such as ensemble averaging, model output statistics (MOS) corrections and probability forecasting are only now beginning to be considered. And of course, aspects of climate other than ENSO remain by and large unexplored. Yet the achievements to date provide optimism for further im-

provements in climate forecasting and forecast products that will be of direct relevance to VAMOS. Given the proximity to the tropical Pacific, the gains made in ENSO prediction will undoubtedly benefit climate prediction over the Americas.

Another set of issues that are crucial to prediction of precipitation (and other variables) over the VAMOS region concerns the initialisation of land surface conditions. At this time, it is not known what the observational requirements are for regional climate prediction. Certainly improvements in present land surface models will be needed, especially at the regional scale. Progress in the representation of land-atmosphere interactions over the last two decades has been sufficient to motivate several operational modelling centres (e.g. the National Center for Environmental Prediction, the European Centre for Medium Range Forecasting and the Japanese Meteorological Centre) to implement and benefit from modern-era, multi-layer soil-vegetation-atmosphere transfer schemes. Planetary, continental and regional atmospheric circulation patterns in such assimilation systems are constrained near truth by the assimilation of atmospheric observations. Nonetheless, the implementation of improved representation of terrestrial hydrologic-atmospheric interactions has undoubtedly improved the quality of the precipitation and low-level temperature analysis products provided by data assimilation systems. The sharp topography of the VAMOS region poses a particular challenge to prediction. At present, it is not known at what scale dynamical model predictions may become useful for the region. It will be necessary to evaluate continuously the state-of-the-art dynamical predictions against mixed statistical-dynamical (or even purely statistical) predictions. It would not be surprising if, at the regional scale, the latter actually prove superior in the short-term, given the complexities involved.

Methodological research akin to that for large-scale predictions is also necessary in the mesoscale domain for the Americas. Such research is essential to meet the objectives of VAMOS, and will be strongly encouraged by the programme.

### **3.4 SPECIAL OBSERVING NEEDS**

#### **3.4.1 Enhanced monitoring in the eastern tropical Pacific region**

VAMOS will encourage the development of enhanced monitoring systems that will provide the observational basis for improvement of operational coupled ocean-atmosphere analysis and prediction systems for the eastern Pacific region, as well as for the tropical Atlantic. Monitoring is understood as continuous atmospheric and oceanic observations during a multi-year period.

Although the TAO array has improved the definition of the surface meteorological conditions and upper ocean thermal structure over the equatorial Pacific, the region to the east of the Line Islands (160°W) remains among the most serious data gaps in the global observing system. Operational atmospheric analyses and forecasts of midtropospheric winds cannot be verified for lack of *in situ* observations, and even some aspects of the climatology are not very well established. A more accurate and detailed description of the annual march of the upper ocean temperature and salinity structure is needed off the west coast of the Americas. The TAO array covers only the equatorial zone, leaving seriously undersampled regions in the warm pool off the central American coast and the vast stratus decks to the south of the equatorial zone in the southeastern Pacific (see Fig. 3.6). Until these observational system gaps are filled through a combination of *in situ* and space-based observations, it is unlikely that the annual variation of the ITCZ-cold tongue complex can be analysed and forecast with the accuracy required for skilful predictions of seasonal-to-interannual variability of the American monsoon.

Concerning the eastern Pacific, several approaches are being considered to enhance monitoring of meteorological and oceanic conditions. For the atmosphere, the augmentation of the continental and island-based rawinsonde network, the use of ship-based soundings of opportunity, and sounding systems operated from manned and/or unmanned aircraft are promising. Extension of the TAO array along 95°W from about 12°S under the stratus deck, across the cold tongue, the equatorial front and into the warm pool to around 12°N could provide valuable “synoptic” information on upper ocean temperature and salinity structure, as



well as data to validate and constrain model-based analyses of the upper ocean heat and freshwater budgets in the ITCZ-cold tongue complex. Other approaches are being considered by the PIRATA programme for the tropical Atlantic.

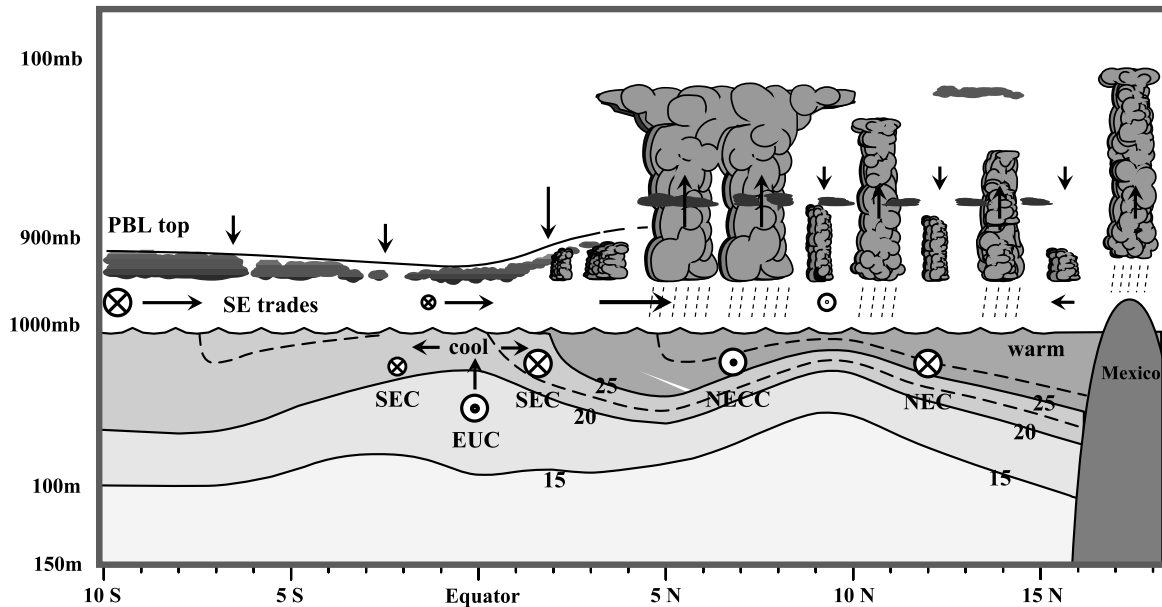


Fig. 3.6: Idealised cross section through the ITCZ/cold-tongue complex along 95°W during July-September, showing features of the ocean-atmosphere stratification and current structure near the interface. SEC refers to the South Equatorial Current, NECC to the North Equatorial Countercurrent and EUC to the Equatorial Undercurrent. Ocean isotherms are in degrees Celsius. The deep convection between 5°N and 10°N indicates the location of the ITCZ. Encircled 'x' (dots) denote westward (eastward) flowing winds or currents (courtesy of S. K. Esbensen and W.S. Kessler).

### 3.4.2 Surface fluxes over the oceans

VAMOS will encourage the realisation of field studies that aim to provide improved description of surface fluxes over tropical oceans. Except for surface marine observations provided by the TAO moored buoy array, the tropical Pacific east of 160°W remains among the most serious data gaps in the operational global observing system. Long records of research quality surface flux estimates that include radiative fluxes and rainfall are very limited over both the eastern Pacific and the Atlantic Oceans and must be augmented to support improvement and validation of boundary layer parameterisations in ocean-atmosphere climate models. Enhanced monitoring of the northeast Pacific warm-pool region, the equatorial cold tongue regime, the southeastern Pacific low cloud trade wind regime and the equatorial Atlantic using a combination of moored buoys and enhanced observing systems aboard ships of opportunity are promising approaches. International co-operation will be needed for effective implementation of these strategies.

### 3.4.3 Atmosphere-ocean interaction in the stratus deck region

The persistent stratus clouds off the Peru coast are believed to play an important role in accounting for the strong equatorial asymmetry in SST and surface wind in the eastern Pacific. Atmospheric and coupled GCMs have difficulty in simulating the extent and properties of these clouds and their interactions with the underlying SST field. The cloud deck is situated in cool air that flows equatorward around the east side of the subtropical anticyclone, and which maintains the atmospheric planetary boundary layer (PBL) in an unstable state as it encounters increasingly warmer waters. VAMOS will encourage projects that address

the existence and variability of these cloud decks, and the way in which their presence affects the insolation and downward flux of infrared radiation at the air-sea interface. There is need to investigate the microstructure of the cloud deck and its variations with time, as well as its height, thickness, radiative properties and position relative the vertical structure of the PBL. It is also of interest to determine how deep into the ocean the influence of the cloud deck extends, and the evolution of the PBL structure as one follows air trajectories northwestward from the stratus deck into the relatively cloud-free equatorial cold tongue region. In addition, it is important to assess whether the temporal variations in the extent of the cloud deck are related to variations in the strength of the low-level flow around the subtropical anticyclone and/or to the subsidence aloft.

#### **3.4.4 High resolution sea surface temperature**

Higher spatial and temporal resolution SST data are required to study regional relationships between ocean boundary and American monsoon systems. The spatial resolution must be sufficient to resolve SST gradients in regions such as the Gulf of California. A  $1^\circ$  long. by  $1^\circ$  lat. COADS monthly SST data set is currently available for the period 1960 to 1993. VAMOS will require updates of these data through the life of the programme and, where the data are adequate, weekly analyses on this spatial scale. Specific requirements for higher spatial resolution weekly SST data will be developed to support studies utilizing nested regional numerical models. VAMOS anticipates these mesoscale modelling studies will require SST on spatial scales near  $0.5^\circ$  long. by  $0.5^\circ$  lat. for limited sub-domains of the VAMOS region. These higher resolution data will be required for time periods coinciding with model experiments.

#### **3.4.5 Soil moisture**

Over land areas, soil moisture is thought to play a role somewhat analogous to that of SST over the oceans (Delworth and Manabe, 1989; Koster and Suarez, 1995, 1996). VAMOS requires estimates of soil moisture in order to investigate these relationships, and will encourage work by the GEWEX programme aimed at providing the necessary observational estimates of soil moisture or some proxy for soil wetness. In principle, monthly, gridded, soil moisture would provide an untold wealth of insight into seasonal precipitation mechanisms over the Americas. Selected numerical and/or field studies require higher spatial and temporal resolution soil moisture data, e.g. weekly on  $0.5^\circ$  long. by  $0.5^\circ$  lat. analyses.

However, recognizing that gridded soil moisture estimates on these scales may not be attainable in the near future, some VAMOS requirements may be met through utilisation of a network of *in situ* soil moisture measurements. These requirements may be partially met over portions of North America by the soil moisture measurements taken as part of GCIP. VAMOS encourages similar observational programmes for Central and South America. In South America, VAMOS will look to the LBA programme to provide some of these data.

#### **3.4.6 Precipitation**

A major focus of VAMOS is understanding and prediction of seasonal precipitation. However, climate-scale phenomena do not generally respect the traditional calendar month boundaries. This is especially true for many aspects of the American monsoon systems including onsets, breaks and monsoon withdrawals. Thus, at a minimum, VAMOS requires the development of daily rainfall data sets over the Americas. This will require the integration of data from a variety of independent sources.

Recent numerical modelling experiments have highlighted the importance of properly capturing the diurnal cycle of evaporation and precipitation. The ability to correctly replicate the observed diurnal cycle is important in the context of climate model simulations. High quality hourly precipitation measurements are required for a better understanding, modelling and prediction of seasonal precipitation. The correspond-

ing datasets are necessary both to validate regional numerical models that are run in a climate setting, and to provide a fuller understanding of the role of climate-scale variability in modulating the diurnal cycle of rainfall.

### 3.4.7 Vertical structure of the atmosphere

A more complete understanding of the evolution and variability of the American monsoon systems requires a full description of the atmospheric circulation associated with the events. While the major large-scale circulation features may be described using one of the GCM-based reanalyses (e.g. the NCEP/NCAR 40 year reanalysis), the study of regional features requires additional observations. For example, the global analyses are consistent with the notion that the flow is northerly along the eastern side of the Andes during the southern summer (Virji, 1981, 1982). The analyses also suggest the existence of a southward-flowing low-level jet from the Amazon basin into Argentina embedded in the large-scale northerly flow (Sugahara, et al., 1994; Stensrud, 1996). It is generally believed that the spatial structure and temporal variability of this jet are similar to that of its well-documented counterpart over the Great Plains of North America. These features are very important for convective developments. Mesoscale convective systems travelling eastward and forming over northern Argentina and southern Bolivia have been associated with a low-level warm and moist flow from the Amazon region (Guedes and Silva Días, 1985; Silva Días, 1989).

Studies have shown that approximately 30% of the southern summer days have a low-level jet east of the Andes at approximately 60°W, 20°S with an average speed of 13 ms<sup>-1</sup> at about 1,500 m above sea level. In fact, the Andes seem to play a key role in the existence of this feature (Gandu and Geisler, 1992; Figueroa et al., 1995). The low-level jet appears to have marked diurnal oscillations in association with buoyancy oscillations above the elevated and heated Andes. The diurnal evolution of convective weather shows that summer showers tend to occur at night over most of Central Argentina (Paegle et al., 1982). The destabilising effects in the PBL of dynamical mechanisms, therefore, appear to be more important than the stabilizing effects of thermodynamical mechanisms during night-time. A marked diurnal cycle in the low-level flow east of the Andes has been simulated (Nicolini et al., 1987). In addition, the regions most favourable for the formation of convective systems are strongly correlated with those where the diurnal cycle has largest amplitudes (Machado and Guedes, 1996).

The available observational datasets are insufficient for study of the southern low-level jet in view of the subsynoptic scales involved and the sparseness of the South American observing system. Further data are needed to address several specific issues that require further clarification:

1. What is the structure of the low-level jet east of the Andes?
2. What are the mechanisms at work for its existence?
3. What are the relationships between the jet and the mesoscale convection that contribute significantly to the total seasonal precipitation in southeastern South America?
4. What is the relationship between the variability of the jet and that of the SACZ?
5. What is the contribution of the moisture advected by the jet to the regional atmospheric hydrologic cycle?

Numerical models have difficulty with the extremely sharp topographic features of the Andes. Understanding the South American monsoon system requires more complete descriptions of the wind fields and atmospheric moisture transports and how they are influenced by these topographic features. Enhanced observations are required for the PBL and free atmosphere over the Southern Pacific, the west coast of South America, the Altiplano region, the lee of the Andes and across the continent into the SACZ. Enhanced observational periods with frequent soundings are necessary for model development and validation, as well as for empirical studies.

## **3.5 FIELD STUDIES**

### **3.5.1 Atmospheric PBL structure above the cold tongue**

Several field studies are required to assess whether it is possible to reconcile the observed vertical profile of wind speed and direction with existing models of PBL structure. The outcome will provide insights into how the models might be improved.

A field programme is under way funded by PACS to collect soundings in the PBL above the cold tongue region in the southerly regime in the far eastern Pacific. Another project is building a more comprehensive background climatology of the PBL structure over the cold tongue in the eastern equatorial Pacific to ascertain the degree to which the PBL reflects the local distribution of SST. Except for a few isolated field observations made during the Eastern Pacific Ocean Climate Studies (EPOCS), the vertical profile of the wind and thermodynamic variables in the southerly surface wind regime in the far eastern Pacific is virtually undocumented.

### **3.5.2 Structure and intensity of ITCZ rainfall**

A PACS shipboard field study was carried out in summer of 1997 to test whether the hypothesis that the eastern Pacific clouds produce more rain than the western Pacific clouds but are not as deep is correct. It has generally been assumed that lower cloud-top temperatures are indicative of greater rainfall amounts. This ship-based study also examined the nature of the low-topped precipitating clouds over the eastern Pacific.

### **3.5.3 Air-sea fluxes in the cold tongue-ITCZ complex**

A PACS field project aims to provide accurate measurements of the heat, momentum and fresh water fluxes in the eastern tropical Pacific. Of special interest is the relation of the vertical structure of the upper ocean and sea surface temperature to the local air-sea fluxes, and particularly, the role of the precipitation in governing SST. In this regard, two surface moorings will be set, one in the ITCZ (10°N, 125°W) and the other in the centre of the oceanic cold tongue (equator, 125°W). Both moorings will make surface meteorological measurements, including wind velocity, air temperature, SST, incoming short-wave and long-wave radiation, relative humidity, barometric pressure, and precipitation. They will also make oceanic observations including temperature, salinity and horizontal velocity in the upper 200 m.

### **3.5.4 Vertical current profiles in the equatorial cold tongue**

A PACS field investigation will deploy a surface mooring at 125°W with a high vertical resolution (1 m) acoustic Doppler current profiler and several temperature and temperature/salinity recorders to sample both the velocity and density structure from a 2 m depth through the mixed layer and the upper portion of the thermocline. It is recognised that measurements at a single location will not be sufficient to resolve the modelling issues concerning the structure and dynamics of equatorial upwelling. In order to effectively address those issues in a field study, it will be necessary to deploy an array of moorings suitable for estimating the vertical profile of divergence and the relevant advection terms in the various budgets.

### **3.5.5 Tropical Rainfall Measuring Mission (TRMM)**

In 1997 NASA/NASDA TRMM satellite was launched to map tropical precipitation. The eastern Pacific ITCZ presents a particular problem in this regard because of the sparsity of island-based stations in that region. The shipborne radar and precipitation measurements obtained over the tropical eastern Pacific Ocean provide valuable validation data for TRMM.

## **3.6 DIAGNOSTICS AND EMPIRICAL STUDIES**

### **3.6.1 Diagnostic studies**

The synoptic climatology of rainfall and significant weather events over the Americas is still in need of further elaboration, particularly for the warm season. There are indications of inverse relationships between monsoonal rainfall and rainfall in adjacent regions that warrant further exploration. There remain outstanding questions concerning the mechanisms of the annual march in the cold tongue/ITCZ complexes and the stratus decks that could be addressed in diagnostic studies based on existing data sets.

VAMOS will encourage the realisation of statistical studies documenting relationships between anomalous boundary forcing and climate anomalies over the Americas, and diagnostic studies elucidating the physical and dynamical mechanisms through which these linkages occur. In this context, anomalous boundary forcing includes both SST and land surface processes, and climate anomalies refer not only to mean temperature and rainfall, but also to the frequency of droughts, floods and severe thunderstorm outbreaks. There is also need for descriptive and diagnostic studies of the tropical and extratropical storm tracks, ocean mixed layer, atmospheric PBL structure, and interfacial fluxes in the ITCZ-cold tongue complexes, based on existing marine surface observations and satellite data.

### **3.6.2 Empirical studies**

It is becoming increasingly apparent that the ENSO phenomenon is subject to variability on decadal-to-century time scales. The warm polarity has become more prevalent since the mid-1970's and particularly since 1990 and the quasi biennial periodicity that characterised much of the previous 20 years has not been in evidence. Empirical studies are needed to clarify whether these long-term changes should be viewed as deterministic fluctuations in the coupled climate system, or whether they are merely a reflection of sampling variability associated with the ENSO cycle. VAMOS will encourage work on the processes that determine the evolution of the more subtle SST anomalies in the tropical Atlantic, and their impact on the atmospheric circulation.

Empirical studies that define and elucidate the fundamental characteristics of the regional distribution of continental precipitation are also needed. Terrain features over the Americas give rise to a number of distinctive local features in the synoptic climatology such as low-level jets with moist, poleward flow to the east of the Rockies and Andes, episodic "gap winds" across central America and strong diurnal variations in rainfall patterns.

### **3.7 DATA SET DEVELOPMENT**

The VAMOS Data Management will be based, as far as possible, on the principle of free and open access to data. Data access will be achieved through existing data centres, research institutions and universities to the fullest extent possible rather than through the establishment of one centralised data centre. To the extent possible, data management links will be established through a World Wide Web Home Page for VAMOS. The project will require assistance from the participants to co-ordinate a variety of data management activities. Specific tasks include further identification of existing VAMOS-related data, procedures for accessing them, and co-ordination of VAMOS-specific data needs for field studies.

#### **3.7.1 Existing sources of data**

An initial review of data sets of interest to VAMOS investigators reveal that some data are already available through existing institutions and distribution mechanisms. Some of these are listed in Table I (Section 3.10).

#### **3.7.2 Historic data sets / data archaeology**

While VAMOS will be able to take advantage of a number of existing data centre activities as well as the data sets discussed above, the programme will require a number of specific data sets. These will be more specifically defined in response to the detailed VAMOS science and implementation plans.

VAMOS will provide an opportunity to merge a number of data sets from several different data sources to provide a coherent description of the American monsoon systems to support diagnostic and empirical studies, model validation studies and prediction activities.

The development of historical daily precipitation and temperature data sets will be a key activity. The development of VAMOS daily precipitation and temperature data sets will build on current activities in PACS, GCIP, LBA, IAI and other regional and national activities.

A unique VAMOS data requirement arises from interest in the Intra-American Seas (IAS). The possible role of the IAS on regional precipitation will be one of the VAMOS research foci. This will require special efforts for improved historic SST, wind, and subsurface data in the Caribbean and Gulf of Mexico.

VAMOS will strongly encourage recovery of precipitation and surface temperature time series that are currently stowed away on non-digital formats in various non-conventional archives. This is especially applicable to data from South America where long term time series of good quality (sometimes going back to the turn of the century) exist in national records or private holdings in paper form. Examples are national and state agencies involved in the management of water resources and landowners. There is an urgent need to develop funding opportunities to rescue this valuable resource which might otherwise be lost due to the frailty of the records.

The private sector has recently engaged in active measurements efforts in some South America countries. As an example, one company has sold 800 automatic stations in Argentina only in the last 5 years. This figure should be compared with less of 100 sites currently available in the GTS. Policies need to be developed to access this important resource and make it available to the science community. A concern is the fact that many of the national weather services do not encourage the open exchange of data. This pressing issue, that threatens the integrity of key scientific data, needs to be addressed at the highest possible administrative levels.

### 3.7.3 The VAMOS data base

VAMOS will require development of a data base which will serve the needs of the diagnostics, empirical studies, modelling and prediction communities in VAMOS. The requirement to link with several data centres, research institutions and regional projects strongly suggests the development of a distributed data base structure linked through a VAMOS Home Page. While these links will not be able to service all of the VAMOS data needs, they will provide an efficient mechanism for providing information about data and for effecting data exchange. Distributed data bases have proven an effective means of servicing data needs without the requirement of a single large and costly data centre.

The distributed data base concept will allow VAMOS to interact efficiently with the Inter American Institute for Global Change Research (IAI), as well as with other regional centres such as CPTEC and regional projects such as GCIP and LBA.

## 3.8 LINKAGES

VAMOS will closely interact and co-operate with a number of national and regional projects as well as with other components of CLIVAR.

### 3.8.1 Within CLIVAR

Naturally, VAMOS has strong interactions with the other core projects of CLIVAR GOALS: G1 (ENSO: Extending and Improving the Predictions), G2 (Variability of the Asian-Australian Monsoon System) and G4 (African Climate Variability). Although VAMOS will focus mostly on seasonal-to-interannual climate variations, decadal climate variability might modulate and affect short-term climate variations of the American monsoons. Therefore, a co-ordination with research projects under the CLIVAR foci D2 (Tropical Atlantic Variability) and D4 (Pacific and Indian Ocean Decadal Climate Variability) is highly recommended.

### 3.8.2 Within WCRP

#### 3.8.2.1 Global Energy and Water Cycle Experiment (GEWEX)

GEWEX emphasises the impact of weather systems on ground hydrology. Mesoscale modelling of continental precipitation in a climate context is an important element of the programme. The GEWEX Continental-scale International Programme (GCIP) focuses on North American rainfall and Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) on rainfall in the Amazon basin. A particularly important issue for GCIP is that the surface energy balance is known to affect the low-level jet over the great plains. Such coupling has been demonstrated by numerical modelling. This low-level jet is, in turn, a major factor in the regional moisture transport and moisture flux divergence in the Mississippi River region (Rasmusson, 1967).

##### (i) GEWEX Continental Scale International Project (GCIP)

The GEWEX Continental Scale International Project (GCIP) is a U.S.-led initiative being carried out in the Mississippi River Basin under the auspices of the WCRP's GEWEX programme. GCIP's mission is to demonstrate an ability to predict changes in water resources on seasonal, annual and interannual time scales within the framework of a global climate prediction system. GCIP has structured its programme around five objectives: 1) to determine and explain the annual, interannual and spatial variability of water

and energy cycles in the Mississippi River Basin, 2) to develop and evaluate coupled hydrologic-atmospheric models at resolutions appropriate to large-scale continental basins, 3) to develop and evaluate atmospheric, land and coupled data assimilation schemes that incorporate both remote and in-situ observations, 4) to provide access to GCIP in-situ, remote sensing and model data sets for use in GCIP and as benchmarks for model evaluation, and 5) to improve the utility of hydrologic predictions for water resources management up to seasonal and interannual time scales.

The second phase of GCIP is currently being planned based on needs to expand the geographical area for process studies to include the western U.S. A GCIP/PACS ad-hoc working group is developing a scientific prospectus focusing on the seasonal-to-interannual variability of warm season rainfall, surface air temperature, and the hydrologic cycle over North America. These improvements are needed to obtain more accurate water budget estimates and better information for model validation for both GCIP and VAMOS.

### **(ii) Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)**

LBA is an international research programme aimed at creating the new knowledge needed to understand the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land use change on these functions, and the interactions between Amazonia and the Earth system. LBA is centred around two key questions that will be addressed through multi-disciplinary research, which will integrate studies in the physical, chemical, biological and human sciences: How does Amazonia currently function as a regional entity?, and how will changes in land use and climate affect the biological, chemical and physical functions of Amazonia, including the sustainability of development in the region and the influence of Amazonia on global climate?

In LBA, emphasis is given to observations and analysis which will increase the knowledge base for Amazonia in six general areas: physical climate, carbon storage and exchange, biogeochemistry, atmospheric chemistry, hydrology, and land use and land cover. The programme will help provide the basis for sustainable land use in Amazonia, using data and analysis to define the present state of the system and its response to observed perturbations, complemented by modelling to provide insight into possible changes in the future.

Meteorological and hydrological studies in the physical climate component will be conducted for nested spatial scales, from plots to the entire Amazonia, with emphasis on the understanding of the spatial and temporal variations of energy and water fluxes. Variations of climate and the responses of the Amazonian system to these variations, will be determined on daily to seasonal time scales. The data fields generated by a numerical weather prediction model will be stored and used in a four-dimensional data assimilation scheme as a primary tool to process the observational datasets.

VAMOS will contribute to co-ordinate the efforts of LBA and GCIP to encompass the largest hydrological basins in the Americas. This co-ordination will facilitate the unification of approaches across national boundaries. It will also facilitate the elaboration of the relative roles of soil moisture over land, and SSTs over oceans in determining precipitation and temperature patterns over a wide range of climate zones.

### **3.8.3 With other programmes**

#### **3.8.3.1 Pan-American Climate Study (PACS)**

PACS is a U.S. project under the GOALS programme. Within the overall framework of CLIVAR, PACS can contribute to extend the scope and to improve the skill of operational seasonal-to-interannual climate prediction over the Americas, with emphasis on monsoons and extratropical summer rainfall and the coupling between them.



### *III. The CLIVAR Principal Research Areas*

The scientific objectives of PACS are to promote a better understanding and more realistic simulation of (1) the boundary forcing of seasonal to interannual climate variations over the Americas, (2) the evolution of tropical SST anomalies in the tropical Pacific and Atlantic, (3) the seasonally varying mean climate over the Americas and adjacent ocean regions, (4) the time-dependent structure of the ITCZ/cold tongue complexes over the Atlantic and eastern Pacific, and (5) the relevant land surface processes over the Americas, including the effects of mesoscale orography and coastal geometry.

PACS sponsors dataset development, empirical studies, modelling and field activities. Dataset development is a decentralised effort designed to make global and American satellite and ground based datasets more accessible to the research community. Empirical studies, both statistical and diagnostic, address all five of the above objectives. Modelling includes atmospheric general circulation model (AGCM) simulations of the atmospheric response to boundary forcing, oceanic general circulation model (OGCM) simulations of the tropical oceans, coupled atmosphere-ocean general circulation model (coupled GCM) simulations focusing on the cold tongue-ITCZ complexes and the associated stratus decks and their interaction with the American monsoon systems, and simulation of the mesoscale structure of monsoon rainfall in a climate context. Field activities (exploratory measurements, enhanced monitoring, and process studies) contribute to the scientific objectives by providing improved datasets for initializing and verifying model simulations of the boundary forcing of rainfall anomalies over the Americas and the evolution of the tropical SST field, and promoting a better understanding and more realistic simulation of the structure of the ITCZ/cold tongue complex. PACS's field studies will focus on different regions of the American climate system in sequence. During the initial phase PACS will focus on atmosphere-ocean interaction in the tropical eastern Pacific, in association with the ENSO cycle and the climatological-mean annual march. During the second half of PACS the emphasis will gradually shift to the tropical Atlantic Ocean.

#### **3.8.3.2 Pilot Research Moored Array in the Tropical Atlantic (PIRATA)**

PIRATA is designed as the Atlantic counterpart of the TAO array in the tropical Pacific. In a three year (1997-2000) pilot project PIRATA aims to provide time-series data of surface fluxes, surface temperature and salinity, and upper ocean heat and salt content to examine processes by which the ocean and atmosphere interact in key regions of the tropical Atlantic. The field phase of PIRATA started with the deployment of two moorings in 1997. Deployment of up to 12 moorings is envisioned as part of a multinational effort involving Brazil, France, and the United States (see figure 6.6, page 203).

PIRATA is also being co-ordinated with the WOCE/ACCE programme scheduled for 1997-98, which will also be taking observations in the tropical Atlantic. VAMOS will provide PIRATA researchers with opportunities for enhanced co-operation with those working in the tropical Pacific under the sponsorship of PACS. It will facilitate the exchange of information with GCIP and LBA researchers on the information required from the tropical Atlantic for a better understanding of the moisture flux to the American monsoon systems.

#### **3.8.3.3 Inter American Institute for Global Change Research (IAI)**

In recognition of the importance of a regional approach to the study of global change, eleven countries of the Americas signed an agreement establishing the Inter American Institute for Global Change Research on May 13th, 1992, at Montevideo, Uruguay: Argentina, Bolivia, Brazil, Chile, Costa Rica, Dominican Republic, Mexico, Panama, Peru, United States, and Uruguay.

The IAI focuses on the 1) increased understanding of global change related phenomena and the societal implications of such phenomena, 2) increased overall scientific capacity of the region, 3) enhanced regional relationships, establishment of new institutional arrangements, and 4) promotion of the open exchange of scientific data and information generated by the Institute's research programmes, implementation of IAI Training and Education Programs.

The following research themes have been identified as initial priorities of the IAI: 1) tropical ecosystems and biogeochemical cycles, 2) impact of climate change on biodiversity, 3) ENSO and interannual climate variability, 4) ocean/atmosphere/land interactions in the inter tropical Americas, 5) comparative studies of oceanic, coastal and estuarine processes in the temperate zones, and 6) comparative studies of temperate terrestrial ecosystems and high latitude processes.

Although they are primarily concerned with the science of climate assessment and prediction on seasonal-to-interannual time scales, the regional programmes organised under the CLIVAR/GOALS contribute to a broader range of human endeavours. The participation of IAI is of special importance to VAMOS in view of the Institute's major thrust on the societal impacts of climate variability over the Americas. VAMOS will provide IAI researchers with opportunities for enhanced co-operation with other science programmes focusing on the American climate system, particularly with the large and regional scale modelling efforts developed in PACS and GCIP. It will also provide enhanced co-ordination of field activities in the American sector.

#### **3.8.3.4 International Research Institute (IRI)**

The International Research Institute for seasonal to interannual climate predictions was launched in 1996 by NOAA, and is developing toward a multi-national organisation focused on seasonal-to-interannual climate prediction, and the application of climate predictions to the benefit of societies. The goals of the IRI are 1) to continually develop dynamically and thermodynamically consistent coupled models of the global atmosphere, ocean, and land, 2) to serve as a basis for improved climate prediction, 3) to systematically explore the predictability of climate anomalies on time scales up to a few years, 4) to receive, analyse, and archive global atmospheric and oceanic data to improve the scope and accuracy of the forecasts, 5) to systematically produce useful climate forecasts on time scales of several months to several years on global space scales, and 6) to shape and augment these forecasts by incorporating additional physical, agricultural, economic and other appropriate data, to the explicit social and economic benefit of national societies.

Toward these goals, the IRI, acting in collaboration with both the climate and applications research communities, and the WMO network of meteorological and hydrologic centres, will foster activities in model and forecast system development, experimental forecasting, applications research, climate monitoring and dissemination, and targeted training. In addition, the IRI will establish selected regional applications pilot projects in which prototypical end-to-end systems are developed, evaluated, and refined, with continuing and active dialogue between climate researchers, technical experts, social scientists, and decision makers. The IRI programme of development and research will lead to improvements in ENSO-related predictions (and eventually more general climate predictions).

VAMOS will contribute to the efforts of IRI on assessing the predictability inherent in the tropical SST field and its impacts upon regional climate with the research programmes in PACS. It will also facilitate the focusing of the field and monitoring programmes in PACS and PIRATA, as well as GCIP and LBA, on the observational datasets that are more urgently needed for prediction improvements.

In terms of applications and human dimensions, the implementation VAMOS will consist of two stages. The first stage is the establishment of partnerships between physical scientists and social scientists. The second stage is the design and realisation of end-to-end problems. The IRI and VAMOS will need extensive climate and applications data base development for the Americas and adjacent oceanic regions. All programmes will benefit from co-ordinating the acquisition, technical support and distribution activities associated with this data base.

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**3.10 Table 1: Preliminary list of data available for VAMOS research**

Variable / source	Internet address
<b>Precipitation</b>	
Monthly precipitation data (NCDC)	<a href="http://www.ncdc.noaa.gov/ol/climate/climatedata.html">http://www.ncdc.noaa.gov/ol/climate/climatedata.html</a>
Legates and Willmott Climatology	<a href="http://www.scd.ucar.edu/dss/datasets/ds236.0.html">http://www.scd.ucar.edu/dss/datasets/ds236.0.html</a>
Daily global tropical cyclone positions (NCAR) Data	<a href="http://www.scd.ucar.edu/dss/datasets/ds824.1.html">http://www.scd.ucar.edu/dss/datasets/ds824.1.html</a>
GOES Precipitation Index (GPI) monthly-means	<a href="ftp://nic.fb4.noaa.gov/pub/cac/cddb/data-req/">ftp://nic.fb4.noaa.gov/pub/cac/cddb/data-req/</a>
MSU - precipitation	<a href="http://ghrc.msfc.nasa.gov/userservices/dataset-catalog.html#msu">http://ghrc.msfc.nasa.gov/userservices/dataset-catalog.html#msu</a>
GPCP	<a href="http://orbit-net.nesdis.noaa.gov/gpcp/">http://orbit-net.nesdis.noaa.gov/gpcp/</a>
<b>OLR</b>	
- Original data	<a href="ftp://nic.fb4.noaa.gov/pub/cac/cddb/data-req/olr-month.doc">ftp://nic.fb4.noaa.gov/pub/cac/cddb/data-req/olr-month.doc</a>
- Complete fields (2.5° x 2.5°)	<a href="http://www.cdc.noaa.gov/cdc/data.interp_OLR.html">http://www.cdc.noaa.gov/cdc/data.interp_OLR.html</a>
- Corrected for satellite drift	<a href="http://terra.msfc.sunysb.edu/data.html">http://terra.msfc.sunysb.edu/data.html</a>
MSU layer temperatures (Spencer and Christy)	<a href="http://ghrc.msfc.nasa.gov/ims/ftp.html">http://ghrc.msfc.nasa.gov/ims/ftp.html</a>
<b>Other Satellite Data</b>	
SSM/I	<a href="http://www.ncdc.noaa.gov/ssmi/html/ssmi.html">http://www.ncdc.noaa.gov/ssmi/html/ssmi.html</a>
ISCCP	<a href="http://isccp.giss.nasa.gov/isccp.html">http://isccp.giss.nasa.gov/isccp.html</a>
HIRS (upper tropospheric water vapour)	<a href="http://www.cdc.noaa.gov/~climsat/waterv/gvap/gvap.html">http://www.cdc.noaa.gov/~climsat/waterv/gvap/gvap.html</a>
GEWEX / NASA Water Vapour Project	<a href="http://www.scd.ucar.edu/dss/datasets/ds722.0.html">http://www.scd.ucar.edu/dss/datasets/ds722.0.html</a>
<b>Surface Observations</b>	
Global Historic Climate Network (GHCN)	<a href="http://www.ncdc.noaa.gov/ol/climate/research/ghcn/ghcn.html">http://www.ncdc.noaa.gov/ol/climate/research/ghcn/ghcn.html</a>
Climatic Research Unit (CRU) land surface temperature	<a href="http://www.cru.uea.ac.uk/cru/cru.htm">http://www.cru.uea.ac.uk/cru/cru.htm</a>
COADS sea surface observations	<a href="http://www.cdc.noaa.gov/coads/">http://www.cdc.noaa.gov/coads/</a>

3. Variability of the American Monsoon Systems (G3)

Variable / source	Internet address
1-degree latitude-longitude resolution	<a href="http://www.scd.ucar.edu/dss/datasets/ds540.1.html">http://www.scd.ucar.edu/dss/datasets/ds540.1.html</a>
<b>SST analyses</b>	
NCEP/NOAA	<a href="ftp://nic.fb4.noaa.gov/pub/ocean/clim1/rsst/">ftp://nic.fb4.noaa.gov/pub/ocean/clim1/rsst/</a> <a href="ftp://nic.fb4.noaa.gov/pub/ocean/clim1/oisst/">ftp://nic.fb4.noaa.gov/pub/ocean/clim1/oisst/</a> <a href="ftp://nic.fb4.noaa.gov/pub/ocean/clim1/oimonth/">ftp://nic.fb4.noaa.gov/pub/ocean/clim1/oimonth/</a>
LDEO analyses	<a href="http://ingrid.ldgo.columbia.edu/descriptions/RSA_MOHSST5.html">http://ingrid.ldgo.columbia.edu/descriptions/RSA_MOHSST5.html</a>
FSU pseudo-stress analyses	<a href="http://www.coaps.fsu.edu/fsuwinds/">http://www.coaps.fsu.edu/fsuwinds/</a>
TOGA-TAO	<a href="http://www.pmel.noaa.gov/toga-tao/home.html">http://www.pmel.noaa.gov/toga-tao/home.html</a>
<b>Reanalyses Data Sets</b>	
NCEP/NCAR reanalysis	<a href="http://wesley.wwb.noaa.gov/reanalysis.html">http://wesley.wwb.noaa.gov/reanalysis.html</a> <a href="http://www.scd.ucar.edu/dss/pub/reanalyses/index.html">http://www.scd.ucar.edu/dss/pub/reanalyses/index.html</a> <a href="http://www.cdc.noaa.gov/cdc/reanalysis/">http://www.cdc.noaa.gov/cdc/reanalysis/</a>
NASA reanalysis	<a href="http://dao.gsfc.nasa.gov/experiments/assim54A.html">http://dao.gsfc.nasa.gov/experiments/assim54A.html</a>
ECMWF reanalysis	<a href="http://www.ecmwf.int/data/era.html">http://www.ecmwf.int/data/era.html</a> <a href="http://www.scd.ucar.edu/dss/pub/ec-reanalysis.html">http://www.scd.ucar.edu/dss/pub/ec-reanalysis.html</a>
<b>VAMOS Related programme and Data Sources</b>	
PIRATA	<a href="http://www.ifremer.fr/orstom/pirata/pirataus.html">http://www.ifremer.fr/orstom/pirata/pirataus.html</a>
Large Scale Biosphere- Atmosphere Experiment in Amazonia (LBA)	<a href="http://www.cais.com/gewex/lambada.html">http://www.cais.com/gewex/lambada.html</a> <a href="http://yabae.cptec.inpe.br/lba/">http://yabae.cptec.inpe.br/lba/</a>
Inter-American Institute for Global Change Research (IAI)	<a href="http://www.geo.nsf.gov/iai/">http://www.geo.nsf.gov/iai/</a>
Global Energy and Water Cycle Experiment (GEWEX)	<a href="http://www.cais.com/gewex/gewex.html">http://www.cais.com/gewex/gewex.html</a>

### *III. The CLIVAR Principal Research Areas*

## **4. AFRICAN CLIMATE VARIABILITY (G4)**

### **4.1 INTRODUCTION**

The African climate system and its surrounding monsoons are key elements of the global atmospheric circulation. Life in Africa revolves around subsistence farming of rain-fed crops, which renders its society vulnerable to climatic fluctuations (Hulme et al., 1996). The adequacy of rainfall is, in many parts of Africa, dependent on prevailing patterns of sea surface temperature (SST), atmospheric winds, the El Niño Southern Oscillation (ENSO), and regional climate fluctuations in the Indian and Atlantic Oceans. Despite the research progress in the last decade that has begun to reveal the extent of the SST influence on African precipitation, much remains to be understood about the interaction between the African climate system and its land surface, and the surrounding ocean-atmosphere climate variability and the global climate system.

Seasonal rainfall predictions, which could improve decision making and benefit the local population, require enhanced observing networks and greater scientific understanding of the physical mechanisms at play. These goals can best be achieved through co-ordinated international research efforts. The CLIVAR African Study Group under the auspices of the CLIVAR Scientific Steering Group will guide the research and facilitate this international co-operation. The Implementation Plan outlined here should be considered a preliminary assessment of what is needed in the next decade to improve prediction of interannual variations in African climate. A primary goal will be to gain an understanding of relationships between seasonal rainfall and ENSO through knowledge of ocean-atmosphere coupling over the tropical Atlantic and Indian Oceans. This contribution to the initial CLIVAR implementation plan addresses priorities for observations, diagnostic analysis and predictive modelling within a CLIVAR-Africa programme. The programme will be further developed in the future.

### **4.2 SCIENTIFIC RATIONALE**

Africa's climate is governed indirectly by monsoon circulations that extend across large parts of the Atlantic and Indian Oceans. In addition, extra-tropical influences are felt from both hemispheres. Recent research provides an indication of current foundations and promising directions for future work.

#### **4.2.1 Past studies**

Year-to-year fluctuations in rainfall over Africa are determined by circulation regimes that alter the preferred location of tropical convection (Harrison 1986) and the Intertropical convergence zone (ITCZ). Skilful seasonal predictions of rainfall depend largely upon our ability to monitor real-time ocean-atmosphere states and to model, using either statistical or dynamical methods, the large-scale atmospheric response over Africa to ocean-atmosphere coupling locally and globally (e.g. Ward et al., 1993; Hastenrath et al., 1995; Mason et al., 1996).

#### **4.2.2 ENSO influence**

El Niño-Southern Oscillation warm events in the equatorial Pacific and Indian Oceans are associated with warm dry conditions over much of Africa (Ropelewski and Halpert, 1987; Janowiak, 1988; Rocha and Simmonds, 1996a; Shinoda and Kawamura, 1996). In addition, the tropical Atlantic Ocean can have a delayed response to ENSO. This process can induce circulation and convective anomalies over significant parts of Africa with a time-lag of order 12-18 months (Tourre and White, 1995).

III. The CLIVAR Principal Research Areas

Global ENSO warm events most often influence rainfall in the eastern and southern part of the continent during the austral spring and summer, respectively, as part of a seasonally dependent response (Meehl, 1988). A strengthening of upper westerly flow throughout the region during warm events (Fig. 4.1), results in a concomitant decline (increase) in moisture confluence over southern (eastern) Africa (Hastenrath et al., 1993). Sub-tropical westerly jet streams converge onto Africa and transient troughs tend to be flatter. The stratospheric QBO plays a role in modulating rainfall (Mason and Tyson, 1992; Jury et al., 1994). The Walker circulation cell connecting Africa and the Indian Ocean interacts with the QBO, and during its westerly phase, rising tropospheric motion occurs over Africa. During the QBO easterly phase, tropical cyclones are more frequent in the Indian Ocean and convection increases significantly over Madagascar (Jury et al., 1995).

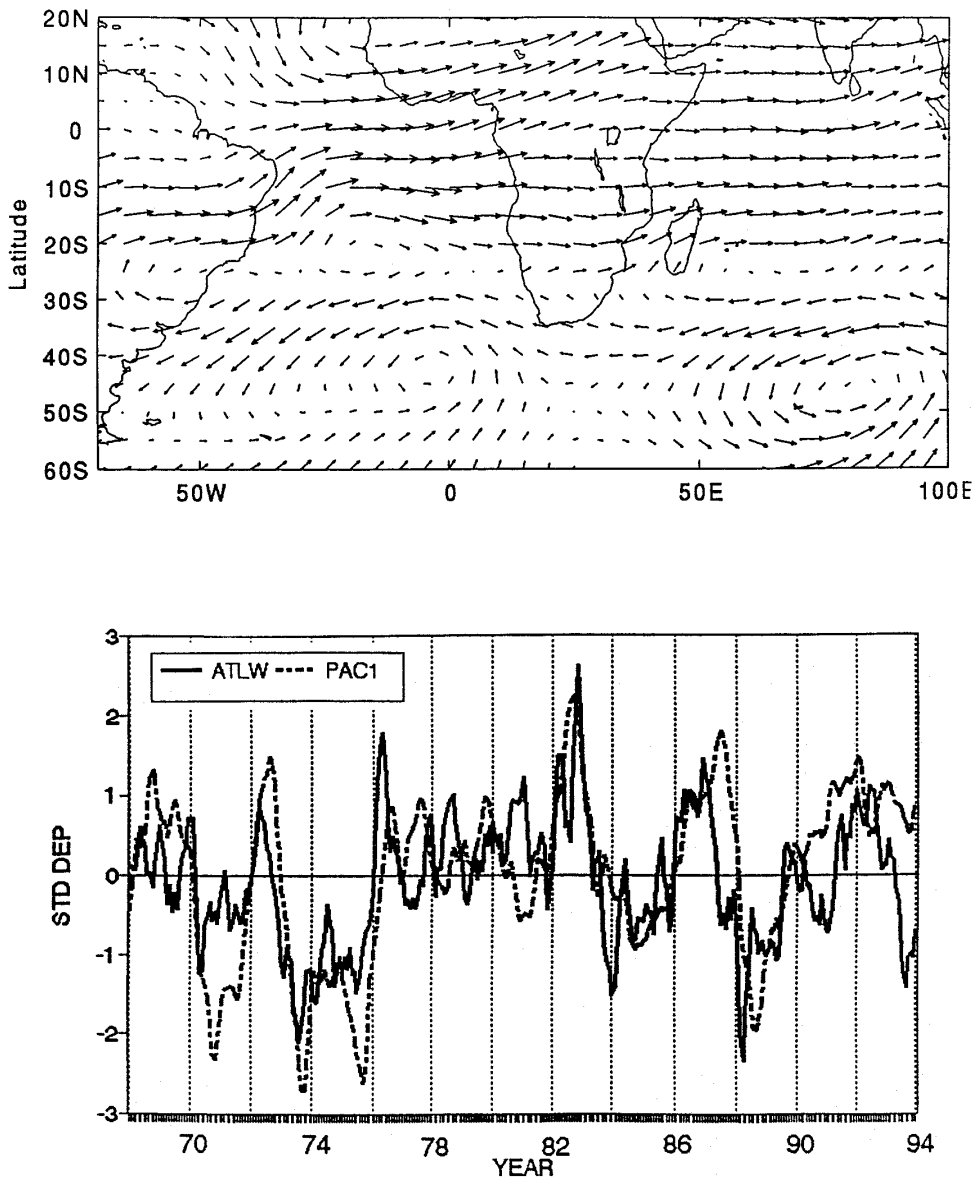


Fig. 4.1: (upper panel): First principal component of 200 hPa upper level winds over the African hemisphere; (lower panel): comparison of zonal upper wind anomalies over the equatorial Atlantic and sea surface temperatures in the central and eastern Pacific (courtesy M. Jury).

The boreal summer rains of tropical north Africa tend to be reduced in ENSO years. Palmer (1986) demonstrated the potential for tropical Pacific sea-surface temperature (SST) to influence the Sahelian region using an atmospheric GCM. Subsequent modelling and diagnostic studies (Semazzi et al., 1988; Folland et al., 1991; Palmer et al., 1992; Rowell et al., 1995; Janicot et al., 1996; Ward, 1998) have supported the hypothesis. The extent to which the connection can be verified using GCMs is however still very model specific (Sud and Lau, 1996; Rowell, 1996) and a precise estimation of the extent of SST influence on tropical north Africa still requires further research.

### 4.2.3 Influence of Indian monsoon and Indian Ocean SSTs

A warmer tropical Indian Ocean is frequently associated with dry conditions over southern Africa and wet conditions over eastern Africa. Establishing a causal relationship from Indian Ocean SSTs to the African atmosphere is difficult because a warmer Indian Ocean is itself part of the global ENSO teleconnection (Cadet, 1985; Meehl, 1993; Jury and Pathack, 1993; Mason, 1995). During El Niño conditions, the central Indian Ocean experiences changes in zonal wind stress (Hastenrath et al., 1993; Latif et al., 1994) and a deepening of the thermocline (McCreary et al., 1993; Tourre and White, 1997). Observational evidence shows that strengthening of convection and latent heat release over the warmer oceanic areas occurs at the expense of convergence over Africa (Jury, 1992). A warmer Indian Ocean is associated with an increased frequency of tropical cyclones (Jury, 1993) and strengthened equatorial surface westerlies (Rocha and Simmonds, 1996a).

In boreal summer, the Southern Oscillation index of Walker and Bliss (1932) focused on the Indian monsoon and its teleconnections both eastward towards the Pacific and westward towards Africa. Interaction with the eastern Sahel and the eastern Mediterranean was implied in their pioneering studies, and recent diagnostic work also points to interaction of the Indian monsoon and Sahelian rainfall (Camberlin 1995; Ward, 1998). This interaction between the African and Indian monsoons and the Mediterranean climate (Rodwell and Hoskins, 1996) may shed light on seasonal climate variability that is partly independent of ENSO.

### 4.2.4 Numerical modelling studies

Modelling studies testing the atmospheric sensitivity to imposed SST anomalies confirm that moisture convergence and simulated rainfall over southern Africa is reduced during Indian Ocean warm events (Mason et al., 1994; Rocha and Simmonds, 1996b). A simulated Walker cell anomaly (surface westerly and upper easterly flow) explains the convective 'dipole' between the subcontinent and the SW Indian Ocean. Whilst the observations suggest that this climate anomaly consists of opposing convective regimes of equal magnitude, numerical experiments exhibit bias: positive rainfall anomalies over the ocean are many times greater than the continental deficits.

GCM sensitivity tests with cold anomalies imposed in the tropical Indian Ocean are unable, thus far, to demonstrate enhancement of summer rainfall over southern Africa (Jury et al., 1996). The source of the forcing may include both the Indian Ocean and tropical Pacific, since circulation anomalies in cold-event years (1974, 1976, 1989 and 1994) are quite clear, supporting the concept of a symmetrical sub-tropical gyre circulation which responds to tropical heating anomalies.

Recent literature on GCM modelling over tropical north Africa has also begun to indicate the impact of regional and global SST patterns. One theme is how the global ENSO signal interacts with the tropical Atlantic and Indian Ocean coupled processes to generate the sub-Saharan climate anomalies (Folland et al., 1991; Janicot et al., 1996; Carton and Huang, 1994).

#### 4.2.5 Extratropical influences

In the subtropical latitudes, climatic responses are more non-linear than the responses at lower latitudes because of the internal dynamics of transient wave perturbations. SST variability in the Agulhas Current southeast of Africa affects moisture fluxes into the boundary layer (Mey et al., 1990; Jury, 1994) which govern overlying weather systems (Walker, 1990). However, it is likely that meridional SST gradients south of Africa are of greater significance in the production of thermal winds. Recent studies indicate that composite La Niña events correspond with significant increases in SST across the higher maritime latitudes south of Africa. For sub-tropical northwest Africa, rainfall is generated when mid-latitude disturbances are steered southward from their usual track into northern Europe. This is often associated with mid-latitude blocking episodes which, over western European longitudes, occur in connection with the North Atlantic Oscillation (NAO) (Walker and Bliss, 1932; Lamb and Pepler, 1987).

#### 4.2.6 Atlantic influences

In the equatorial Atlantic, coupled ocean-atmosphere variations have been identified which bear some resemblance to the El Niño events of the tropical Pacific (Weare, 1977; Philander, 1986; Tourre et al., 1985, Nicholson and Entekhabi, 1987; Servain, 1991; Zebiak, 1993; Huang et al., 1995; Tourre et al., 1998). This Atlantic SST variability affects rainfall over the western half of southern Africa (Jury, 1996a) and over tropical north Africa (Lamb, 1978; Folland et al., 1986; Lough, 1986; Lamb et al., 1986; Parker et al., 1988; Janicot, 1992; Ward, 1998). The possible mechanism is through a modification of regional moisture fluxes through direct impacts on temperature and pressure gradients (Hirst and Hastenrath, 1983; D'Abreton and Lindesay, 1993). A consequential latitudinal shift in the African easterly jet stream is a further candidate.

A further theme for research is the source of the strong common variability at interannual and multi-decadal time scales between tropical north African climate and ocean-atmosphere variations across much of the Atlantic. This includes surface wind variations (Hastenrath, 1990; Ward and Hoskins, 1996) and Atlantic hurricane activity (Landsea and Gray, 1992; Goldenburg and Shapiro, 1996).

The analysis of a recent atmospheric numerical model simulation forced with a composite tropical SE Atlantic cold event (deW Rautenbach and Jury, 1997) has provided some support for an Atlantic influence on southern Africa. Late summer rainfall in the simulation was significantly enhanced over much of southern Africa, coincident with a reduction in speed of the southern sub-tropical westerly jet.

A substantially enhanced observational network, including sub-surface observations through the adjacent tropical oceans, is required to further develop the above research foundations. Such data would help to define the relevant processes and support the science necessary to underpin a predictive capability for adjacent monsoon variability and interaction with the African climate system.

#### 4.2.7 Influence of land-surface processes

The above discussion suggests that changes in boundary-surface forcing are important for seasonal climate anomalies in the tropics. However, the size of the African continent dictates that changes in land surface conditions are also of potential importance to large-scale climate anomalies. Charney (1975) proposed that a change in surface albedo, e.g. through overgrazing, could have significant impacts on semi-arid climates. Since that seminal work, other effects of a changed land-surface have also been investigated, including changes in available moisture from the land-surface, changes in land-surface roughness and changes in aerosol properties of the atmosphere (reviewed in Nicholson, 1988). Modifying the land-surface in GCMs that contain sophisticated land-atmosphere interaction can clearly impact regional precipitation over Africa (Xue and Shukla, 1993; Dirmeyer and Shukla, 1996). Though the realism of the land-surface changes imposed is not yet secured, the results suggest a distinct role for the African land-surface, which warrants further investigation.

#### 4.2.8 Role of CLIVAR-Africa

Observations of the African climate system and its oceanic teleconnections, both real-time and historical are essential to the aims of a CLIVAR-Africa programme. The observing network must be supplemented by stations with telemetering capability, application of satellite technology, and measurements from aircraft and ship platforms. Through additional observations which improve our knowledge of the initial state of Africa's weather, the detection of linkages with the global climate can be revealed. Accurate specification of atmospheric conditions will ensure that 'control runs' for numerical experiments can function as a true baseline for 'perturbation runs', and that GCM predictions evolve from known states. Integral components of our observational efforts are continued archive searches and data base development. Expanded observational coverage of sub-surface ocean conditions and air-sea interactions in the tropical Atlantic and Indian Oceans adjacent to Africa is seen as pre-requisite to improved seasonal rainfall forecasts.

A number of approaches to long-range forecasting of African climate are being explored, and over the last decade, some of these have been employed in real-time with promising success. CLIVAR-Africa can build on these foundations, through underpinning scientific observations, diagnostic analysis and modelling efforts.

Considering the modes of inter-annual climatic variability (Janowiak, 1988) and Africa's heterogeneous terrain and vegetative cover, it is desirable to partition Africa into three regions:

- north and west Africa;
- east and central Africa; and
- southern Africa.

Each region has distinctive interannual climate anomalies and teleconnections (Semazzi et al., 1988). The eastern and southern regions are dominated by the ENSO signal with opposite polarity, while the northern and western regions experience climate anomalies that are generated through a mix of regional processes combined with global ENSO influences. A tropical Atlantic SST influence is known to be present in tropical north Africa (e.g. Rowell et al., 1995), whilst the north Atlantic Oscillation (NAO) dictates a component of climate variance over the northern rim of the continent (Lamb and Pepler, 1987). However, ENSO-based predictability appears to be highest for southern Africa. To capitalise on this, one focus of the CLIVAR-Africa research programme will be statistical and numerical modelling efforts directed at securing the knowledge of the climate system in this region that will improve the reliability and confidence in seasonal forecasts for southern Africa. Because of the demonstrated links between Africa and the Indian monsoons, CLIVAR-Africa would naturally focus on the southwest Indian Ocean climate, including such islands as Madagascar, the Mascarene islands, the Comores islands, and the Seychelles islands.

Another focus of research will be empirical and modelling studies that explore the limits of predictability of the African climate system. It will be necessary to quantify the relative contribution from ENSO and regional influences, and relationships between remote boundary conditions and internal dynamics over the continent. To achieve these goals, the CLIVAR-Africa Implementation Plan proposes a number of themes relating to the interaction of African climate with tropical monsoon convection, coupled ocean-atmosphere-land processes and extra-tropical circulation regimes (Tyson, 1986). To achieve success, it will be necessary to characterise climate anomalies over Africa and to perform modelling and diagnostic studies leading to predictability at interannual scales.



### 4.3 PROGRAMME OBJECTIVES

The more detailed implementation plan to be developed for CLIVAR-Africa will promote multi-lateral projects along the following lines:

- analyse and describe the spatial structure and temporal variability of the African climate system from intraseasonal to interdecadal time scales;
- construct quality data bases of precipitation, temperature, etc. to characterise intraseasonal weather events and lower frequency climatic oscillations and their spatial character;
- evaluate reanalyses products over Africa and the surrounding oceans for adequacy and reliability, and assess which additional observations will lead to the necessary improvements for useful climate studies at synoptic and intraseasonal scales;
- in a similar way, assess the additional real-time observations that are needed for climate prediction;
- develop innovative, low-cost solutions for enhancing land-based observing networks and telecommunication needs;
- identify the nature of and the mechanisms for intraseasonal convective activity and their links with:
  - rainy season onset
  - African weather systems
  - large-scale circulation features like jet streams and monsoon circulations
  - regional coupled ocean-atmosphere processes
  - the global ENSO and its interannual variability
- identify regions where oceanic anomalies influence monsoon circulations over the Atlantic and Indian oceans and quantify the underlying physical processes;
- determine the relative contribution of internal dynamics (e.g. soil moisture, vegetation cover, etc.) and external forcing, and study synergistic relationships between tropical circulation cells over Africa and the Pacific hemisphere, and linkages with the extra-tropics and southern ocean;
- explore the limits of predictability of African climate taking a regional approach, with special attention to ENSO response areas, monsoon circulation systems, and the tropospheric biennial oscillation and its regional interaction (Yasunari, 1991; Meehl, 1993; Tourre et al., 1998);
- apply GCMs (both atmospheric and coupled ocean-atmosphere models) to African climate prediction and inter alia oceanic controls of climate variability, consider also the influence of African climate anomalies on the nearby oceans;
- analyse tropical/mid-latitude interactions and predictability, particularly for northern and southern Africa and the adjacent high latitudes, with an emphasis on NAO for northwest Africa;
- monitor and understand land-sea-air interactions by remote and in situ observations and numerical modelling, to establish feedback pathways and processes (e.g. evapotranspiration, surface heat fluxes);

- develop the potential to accurately predict SST and ocean-atmosphere coupling processes in the tropical Atlantic and Indian Oceans at interannual to interdecadal time scales; and
- assess the interaction of interannual to interdecadal processes in the coupled ocean-land-atmosphere system, including the role of changes in land surface characteristics and the process of desertification.
- identify centres of existing expertise in African climate dynamics and develop assistance programmes and multi-lateral projects to ensure the potential for on-going CLIVAR research in Africa;

To monitor the evolution of global ENSO events, tropical meridional SST differences and regional coupled ocean-atmosphere events in the tropical Atlantic and western Indian Oceans, an African TAO array is proposed. Given limitations of internal funding, such a project will be international in character, yet of benefit to neighbouring continents. It is expected that much of the work described in this Implementation Plan will be planned and co-ordinated in 1998-2000 and conducted up to 2010.

#### **4.4 OBSERVATIONAL REQUIREMENTS**

A detailed observational strategy for CLIVAR-Africa remains to be developed but certain elements can be specified at this time.

##### **4.4.1 Atmospheric needs**

Routine weather observations provide the foundation for CLIVAR-Africa's scientific research plan. Data from radiosonde and surface observations in many key areas are lacking (Fig. 4.2). Evaluation of re-analyses products will determine reliability, and discrepancies could point to where new observational efforts are needed. For monitoring purposes, satellite data will play a critical role in filling out the observing system. Satellite-derived winds have been unavailable over the Indian Ocean from 55° to 85°E, and profiles of thermal stability and moisture flux are required to supplement the observing system. Real-time satellite data from METEOSAT, INSAT and TRMM need to be made available to CLIVAR-Africa researchers. The deployment of instruments to measure the hydrological and radiation budgets both over land and in key ocean areas will also underpin the science. Finally, wind profilers would provide valuable information in key regions where intraseasonal oscillations occur, e.g. in the region of the Seychelles. This would allow for continuous monitoring of boundary layer and upper wind conditions. The ways to achieve these observations and to utilise them for predictive purposes need careful consideration.

##### **4.4.2 Oceanographic measurements**

Our understanding of the mechanisms that produce SST anomalies in the Atlantic and Indian Oceans is quite limited. The air-sea interactions are complex and estimates of fluxes derived from NWP models will contain errors. Regular subsurface data in monsoon regions adjacent to Africa are insufficient. Blended SST products based on satellite and irregular ship reports are likely to be in error in cloudy regions outside shipping lanes. The XBT network needs to be expanded in the Atlantic and Indian Ocean in conjunction with the TRITON and PIRATA ocean moorings. Extension of these ocean observing systems towards Africa would benefit climate prediction efforts across the region. Some of these requirements should be met through the implementation of the CLIVAR sustained observation system and the initial GOOS/GCOS observing system.

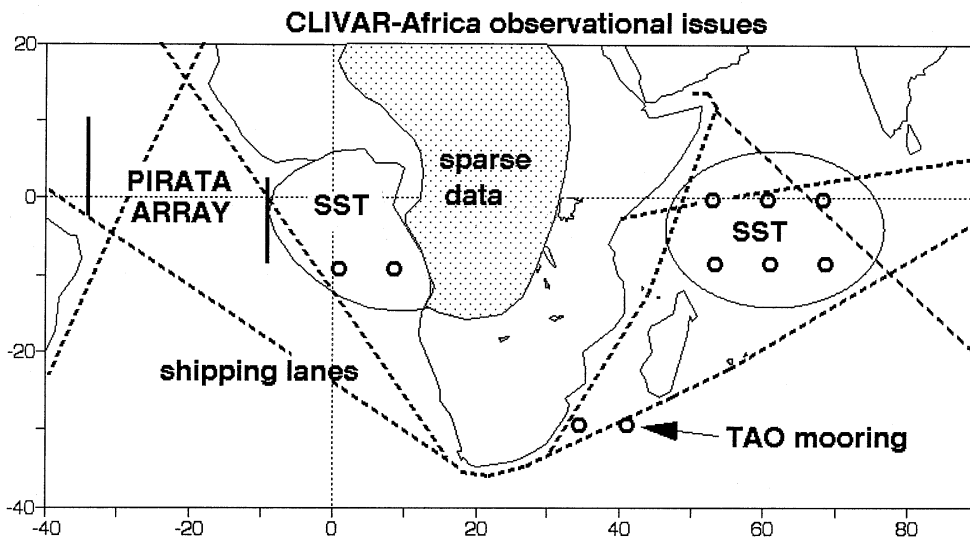


Fig. 4.2: Proposed supplementary observations: TAO type ocean moorings in the Indian Ocean 0-10°S, 50-70°E, in the Agulhas region at 30°S, 35-45°E and in conjunction with PIRATA in the 'Angola dome' 10°S, 0-10°E. Shipping lanes, continental areas with sparse data and key monsoon regions (SST) are outlined.

#### 4.4.3 Land-based observations

In order to understand the mechanisms of boundary forcing and internal dynamics of the African climate system, monitoring of land surface processes is necessary. Key land variables include soil moisture, vegetation, streamflow, run-off, and surface heat and radiation budgets. Some of these observations are becoming available. Together with GEWEX, multi-lateral monitoring studies to compare land- and marine-based heat fluxes are needed. Satellite estimates of land surface characteristics such as the vegetation index NDVI (Normalised Difference Vegetation Index) and microwave satellite SSMI-derived soil moisture will be exploited.

#### 4.5 DATA BASES, ANALYSIS AND PREDICTION

Because of high surface water losses over Africa, particularly in drought years, parameters that describe both hydrological inputs (rainfall) and deficits (evaporative losses) are crucial to furthering CLIVAR-Africa objectives. Although a number of useful historical rainfall data sets have been compiled (Nicholson, 1986), temporal and spatial gaps covering 20-30% of Africa are apparently due to a lack of observing stations, and local archiving procedures and infrastructure. Historical records of daily rainfall over the entire continent are needed. Gridded 1°x1° resolution, daily precipitation estimates from METEOSAT, INSAT, and TRMM could be valuable. Additionally, gridded 1°x1°, weekly blended SST over the Atlantic, Indian and southern Oceans for past decades and daily surface temperature and soil moisture data from historical archives are required. Surface flux data over the monsoon oceans, including data from historical archives, satellites and in situ measurements; and upper air data from a regular radiosonde network are in short supply. CLIVAR-Africa will engage in multi-lateral efforts to recover and archive data on the African climate system. Quality assurance tests should be conducted in parallel with data retrieval to ascertain validity. Comparisons between station data and reanalyses products are proposed to lend confidence to analyses of intraseasonal to interannual oscillations.

The CLIVAR-Africa programme, while focusing on the scientific basis for climate prediction, will take into account environmental and societal aspects through the involvement of multi-disciplinary scien-

tists and forecast users. In this regard, the international CLIVAR effort will be relied on to foster capacity building efforts in African (and SW Indian Ocean) countries. Firstly, existing data networks will be established mainly through the Internet to support exchange of information within the scientific community and its users. Capacity building programmes will be developed for research and product utilisation in conjunction with START and CLIPS programmes. Expanded activities of the IRI with national meteorological services and research labs in Africa will assist end-to-end prediction capabilities. Centres such as ACMAD, and DMC Nairobi and Harare will be focal points for dissemination of predictions and related activities.

## 4.6 DIAGNOSTIC AND PROCESS STUDIES

A number of diagnostic studies are required, including observational campaigns, to improve our understanding of physical processes in the African region in conjunction with modelling experiments. Our understanding of the African climate system is developing, so new research themes are expected to evolve in the coming decade, depending on preliminary findings.

### 4.6.1 Atmospheric circulation and convection

CLIVAR-Africa proposes a number of thrusts, initially mainly of an empirical and diagnostic nature. As the seasonal distribution of rainfall (seasonal onset, peak, decay) is particularly important at regional scale (Taljaard, 1986), it is proposed that investigations be conducted to establish the spatial and temporal nature of this variability and its regional teleconnections. The role played by the surrounding monsoons in the annual cycle of African convection should address the relative importance of ocean-atmosphere coupling and land processes, and analyse relationships between propagating intraseasonal oscillations, continental wet and dry spells (Lyons, 1991), and the background ENSO circulation (Lindesay, 1988). It will be necessary to develop appropriate indices based on rainfall, temperature and other continental variables. Correlation maps with respect to the SOI, regional SST and monsoon indices should be prepared in order to quantify monsoon, continental convection, ENSO relationships and to identify key oceanic regions where ocean-atmosphere coupling is most sensitive (Jury, 1996a) (see for example Fig. 4.3). Re-analysis data will be employed in these efforts, together with field programmes and numerical modelling experiments.

The physical mechanisms by which the QBO modulates convection in the region are unexplored, both in terms of global influence and internal dynamics. A better understanding of processes operating at various time scales is needed. For example historical rainfall spectra display shifts in the prevalence of cycles at 18 years, 4-5 years, and 2-3 years in southern Africa (Lau and Sheu, 1988; Currie, 1993). These shifts may be associated with the irregularity of the ENSO and its transmission to the African hemisphere (Nicholson and Chervin, 1983).

The variability of the North Atlantic Oscillation and its association with the rainfall regimes of the northern rim of Africa at time scales from intraseasonal and interannual to decadal, requires careful diagnosis, using observations and atmospheric and coupled GCMs. Success in these endeavours will lead to reliable climate predictions and mitigation strategies.

### 4.6.2 Ocean forcing and monsoons

There is a need to quantify the ocean processes that contribute to SST anomalies and tropical SST differences of importance to the African climate system, particularly ENSO responses in tropical monsoon regions. Oceanographic studies are proposed which illuminate remote and local influences on heating anomalies, and distinguish mixing near boundaries and entrainment from the thermocline. There is a need to analyse ocean models and observations to establish oceanic processes; Kelvin and Rossby wave dynamics; the character of equatorial currents and counter-currents and their variability, and effects of wind-driven

circulations on SST variations in ocean areas adjacent to Africa (Allan et al., 1995). Diagnostic work, using satellite, reanalyses data and outputs from GCM sensitivity tests, needs to answer questions on how ocean dynamics and anomalous heat fluxes induce responses in deep convection over the tropical Atlantic and Indian Oceans.

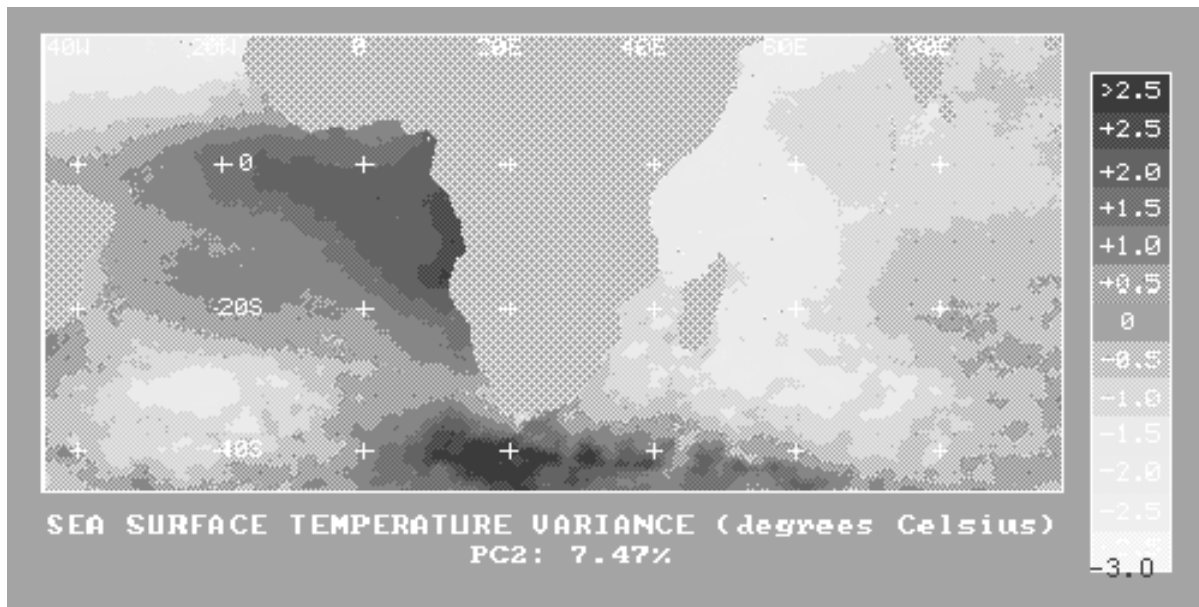


Fig. 4.3: Principal component pattern for first tropical mode of sea surface temperatures in the Atlantic and Indian Oceans based on satellite IR data. The pattern indicates regional responses to the El Niño Southern Oscillation and also highlights the anti-phase relationship between the tropical SE Atlantic and western Indian Ocean (courtesy M. Jury).

The interbasin flux of warm Indian Ocean water into the South Atlantic is intermittent and highly variable (Garzoli and Gordon, 1996; Feron et al., 1992). Its interannual and interdecadal variability may be related to ENSO and to interdecadal variations of the gyre scale wind field over the subtropical Indian Ocean (Allan et al., 1995). These variations of interbasin fluxes have a direct impact on the regional climate variability (e.g. Jury, 1996b). They are also expected to affect larger scale climate fluctuations as they propagate in the South Atlantic gyre and partly feed into the conveyor belt circulation.

#### 4.6.3 Oceanographic measurements

Ocean moorings in the African sector of the Atlantic and Indian Oceans, supplemented by field programmes to expand our knowledge of how monsoons couple with continental circulation regimes, would significantly advance the goals of CLIVAR-Africa. The last international field campaign of the austral summer monsoon dates back to the IIOE of 1964. Since then, technology has outpaced knowledge. The INDOEX and PIRATA field campaigns could fill some of these gaps. Further co-operative research within CLIVAR-Africa could enhance knowledge of ocean-atmosphere coupling over adjacent oceans and its modulating continental convective spells. An in situ TAO-type array could be located in the domain 5°N to 10°S in the Atlantic Ocean east of 10°W (as a supplement to PIRATA) and in the western Indian Ocean in the area 5°N to 10°S from 45°E to 75°E as shown in Fig. 4.2. It is further proposed that moorings be located in the southwest Indian Ocean near Durban, South Africa to assess interbasin exchange and its influence on regional climate. A sea going programme should complement this to determine its propagation into the S. Atlantic and its interaction with the overlying atmosphere and adjacent ocean.

#### 4.6.4 A terrestrial focus

To analyse changes in land surface processes during drought and flood years and delineate impacts of surface processes in ENSO coupling with the African climate system, multi-faceted research is proposed making use of GCM experiments, satellite and reanalysis data. Parameterisation of convection, moisture transport and cloud-radiative processes would be required to determine coupling between large-scale vertical motions and boundary layer processes. Improvement of land and ocean surface fluxes estimates from field campaigns and satellite application tests is envisaged. Limited computational facilities and expertise in Africa suggests that numerical model development will be externally forced through multi-lateral projects with other CLIVAR GOALS thrusts. Priorities for research in CLIVAR-Africa will focus on the exploitation of satellite and re-analysis data, the application of GCM output that is statistically adjusted to give better information over Africa (e.g. Moron et al., 1998) and intensive field campaigns to improve knowledge of the terrestrial boundary layer.

### 4.7 NUMERICAL MODELLING

To meet the stated goals of a CLIVAR-African, a numerical modelling effort will be promoted initially applying simple, low-resolution atmospheric GCMs, and later advancing to fully-coupled GCMs. Simple models often yield basic understanding of physical processes in conjunction with subjective interpretations of observations. The work can progress from model development, to validation, to application. In the initial phase, sensitivity tests will be guided by statistical studies of observed climate variability and its sensitivity to changing lower boundary conditions, namely SST. Quite a number of global experiments have been conducted, for which little emphasis has been given to African climate. CLIVAR-Africa can remedy this through joint interpretative efforts.

Monsoon circulations over Africa are part of the coupled ocean-land-atmosphere system, so it is natural to expect that coupled GCMs will be used to address regional predictability. Existing coupled models are capable of simulating certain aspects of interannual variability over Africa, but it may be premature to apply these to the problems of scale interactions, without support from extensive empirically-based insights. Similarly, studies of coupled ocean-atmosphere processes in the Atlantic and Indian Oceans using appropriate numerical models needs the support of diagnostic studies based on thorough observations - many of which are currently lacking. The modelling efforts would be co-ordinated with the CLIVAR NEG-1 thrust and with other WCRP programmes.

In view of the current limitations of coupled models for African climate studies, the main requirement of the CLIVAR-Africa modelling component in the initial stage, is the assessment of atmospheric GCMs driven by historical SSTs to reproduce the mean climate of Africa, its seasonal cycle and interannual variability. Statistical correction of the results maybe required to account for systematic errors in response to SST (Moron et al., 1998) and the heterogeneous terrain. Such studies will enable estimates of atmospheric predictability over Africa. The relationship between a model's ability to generate realistic intraseasonal variability and a model's skill at the seasonal time scale will be addressed. The potential benefits from nesting mesoscale limited area models inside GCMs will also be considered.

### 4.8 TRAINING EFFORTS AND PROGRAMME LINKAGES

CLIVAR-Africa will collaborate with and support expanded training efforts to establish research expertise and infrastructure in Africa. These training efforts could be carried out in conjunction with the existing programmes, for example, training programmes at the African Centre for Meteorological Applications and Development, and conferences with the African Meteorological Society. Other opportunities could include regional conferences and workshops, African university and national weather service 'summer schools', and projects under internationally sponsored programmes of WMO/UNDP, IGBP/WCRP/IHD-START, MEDIAS, the IRI, FIRMA, and the European Community (e.g. WAMP (West African Mon-

### III. The CLIVAR Principal Research Areas

soon Project). Funds will be requested to support meetings, for scholarships to promising researchers, for infrastructure to enable CLIVAR-Africa research, and for networking and information exchange.

Linkages to other research programmes are critical to the success of CLIVAR-Africa. Major linkages are envisaged with:

CLIVAR principal research areas G1, G2, D1, D2, and D3, as espoused in this implementation plan. GOALS NEG-1 ENSO modelling and prediction; the CLIVAR Upper Ocean Panel; and international programmes such as the WCRP/GEWEX. International field campaigns such as TRITON, PIRATA and other extensions to TOGA and the INDOEX study. Much of its work will require support from international satellite missions of NASA/NASDA TRMM, EOS, etc. Ocean monitoring efforts will require co-ordination with the TAO Implementation Panel and GOOS (OOPC). Modelling studies can make use of ongoing WCRP/AMIP work. Research on climate predictability will be co-ordinated with the IRI and the WMO/CLIPS programmes to ensure that the research will underpin useful applications and enable mitigation strategies that can be successfully implemented to reduce environmental and societal vulnerability to fluctuations of African climate.

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### III. THE CLIVAR PRINCIPAL RESEARCH AREAS

#### (ii) CLIVAR DecCen

Research programmes such as the WCRP sponsored World Ocean Circulation Experiment (WOCE) have made great strides in advancing our understanding of the role of the oceans in the present climate. The essential contributions of the oceans to the storage, redistribution and release of heat, water and carbon dioxide around the planet are now abundantly clear. In addition, WOCE time series stations and repeat sampling of earlier hydrographic sections have revealed a much more variable and dynamic ocean than previously envisioned (see Figure III.2). That is, inadequate sampling in the past meant that little could be said about long term oceanic changes, and a steady state was often assumed. The concerted global survey of WOCE, its times-series stations and repeat sections, and new technology for autonomous sampling has given us an unprecedented and tantalising glimpse of strong, low frequency oceanic change and provides a firm knowledge base on which CLIVAR can build.

It is also clear that the ocean holds the primary memory of the climate system. The wind driven circulation carries deep heat and freshwater anomalies around the ocean basins, which present a slowly changing SST field to the winter atmosphere. The thermohaline circulation, involving high latitude sinking and distributed upwelling and mixing at lower latitudes, is heavily involved in the longer time scales of climate variability. Tropical SST changes have displayed decadal trends and strong correlations with long term rain and drought cycles as well as tropical storm frequency. However, we remain largely ignorant of the processes controlling such variability.

The scientific objectives of CLIVAR DecCen are:

- to describe and understand decadal to centennial climate variability and predictability through the analysis of observations and the modelling of the coupled climate system;
- to extend the record of decadal to centennial variability through paleoclimatic studies, data archaeology, reanalysis of atmospheric and oceanic data;
- to develop and implement appropriate observing, computing and data archiving and dissemination programmes needed to understand the mechanisms of decadal to centennial climate variability and predictability, in co-operation with other relevant climate research and observing programmes.

Thus, much remains to be done to achieve some measure of predictability. Monitoring strategies and systems need to be refined and expanded. TRITON deployments in the western North Pacific Ocean shall contribute to monitor decadal changes in the Pacific Ocean. Process studies are essential for understanding the mechanisms controlling long term variability of SST. Models are essential tools for developing adequate understanding and predictive capabilities. Paleoclimatic data are essential for describing the past states of the ocean-atmosphere system the decadal to centennial time scales. The major elements of CLIVAR DecCen will focus on climate phenomena, processes and regional studies. Phenomena include the North Atlantic Oscillation (NAO), which is associated with much of the recent increase in Northern Hemisphere temperature, and has a pattern quite similar to the expected “fingerprint” of global warming. Strong SST variability in the tropical Atlantic, often appearing as a “dipole” pattern across the equator, is a second phenomenological focus.

The thermohaline circulation, with its strong conveyor belt circulation, is a major factor in climate, as it carries much of the poleward heat flux, and has been characterised as having dramatic variability in the paleoclimatic record. A major focus will be on the thermohaline circulation in the Atlantic, but the thermohaline circulation in the Southern Hemisphere is of interest as well. Also, the role of the Southern Ocean in the communication of heat and freshwater anomalies and water masses between basins, and their influence on climate is of interest. It is especially important to develop a monitoring strategy for this vast, infrequently sampled stretch of ocean. Similarly, sampling and monitoring strategies must be designed for the Indian and

Pacific oceans. The Pacific displays a basin-wide decadal oscillation of SST, in which the mid-latitudes are out of phase with the tropics, that correlates with the Pacific-North American (PNA) teleconnection pattern and may be related as well to Indian Ocean variability. The following sections discuss these phenomena, processes, and regional studies in greater detail.

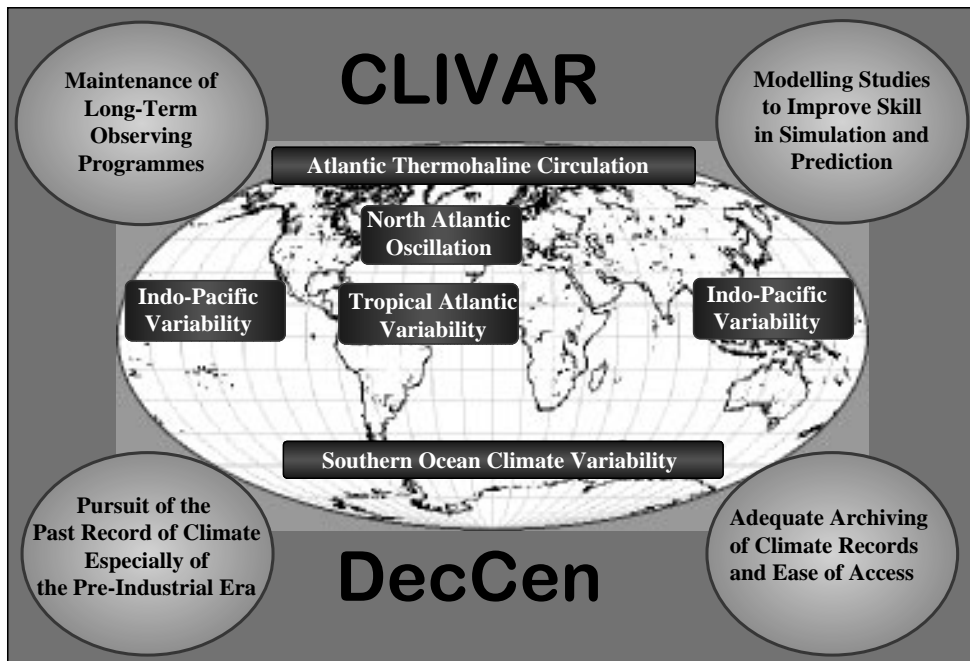


Fig. III.2: The five components of CLIVAR DecCen span the globe and emphasize the role of the oceans in modulating climate variability and change on long time scales.

DecCen will improve our understanding of decadal to centennial variability and predictability through an integrated programme of modelling, observations and analysis. The strategy will be to focus on the following principal research areas (see Fig. III.2):

- The North Atlantic Oscillation (D1):  
Improving the description and understanding of decadal ocean and atmosphere variability in the North Atlantic region involving the North Atlantic Oscillation.
- Tropical Atlantic Variability (D2):  
Improving the description and understanding of the patterns of decadal variability originating in the tropical Atlantic.
- Atlantic Thermohaline Circulation (D3):  
Improving the description and understanding of decadal to centennial variability and the possibilities of rapid climate change associated with the Atlantic thermohaline circulation.
- Pacific and Indian Ocean Decadal Variability (D4):  
Improving the description and understanding of the decadal variability and its predictability in the Pacific and Indian Ocean basins, and its relationship with ENSO and teleconnections.
- Southern Ocean Climate Variability (D5):  
Improving the description and understanding of the variability of the Antarctic Circumpolar Current, ocean overturning and water mass transformations in the Southern Oceans.

## 5. THE NORTH ATLANTIC OSCILLATION (D1)

### 5.1 SCIENTIFIC RATIONALE

#### 5.1.1 Introduction: Characteristics of the North Atlantic Oscillation (NAO)

The NAO is a large-scale alternation of atmospheric mass with centres of action near the Icelandic Low and the Azores High. It is the dominant mode of atmospheric behaviour in the North Atlantic sector throughout the year, although it is most pronounced during winter and accounts for more than one-third of the total variance in sea-level pressure (Cayan, 1992a). Simplifying the more complicated index of Walker and Bliss (1932), Rogers (1984) defined an index of the NAO using sea level pressure anomalies from Ponta Delgada, Azores and Akureyri, Iceland, while Hurrell (1995a; 1996) extended the index further back in time by using data from Lisbon, Portugal and Stykkisholmur, Iceland. A “high-index” pattern, indicating strong midlatitude westerlies, is characterised by an intense Iceland Low with a strong Azores Ridge to its south, while in the “low-index” case, the signs of these anomaly-cells are reversed. Note however that the associated sea level pressure (slp) patterns are not merely reversed between these NAO extrema; their actual configuration, which may critically affect the ocean’s response, is illustrated in Rogers, (1990, his Fig. 7a,b). It is worth noting also that year-to-year departures from high- or low-NAO index sea level pressure composites are large, so that simple two station indices such as those defined by Rogers (1984) or Hurrell (1995a) have signal-to-noise ratios near 2.5 for winter anomalies (Hurrell and van Loon, 1997). The noise, in this case, is a measure of all fluctuations where the two centres of action in the NAO are operating in phase and therefore are not part of the oscillation.

Among its rich blend of frequencies, the NAO index has exhibited considerable long-term variability (Fig. 5.1; from Hurrell, 1995; Rogers, 1984 and Cook et al., 1998). Cook et al. (1998) (see also Hurrell and van Loon, 1997) describe concentrations of spectral power around periods of 24, 8 and 2.1 years, but also identify a multi-decadal oscillation with a period of 70 years. Though of interest in itself as the dominant mode of atmospheric behaviour in the Atlantic sector, CLIVAR interest can be expected to centre on the extent to which these multi-annual to interdecadal changes in the NAO index are predictable.

Of recurrent modes of atmospheric behaviour, the NAO is among the most robust. From the 13 atmospheric circulation modes worldwide considered by Barnston and Livezey (1987), the NAO was the least seasonally-ephemeral (i.e. was the only recurrent mode that is robustly present in every month of the year). Rogers (1990) shows that the NAO accounts for the largest amount of interannual variability in monthly North Atlantic sea level pressure in all but four months of the year. The NAO was also the only circulation mode tested that was coherent with the periodic behaviour of the 700 year stable isotope record from the GISP-2 ice core from central Greenland (White et al., 1996; see also Barlow et al., 1993).

On shorter time scales, Cayan (1992, a, b, c) has analysed composites of positive and negative NAO months in winter (October to April) to show that the NAO is responsible for generating systematic large amplitude patterns in the anomalies of wind speed, latent and sensible heat fluxes, and hence sea surface temperature over much of the extratropical North Atlantic (around 10-40% of the monthly change in SST anomaly is estimated to be due to these flux anomalies over the winter months and over much of the ocean; Cayan, 1992c). In a range of other studies, the interannual and longer-term changes in the winter NAO from one extreme state to the other has also been suggested to determine or modulate deep temperature (T) and salinity (S) on the West Greenland Banks (Buch, 1995), temperature and salinity fluctuations in the currents of Greenland-Labrador (Reverdin et al., 1997) temperature anomalies of the western subtropical gyre (Molinari et al., 1997), the baroclinic transport of the subtropical- subpolar gyre system (McCartney et al., 1997), the Atlantic storm track (Rogers, 1990; Hurrell, 1995b), the midlatitude westerly wind strength and significant wave height (Bacon and Carter, 1993; Kushnir et al., 1997), evaporation and precipitation patterns (Cayan and Reverdin, 1994; Hurrell, 1995a), the meridional heat flux by the atmosphere (Carleton, 1988), the transport of the Labrador Current (Myers et al., 1989; Marsh, 1997), Arctic sea-ice (Fang and

Wallace, 1994; Mysak et al., 1996), Davis Strait ice volume (Deser and Blackmon, 1993), the iceberg flux past Newfoundland (Drinkwater, 1994 and Rhines, 1994), and dust transport from Africa across the Mediterranean and the subtropical Atlantic (Moulin et al., 1997). Decadal changes in the NAO have recently been held responsible for determining 18° water characteristics, including convection strength (Talley, 1996; Joyce and Robbins, 1996; Houghton, 1996), Labrador Sea Water characteristics, including convection strength (Lazier, 1995; Houghton, 1996), as well as for controlling and co-ordinating the intensity of deep convection between the three main Atlantic sites (Greenland Sea, Labrador Sea and Sargasso; Dickson et al., 1996), thus driving decadal change to considerable depths in the ocean. Further, the amplification of the northern cell of the NAO dipole to record levels in the 1960's was the key factor in generating the largest known dislocation of the freshwater balance of the Northern Gyre, the so-called Great Salinity Anomaly (Dickson et al., 1988), which circled the subpolar domain of the North Atlantic over a 14 year period from the late sixties (possibly with some recirculation thereafter; see Belkin, et al., 1998).

As might be expected, these radical changes in the climate and marine environment of the North Atlantic sector are held responsible for a wide range of effects on the marine ecosystem, including changes in the production of zooplankton and the distribution of fish (e.g. Fromentin and Planque, 1996; Friedland et al., 1993).

### 5.1.2 The NAO and global change

As the Second Assessment Report of IPCC points out (Nicholls et al., 1996), the current global change debate remains centred around six questions related to the detection of climate change and sensitivity of the climate to anthropogenic activity. They are:

- Has the climate warmed?
- Has the climate become wetter?
- Has the atmospheric/oceanic circulation changed?
- Has the climate become more variable or extreme?
- Is the 20th Century warming unusual?
- Are the observed trends internally consistent?

Karl et al. (1995) conclude that for many of the climate variables important in documenting, detecting and attributing climate change, the data are not presently good enough for rigorous conclusions to be drawn. Nevertheless, in the first of its series of authoritative reports, IPCC (1990) concluded that global average surface air and sea temperatures had risen by 0.3°C to 0.6°C since the mid 19th Century. Supplementary analysis (IPCC, 1992, 1996) subsequently confirmed this, using an updated, improved and expanded dataset. The warming has not been uniform in either time or space. Approximately 0.2° to 0.3°C of the global increase took place over the last 40 years or so (the period with the most credible data; see Jones, 1994a, b), and the greatest warming has been located over the continents between 40°N and 70°N, with weak cooling over the intervening oceans (Wallace et al., 1996).

The clearest scientific rationale for the study of the NAO lies in the fact that the NAO and its time-dependence appear central to three of the main questions in the global change debate: has the climate warmed, and if so why and how? Fig. 5.2, from Hurrell (1996), explains the connection. Using multivariate linear regression, Hurrell has quantified the effect of observed changes in the North Atlantic Oscillation and Southern Oscillation (SO) on Northern Hemisphere extratropical (20°N - 90°N) temperatures during winters since 1935. The individual and combined response to these circulation changes is shown in the upper three graphs of Fig. 5.2. Together, these two circulation modes explain 49% of the observed interannual variance in hemispheric extratropical temperatures, with the NAO individually accounting for 34% and the SO

for 16% (Hurrell, 1996, updated). Moreover, when the linear effects of the NAO and SO are removed, the residual time-series (lower panel, Fig 5.2) is found to exhibit no significant trend.

Such results do not tell us if the observed warming is natural or anthropogenic, but we can justifiably conclude that the mechanism of hemispheric warming - whatever its cause - is acting through an amplification of the NAO in the Atlantic sector and the ENSO (or PNA) signal in the Pacific. Either way the NAO is revealed as a major source of interannual variability in global weather and climate.

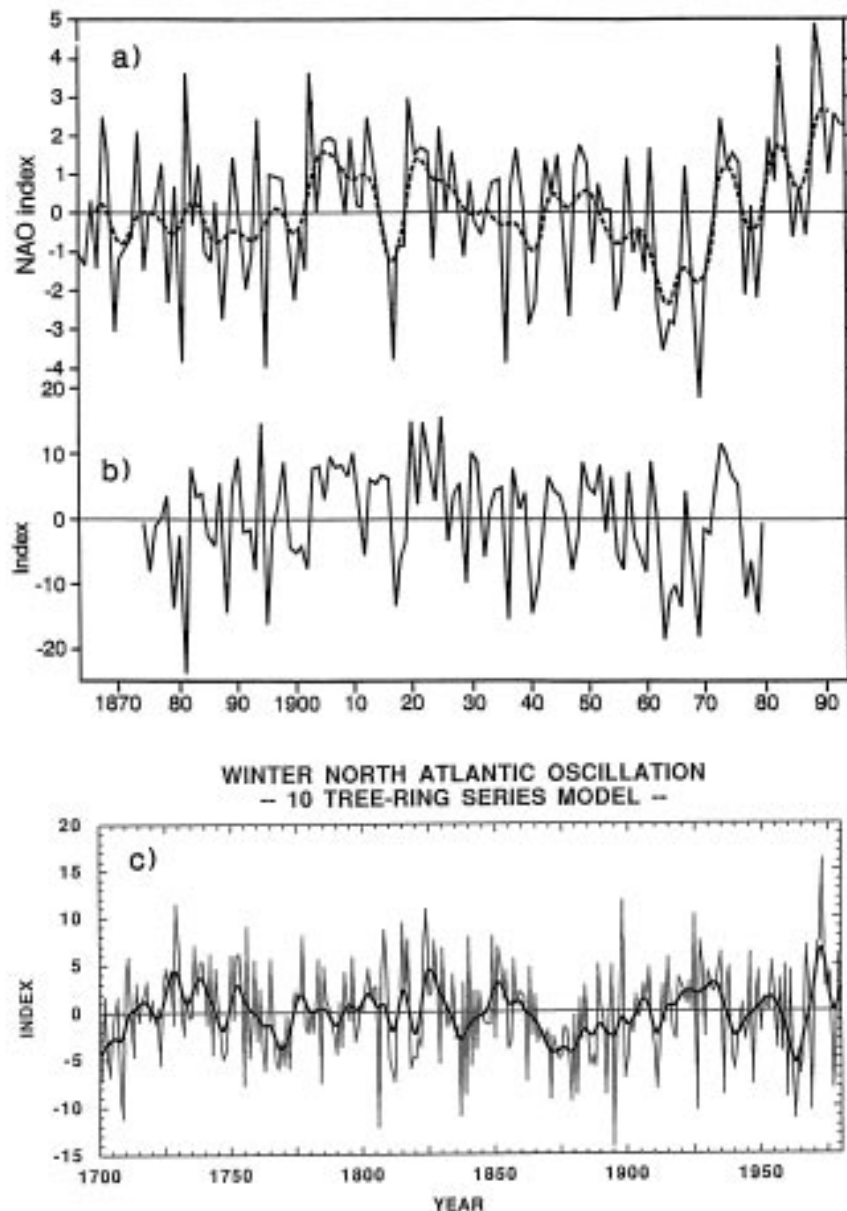


Fig. 5.1: Variations since 1865 in (a) the Iceland - Lisbon and (b) the Iceland - Azores versions of the winter NAO Index (from Hurrell, 1995 and Rogers (in Cook et al., 1998) respectively); (c) the winter NAO index since 1700, reconstructed from tree rings. The series explains 41% of the variance (from Cook et al., 1998).



### 5.1.3 Decadal changes in the NAO index

Apart from its role in driving large amplitude interannual fluctuations in the climate of the Atlantic sector, the NAO Index has shown signs of variability at decadal time scales also. It appears, however, that this decadal modulation is itself time-dependent.

In the indices of Rogers (1990) and Hurrell (1995a) there is evidence of a long-period, decadal alternation in amplitude since the late 19th century, with low-index extrema during the 1960s (Fig. 5.1a, b), and with high-index extrema from 1900-1930 and in the 1990s. From both proxy and observational evidence, however, there is evidence that the multi-decadal signal in the NAO Index has been amplifying with time.

Cook et al. (1998) use a 10 tree-ring model (trees from both North America and Europe) to develop the first reconstruction of the winter NAO index back to 1701 (Fig. 5.1c). From spectral analysis of this proxy, they show little sign of decadal variation in the index before 1850, but an amplifying 70-year oscillation after that. Jones et al. (1997) have used early pressure records to construct a November-March version of the Index for Iceland-Gibraltar, thus extending the instrumental series back to 1823. A high-amplitude interannual variability becomes modulated with an amplifying decadal signal with time, so that - as shown in other versions of the index (e.g. Hurrell, 1995a), - the period since the early 1970's is the most prolonged positive phase of the Oscillation, the late 1980s / early 1990s is the period with the highest values, and the change from the low-index 1960's to the high index 1990's is the largest low-frequency change of record. Interestingly, the change from the 1994-95 winter value (2nd highest) to the 1995-96 winter value (lowest) is also the largest year-to-year change in the 173 year series. Power spectra computed from running 60-year intervals for the Iceland-Lisbon series since 1865 also clearly demonstrate the tendency for the NAO spectrum to become redder with time (Fig. 5.3, from Hurrell and van Loon, 1997).

Thus in summary, there is a 3-fold a priori justification for studying the NAO within CLIVAR. (1) It controls the factors which effect change in the ocean (i.e. heat flux, wind speed and direction, and P-E). (2) It seems to have made the largest individual contribution to the observed hemispheric warming trend, though we cannot yet tell whether this change owes anything to human activity. (3) The amplitude of its decadal variability component appears to be increasing with time.

The fact that the year-to-year changes in the NAO index are also exceeding the range of past experience suggests that mere "persistence" is likely to be a poor guide to the future behaviour of the NAO. Instead, prediction of the NAO will require an adequate understanding of the factors which provide its long-period memory, protracting, repeating or in some way structuring its short-term behaviour into the multi-annual trends that our records seem to show us (Fig. 5.1).

## 5.2 MODELLING AND PREDICTION

To understand and eventually predict the complex dynamical ocean-atmosphere-land system in the North Atlantic and its decadal-centennial interaction, major emphasis must be placed on numerical modelling. The modelling efforts, which should adopt a hierarchical approach, must determine whether variability simulated in models is fundamentally coupled, whether one component of the climate system drives variability in another, whether simulated variability modes are related to observed variations, and whether modes of variability once identified are predictable. The modelling component is also particularly crucial because of the lack of observational records of sufficient length, combined with the need to synthesise sparse data from both the ocean and the atmosphere. Since the distinction between coupled and uncoupled modes of variability is difficult to identify through observations alone, progress in understanding the mechanisms of the NAO will be made primarily through modelling and theoretical work. Two broad hypothesis for the observed variability provide a relevant framework: uncoupled and coupled modes of variability.

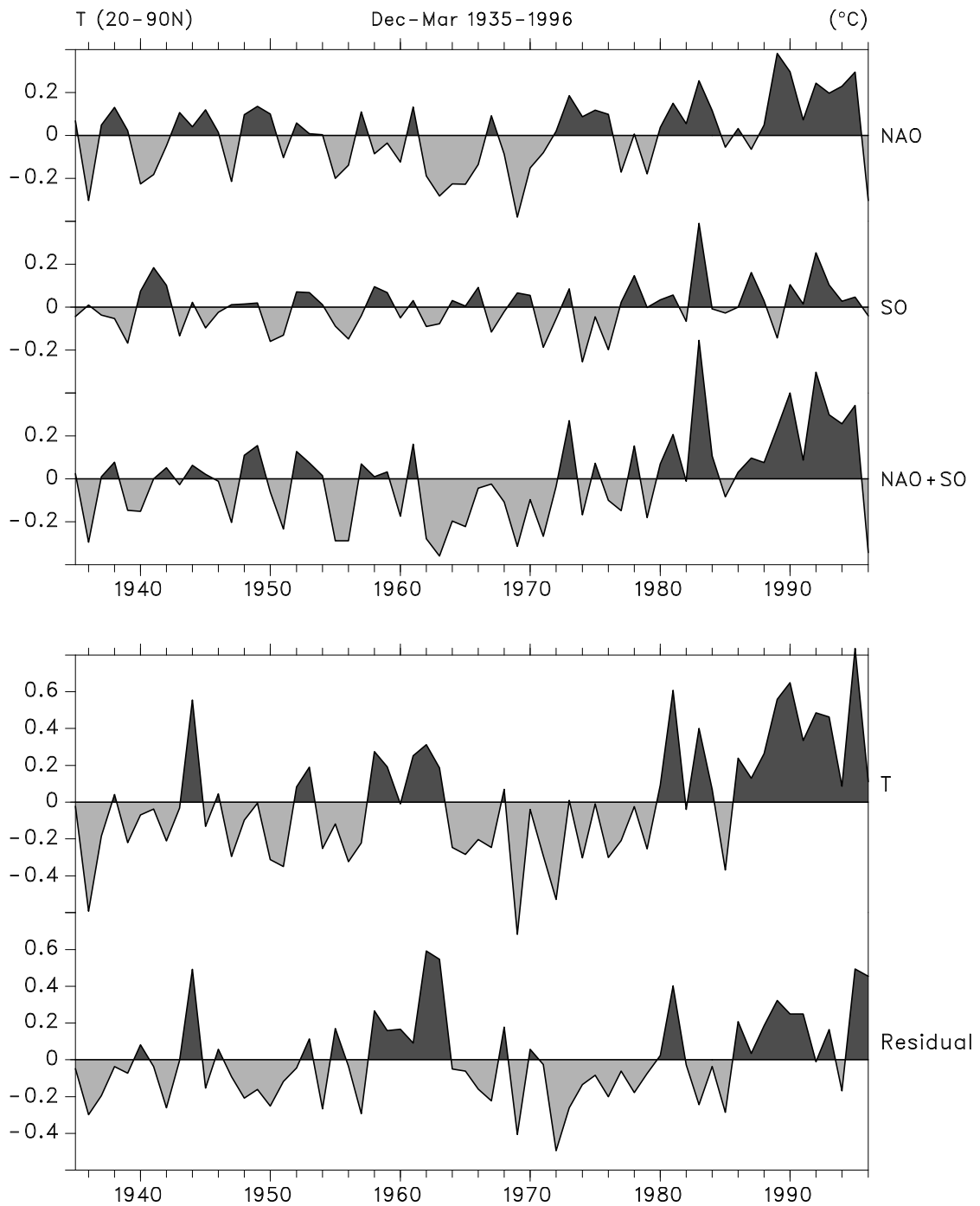


Fig. 5.2: Surface temperature changes of the Northern Hemisphere (20°N-90°N) for December to March associated with the North Atlantic Oscillation (NAO)- top series, upper panel; the Southern Oscillation (SO)- middle series, upper panel; and combined - bottom series, upper panel, relative to the total change - top series, lower panel. The residual temperature record (bottom series, lower panel) is that remaining after the NAO plus SO effects are removed. Note the predominance of positive contributions in the NAO and SO after about the late 1970s (after Hurrell, 1996)

III. The CLIVAR Principal Research Areas

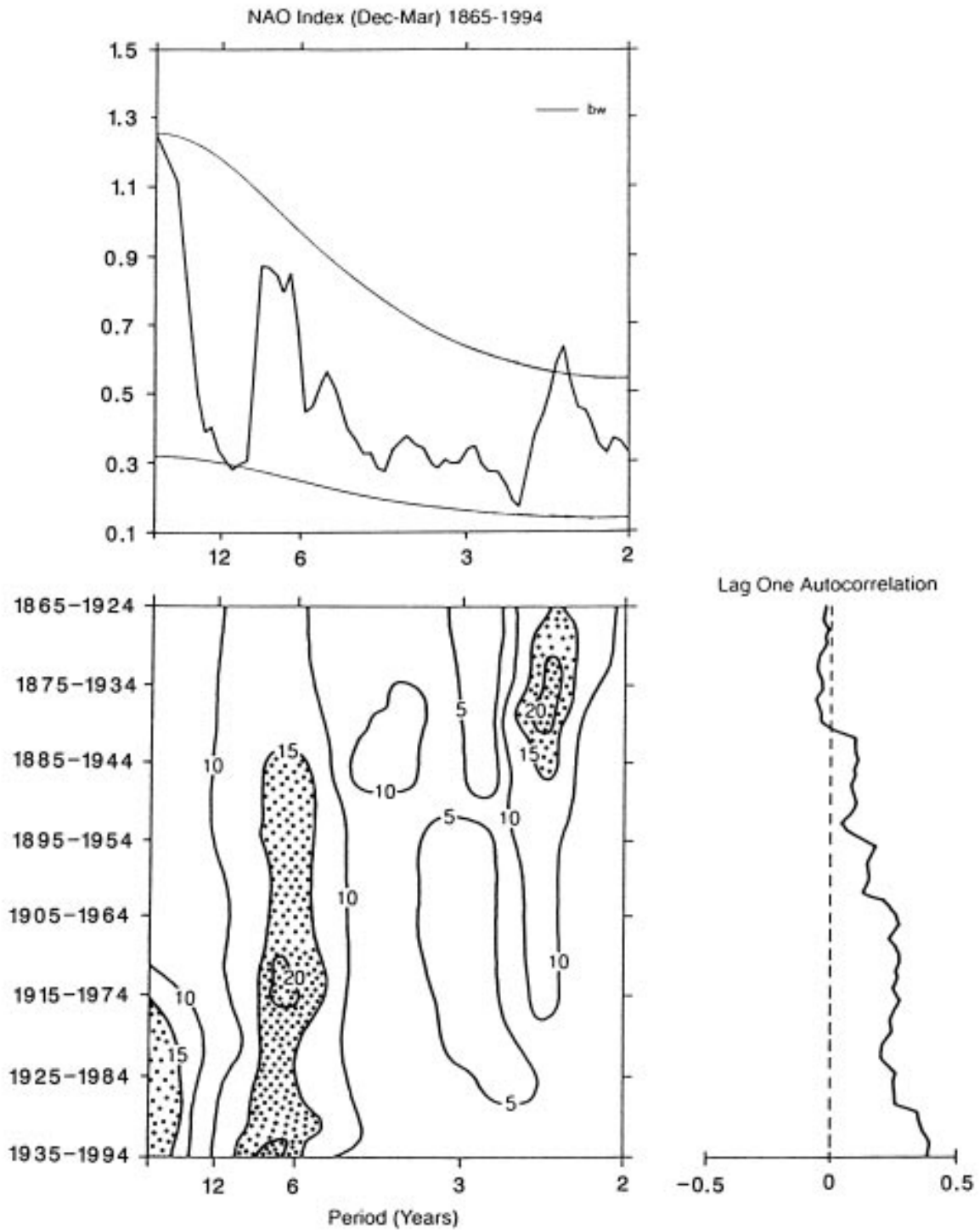


Fig. 5.3: Power spectra of the winter (December - March) NAO index for 1865-1994 (top) and running 60-year intervals (bottom). Variances greater than  $0.15 \text{ mb}^2 \text{ frequency}^{-1}$  are stippled in the lower panel. Also shown is the lag one autocorrelation coefficient for each 60-year interval (from Hurrell and van Loon, 1997).

### 5.2.1 Uncoupled variability

Atmospheric general circulation models, forced with temporally non-varying SSTs, display NAO-like fluctuations, so it would seem that the fundamental mechanisms of the NAO arise mostly from atmospheric processes (Barnett, 1985). The idea that much of the observed climate variability can be explained as the integral response of the slowly varying parts of the climate system to stochastic atmospheric variability was first proposed by Hasselmann (1976). Recently, Frankignoul et al. (1997) have shown that substantial decadal SST anomalies can indeed be generated by stochastic wind stress forcing, while Griffies and Tziperman (1995) attribute decadal fluctuations of the thermohaline circulation evident in some coupled integrations to stochastic atmospheric forcing. These studies suggest the possibility that the variability of the North Atlantic is merely the response of the ocean to chaotic, high-frequency forcing by the atmosphere. They do not, however, rule out feedback of the resulting oceanic changes on the atmospheric circulation.

One way in which atmospheric processes alone might produce strong interannual and perhaps longer-term variations in the intensity of the NAO is suggested by the observational and modelling work of Perlwitz and Graf (1995) and Kodera et al. (1996). Both studies demonstrate a strong statistical connection between the strength of the stratospheric cyclonic winter vortex and the tropospheric circulation over the North Atlantic. During winters of an anomalously strong stratospheric polar vortex, the NAO tends to be in a positive phase with enhanced westerlies across the Atlantic, perhaps associated with changes in vertically-propagating planetary waves. The stratosphere can be forced into this mode by several different mechanisms, including explosive tropical volcanic eruptions (Robock and Mao, 1992), ozone depletion and global warming (Graf et al., 1997). In the latter case, the idea is that warming produces an enhanced stratospheric height gradient through an expansion of the tropical troposphere, which could explain the continuous strengthening of the NAO during winters since the late 1960s.

Uncoupled variability could also be viewed as the passive response of the atmosphere to internally-generated oceanic variations. In the coupled model results of Delworth et al. (1993), for instance, the strongest multi-decadal signals are located in the mid-latitude to subpolar Atlantic regions associated with variations in the intensity of the thermohaline circulation, as well as variability in the high-latitude Greenland Sea region associated with the propagation of freshwater anomalies southward from the Arctic. The modelled variations in the thermohaline circulation are associated with changes in sea surface properties and include a NAO-like response in the atmospheric circulation. The inherent time scale of the variability is multi-decadal and is associated with adjustment processes of the overturning oceanic circulation.

### 5.2.2 Coupled variability

Although the NAO pattern itself may arise and recur without surface feedback as some sort of internal atmospheric mode, this cannot explain its decadal variability. There is growing observational and modelling evidence to suggest that decadal variability over the northern ocean basins is governed by the coupled ocean-atmosphere system, including processes which might determine longer period fluctuations in the NAO. In such scenarios, low-frequency responses of the ocean to atmospheric forcing, and their feedback on the atmosphere, result in oscillatory behaviour.

The mutual interaction between the upper ocean and the atmosphere was studied by Deser and Blackmon (1993) who showed that wintertime SSTs, sea ice and atmospheric fluctuations over the subpolar gyre change synchronously on decadal time scales. Kushnir (1994), in support of the earlier arguments of Bjerknes (1964), concluded that pronounced decadal changes in SST and sea level pressure over the subpolar and subtropical Atlantic gyres were indicative of coupled ocean-atmosphere interactions. Moreover, Kushnir's composites showed that middle-latitude Atlantic SST anomalies were warm (cold) during low (high) NAO index phases. Molinari et al. (1997) relate subsurface temperature variability in the western middle-latitude Atlantic to decadal variations in the intensity of the NAO, and they also find that the regional temperature variability is similar to the basin-wide variability at 125 m observed by Levitus et al. (1994). Hansen and Bezdek (1996) present evidence of surface temperature anomalies circulating around the subtropical and

subpolar gyres coincident with decadal changes in the NAO. Moreover, the warm and cold SST anomalies reflect anomalies in the heat content of the deep winter mixed layers (McCartney et al., 1997) which, when exposed to the atmosphere in winter, could provide the forcing to drive the NAO on the advective time scale of the gyre.

Another hypothesis which suggests a mode of coupled air-sea variability in which the memory of the system resides in the ocean has emerged from the coupled model results of Latif and Barnett (1996), Grötzner et al. (1998) and Latif (1998). These studies submit that positive SST and sub-surface heat content anomalies in the central North Atlantic are created by an enhanced subtropical ocean gyre circulation which transports warm tropical waters poleward by the western boundary current and its extension. The response in the atmosphere is an anticyclonic circulation and a weakened storm track, which enhances the SST anomalies through anomalous surface heat fluxes and Ekman pumping. The atmospheric response, however, also consists of a wind stress curl anomaly which spins down the subtropical gyre, thereby reducing the northward transport of heat and creating negative SST and sub-surface heat content anomalies. This anomaly pattern has a similar effect on the atmosphere but of opposite sign, leading to oscillatory behaviour on decadal time scales. The anomalous atmospheric height pattern created by this mode bears some resemblance to the NAO, although the centres of action in the coupled model are displaced equatorward by about 10 degrees.

Timmermann et al. (1998) used a coupled model and showed that positive SST anomalies occur over the North Atlantic when the thermohaline circulation is anomalously strong. The atmospheric response to the SST anomalies is a strengthened NAO, which leads to anomalous fresh water fluxes off Newfoundland and the Greenland Sea. The resulting negative sea surface salinity anomalies are advected by the subpolar gyre, eventually reaching the convectively active region south of Greenland. The convection and subsequently the strength of the thermohaline circulation are weakened, leading to reduced poleward oceanic heat transport and the formation of negative SST anomalies. The completion of this phase reversal takes about 35 years.

#### 5.2.3 The role of transients

The above coupled and uncoupled scenarios all underscore the point that several mechanisms could be responsible for both interannual and longer time scale variations in climate over the North Atlantic, and all of these are generally poorly understood. Modelling investigations within CLIVAR will be central to an identification of which components of the climate system, acting either together or independently, produce climate variability over this region of the globe. With respect to the NAO, a key unresolved question is whether observed anomalies in oceanic conditions represent a passive response to decadal changes in the atmospheric circulation, or whether they feedback to force decadal and longer period oscillations in the NAO.

Recent modelling work by Griffies and Bryan (1997) suggests that the North Atlantic ocean may have climate predictability on the order of a decade or longer. Since the oceanic variations are manifest at the surface as decadal to multi-decadal SST anomalies, a key question relevant to predictability is the response of the atmosphere to middle and high latitude SST anomalies. This question has been addressed by many previous theoretical and modelling studies, yet no clear consensus has emerged. In the wintertime extra-tropics, transient phenomena with time scales of several days consist mainly of migratory baroclinic cyclone waves. The transport of heat and vorticity by transient atmospheric eddies along storm tracks results in strong dynamical interactions between the time-varying and stationary components of the atmospheric circulation, which dictates that a full understanding of the steady-state response to middle latitude SST anomalies must take into account the total effects of the transient waves, including their influence on surface fluxes and further changes to the SST anomalies. Studies have shown that storm track variations accompanying interdecadal changes in the background flow exert a positive feedback on the low-frequency component of the circulation (e.g. Trenberth and Hurrell 1994; Hurrell and van Loon, 1997). A design study to further elucidate such relationships is suggested in the next section.

## 5.3 DIAGNOSTICS AND EMPIRICAL STUDIES

### 5.3.1 Optimising the NAO index

Section 5.1 established that the North Atlantic Oscillation is of global climatic importance and has shown a growing decadal variability since the 1820s. Though we cannot yet tell whether any part of this change is attributable to a growth in human activity, any tendency for the NAO to undergo structured long-period change over years to decades must have predictive value, whatever the cause, if it can be rigorously established. The first diagnostic need is therefore to extend and reduce uncertainties in the NAO Index.

Using different station-pairs, the instrument-based index of NAO behaviour has been successively pushed back to 1873 (Iceland-Azores: Rogers 1990), 1865 (Iceland-Lisbon: Hurrell, 1995a) and 1821 (Iceland-Gibraltar: Jones et al., 1997). Early weather records from Reykjavik and Cadiz may permit one further extension back to about 1780 (Jones, personal communication). Beyond that we are forced to use proxies of NAO variability such as the tree-ring model used by Cook et al. (1998) in reconstructing the NAO winter Index back to 1701. Though the winter season is of most interest, as it is the period of strongest pressure gradients and interannual variability (Moses et al., 1987), tree-ring chronologies from mid- to high-latitudes will tend to respond largely to summer temperature variations, as Cook et al. (1998) point out. They base their first long (280 year) reconstruction empirically on the 10 (out of 102) circum-Atlantic chronologies which are best related to the winter NAO Index, and succeed in capturing the spectral characteristics of the instrumental data very well.

One thousand year tree-ring chronologies also exist for cedars from the Atlas mountains of Morocco, (Till, 1985; Chbouki, 1992; Chbouki et al., 1995) where tree growth is a function of winter rainfall. The link to precipitation there (Lamb and Pepler, 1987) is also stronger than for the alternate long proxy of the NAO: the stable isotope relation from the GISP-2 ice-core in Central Greenland. Moroccan tree-ring data might therefore provide a stronger, more-direct and extended (perhaps 1000-year) proxy for the long-term behaviour of the winter NAO and should be analysed for this purpose. Ultimately, if a 1000-year paleo-temperature curve can be developed for the West Atlantic shelf as is currently planned ( $O^{18}$  analysis of the bivalve Arctica; G. Goodfriend, CIW and C. Weidman, WHOI, pers. comm.), the optimum NAO proxy might be developed from the combination of all three of these widely-scattered and independent millennial proxies.

If, by this means, we can demonstrate whether the current amplification of the NAO had occurred previously in a thousand-year record, it may be useful guidance as to whether the present change is natural or anthropogenic.

### 5.3.2 Detailed study of storm-surface interactions

In McCartney's analyses (McCartney et al., 1997; Curry et al. 1998), there is clear evidence of a systematic space-time evolution in the temperature anomaly distribution of the upper ocean over much of the extratropical Atlantic and over many decades. These warm and cold epochs in SST reflect anomalies of the heat content of the deep winter mixed layers tracking around a "warm water transformation pathway" (see Section 5.4.2, below) from the Sargasso to the Labrador Sea, and are coincident with the trends in NAO behaviour. The key unresolved question for CLIVAR is whether they represent the passive response of the ocean to a decadal evolving atmosphere, or whether they feed back to force decadal changes in the pattern of NAO activity (McCartney's so-called "missing link").

Monthly aggregates of SLP and SST remain notoriously difficult to interpret in terms of cause and effect, forcing and feedback. The problem may be more tractable when we disaggregate the apparently-robust changes in the mean Atlantic pressure field or storm climate associated with the NAO into their component cells. Then, robust pressure anomaly patterns may prove to be quite delicate features - the result of a few more storms, or the usual number of storms exhibiting a slightly faster deepening-rate or a slightly slower eastward progression than usual, for example. We are likely to gain insight into the "sense" of the

feedback when the short-term (3-hourly?) changes in the characteristics of storms are identified cell by cell and compared with the slower-evolving temperature anomaly gradients of the underlying surface. (Namias, 1951, gives us an analogous example of such a disaggregation study).

There is therefore merit in examining the storm characteristics of two contrasting winter pentads-winters of 1965/66-69/70 (coinciding with extreme low index NAO conditions) and 1988/89-92/93 (high index) - in relation to the underlying temperature anomaly gradients. These periods had the lowest and highest postwar incidence of Atlantic storms deeper than 950 mb (Fig. 5.4a).

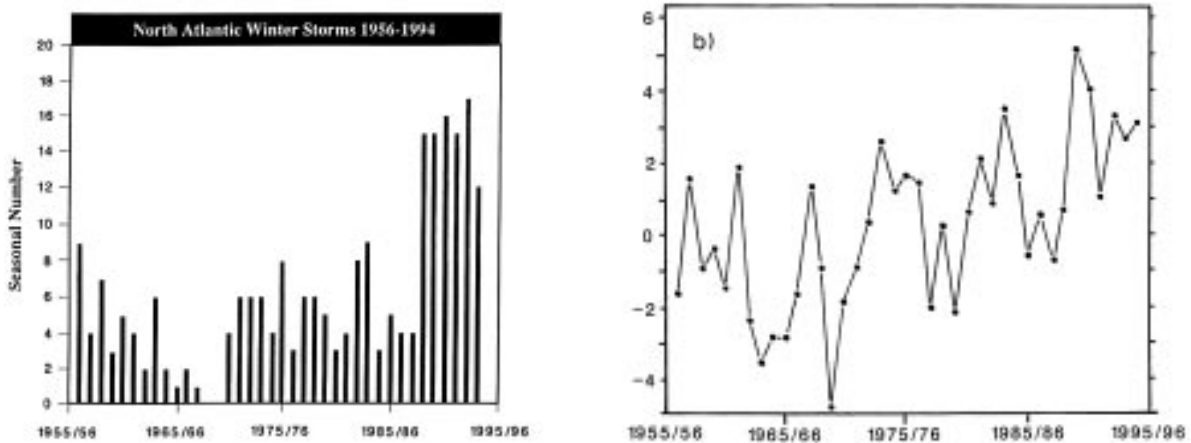


Fig. 5.4: a) (left): Number of North Atlantic low pressure systems (950hPa and lower, counted once per lifetime) determined from four to eight weather maps per day for the winter season (November-March 1956 to 1994) (from Franke, pers. communication). b) (right): NAO index for the same time period (courtesy B. Dickson)

### 5.3.3 Data archaeology

In attributing cause and effect, forcing and feedback to the multi-decadal shifts of the NAO, the longest possible ocean data sets are needed. Multi-decadal ocean records are rare. Nonetheless, Curry et al. (1998) for the Labrador Sea, and Joyce and Robbins (1996) for Station S off Bermuda were both able to extend the postwar deep instrumented records at these sites back to the 1920's using only a very few supplementary data points, permitting a view of the ocean's response throughout one full cycle of NAO behaviour from the high-index 1920's through the low-index 1960's to the high index 1990's.

In the case of the third and deepest-reaching centre of Atlantic convection - the Greenland Sea - the available instrumented record from the deepest layers (>2000m) since the late 1950s suggests that trends in convective activity are the inverse of those in the Labrador Sea, driven by the same decadal changes in the NAO (Dickson et al., 1996). Thus, there is great merit in attempting to extend this record and, though deep data from the Greenland Basin are rare, there is at least one lost high quality data set (Stations 149-162 from the METEOR in October-November 1935) that would make the search for it and others worth while. METEOR stations 100-104 from August-September 1933 may also be relevant.

## 5.4 SPECIAL OBSERVING NEEDS

This section does not aim to cover all questions of DecCen variability in the North Atlantic, or the observational effort needed to resolve them. A complete and up-to-date discussion will be found elsewhere in this report. Here we describe only that subset of Atlantic variability that concerns the NAO.

The central motivating question of the NAO in CLIVAR is whether the observed changes in SST and mode water formation are merely the response of a passive ocean to a decadal evolving atmosphere, or whether (and how) the ocean might feed back to encourage recurrent behaviour in the NAO. The non-white character of its spectrum suggests that the link is not merely one of stochastic atmospheric forcing (Hasselmann, 1976), but implies that the system may be coupled (Grötzner et al., 1998; Timmermann et al., 1998), and an amplifying decadal periodicity in the NAO would seem to suggest an increasing involvement of the ocean. However we lack both the evidence and a physical mechanism for the ocean “driving the atmosphere” - McCartney’s so-called “Missing Link”.

The field programme for NAO in CLIVAR is thus largely set by the need to confirm and quantify the factors which redistribute, protract, or amplify the SST anomaly field of the North Atlantic, and our ideas as to what these factors might be form a necessary introduction to the field plan.

### 5.4.1 Variability of North Atlantic heat fluxes and storage

Beneath the NAO fluctuations in the North Atlantic is a powerful oceanic heat engine transporting about 20% of the combined meridional heat transport by the atmosphere and oceans at 24°N (Bryden, 1993). Large changes in the atmosphere's hemispheric meridional heat transport are linked to the North Atlantic sector's NAO fluctuations (Carleton, 1988). The heavy involvement of the North Atlantic Ocean in redistributing heat in the climatological mean leads to an expectation that fluctuations in oceanic heat transport may accompany fluctuations in the NAO. This section outlines a programme directed at balancing the heat budgets of atmosphere and ocean over the North Atlantic.

There are three known methods for estimating the exchange of heat (and fresh water) between the ocean and atmosphere, although at present there is considerable uncertainty over the real accuracies of these methods. A first step would be to fully analyse the error budgets of atmospheric model residual flux estimates; existing bulk formula methods; and direct oceanic flux divergence estimates. Although some accuracy estimates already exist, none of them is complete nor wholly convincing.

In the late 1970s, a feasibility study for the “CAGE” experiment (Bretherton et al., 1982) explored each of three distinct methods of estimating ocean heat transport:

A) From ocean temperature and velocity measurements, producing estimates of oceanic heat transport and its divergence. B) From top of the atmosphere (TOA) net radiation plus atmospheric heat flux divergence as computed from numerical models and directly from sub-sets of the atmospheric observations. C) From the net air-sea surface heat flux (bulk formulas) and ocean heat storage.

The CAGE study concluded that only the first two were viable, and recommended that both be measured in a single ocean basin - the North Atlantic - and compared. No explicit CAGE programme was ever carried out but some of the CAGE concepts influenced the planning of WOCE. There have been attempts to estimate the heat transports in each ocean basin, using the above three methods. At the present time, the mean meridional heat transports are still poorly constrained in all ocean basins. There are several notable discrepancies between those estimates. Their uncertainties are estimated to be within +/- 0.3 PW in the meridional heat transport and most of the differences encountered are within those limits.

Before D1 can address many of the variability and predictability questions associated with the atmosphere and ocean aspects of phenomenon like the NAO can be addressed, we first require to substantially reduce the unacceptably large error bars on the mean state. The time variability of the meridional heat flux,



particularly interannual, is almost completely unknown and must be determined before the accuracy of a time-average could be assessed.

Within D1 it is proposed to move beyond the concepts of CAGE and the experience of WOCE and to launch a concentrated observational, analysis and modelling programme of both the North Atlantic Ocean and its neighbouring atmosphere, with the goal of reducing the uncertainty in meridional heat transports in both fluids on the month to interannual time scales, to the point where the effects of the North Atlantic on climate variability and predictability can be studied. If this goal is to be achieved, the strengths of all three methods must be used. Independent estimates from each, with careful error estimates, are needed to ascertain the presence of systematic errors in the methods. A goal would reduce the errors in all three methods to about  $10 \text{ Wm}^{-2}$ ; if independent, estimates from all three combined would come close to an accuracy of  $5 \text{ Wm}^{-2}$ . But simply understanding of what the actual errors are would be a very great advance. All three methods are now discussed as a first step in defining a viable strategy for the programme.

### Measuring the Oceanic Heat Flux divergence

The transport of heat in the ocean is the combined effect of the large-scale circulation, vertical overturning with the associated effect of mixing and water mass conversion, and small-scale eddies. To determine the relative magnitude and distribution of heat transports by those processes is a primary objective of this experiment. The central approach is through the direct estimate of the heat carried across a basin-wide zonal section. Two such sections bounding a mass-conserving volume of fluid permit estimates of the heat flux divergence to the atmosphere if changes in the heat storage within the volume are also known. Transfers to the atmosphere can occur through winter-time cooling and convection; transfers can also occur during the course of the year through internal oceanic mixing across isopycnic surfaces. An understanding of those processes is of importance for the understanding of heat fluxes in the ocean and their uncertainties. For the discussion of oceanic heat fluxes the following subdivision is useful.

1. *The geostrophic interior flow field*: The fundamental problem here is the uncertainty in geostrophic transport errors and related uncertainties in the heat fluxes combined with cross-isopycnic mixing. Geostrophic transport errors are to first order related to the determination of absolute reference velocities. The determination of those velocities is complicated since it is intimately related to the other two components discussed below, and there are errors, perhaps systematic, in calculating geostrophic flows from density data in the presence of strong topographic structures. Potential locations for some transocean sections are given in 5.4.4. Analysis of WOCE sections can provide further guidance in transocean section locations.
2. *Ekman transport*: Estimation of the Ekman mass transport depends directly on estimates of the wind stress. The associated heat transport is that mass-transport times the specific heat and the mean temperature difference between the Ekman layer flow and the compensating geostrophic return flow. Accuracies of Ekman heat fluxes are believed to be limited by those of the meteorological wind stress estimates. Improving these estimates is primarily a requirement in low latitudes, where the contribution of the Ekman heat transport to the total is substantially enhanced. It is unclear to what extent the high-frequency Ekman transport fluctuations (i.e. the transient eddy flux terms) affect the general budget. The extent to which fluctuations in Ekman convergences and divergences result in mass storage or large-scale geostrophic adjustment needs to be determined.
3. *Boundary current transports*: Boundary currents show the largest variability in the ocean with small spatial scales and with time scales from a few days to decades. To estimate the heat fluxes associated with boundary currents may require direct measurements of temperature and velocity which capture small-scale changes over the entire water column, including those in the deep return flow in those regions. On the other hand, observations of transport fluctuations by altimeters, and/or near-surface instruments such as XBTs may provide adequate accuracy.

For each of the above three components it is necessary to obtain estimates of the heat flux with an accuracy better than 0.2 PW. The fact that each individual component is related to the computation of the reference velocity and its uncertainty, makes the problem of computing error bars on heat flux estimates

somewhat complicated, but the general methodology of inverse methods with both static and dynamic (time-evolving) models is well understood.

4. *Heat Storage*: Over most of the ocean and much of the year, a large amount of heat is stored and released. On seasonal to interannual time scales, this storage primarily takes place within the seasonal surface mixed layer covering typically the top few hundreds of meters of the ocean.

On longer time scales, however, changes in heat storage occur over most of the water column. Therefore, to estimate changes in ocean heat storage, the annual cycle and inter-annual variations need to be estimated from measurements and models of the entire water column. It is known that large changes of heat storage occur on seasonal time scales and longer time scales. The amplitude of heat storage fluctuations on interannual to decadal time scales are not known in detail. The proposed CLIVAR sustained observations of the upper ocean using XBTs from VOS and the increasingly important use of PALACE floats are key to determining variability in the oceanic heat storage for D1.

Various estimates of long term North Atlantic heat flux exist (e.g. Bryden, 1993; Roemmich and Wunsch, 1985; Macdonald and Wunsch, 1996; Lavin et al., 1997). According to Macdonald and Wunsch the uncertainties are about  $\pm 0.25\text{PW}$ ; potential systematic errors could make this a factor of 2 larger. The estimate of uncertainties of ocean heat fluxes is a complicated scientific problem at the core of this project. Design of a field component would depend upon a much clearer understanding of the error budgets and the relative tractability of the different elements.

### Measuring the Atmospheric Heat Flux Divergences

The use of atmospheric budgets as a constraint on surface fluxes, and hence meridional transports, is dealt with extensively in Trenberth (1997). This work outlines the advantages of the method when it uses global NWP analyses from four-dimensional-data assimilation, focuses on the heat and moisture, but recognises the need to balance the mass budget, highlights the need to resolve the diurnal cycle with four times daily data, finds that gross violations of the mass budget are present, but can be accommodated, and discusses other sources of error.

The strawman method advocated is essentially that of Trenberth and Solomon (1994) who used 1988 data. It could be applied in a consistent manner over all the years of reanalysis (early 1970s to the present). The results over land suggest an uncertainty in the local heat budget of  $30\text{ Wm}^{-2}$  on scales of order 1000 km, although this has been reduced somewhat in the reanalyses. The estimate of the errors in the top-of-atmosphere radiation are  $5\text{ Wm}^{-2}$ , after corrections for the overall imbalances. Trenberth (1997) states that much larger uncertainties should be ascribed to the various components of the atmospheric transports but these tend to cancel for the heat budget as a whole. The other main sources of error are atmospheric divergence, the diurnal cycle, mass imbalances, vertical resolution and interpolation to pressure surfaces. Many of these are improved in the reanalyses so that this method is competitive and is complementary to the others. Improved observations in the North Atlantic, assimilation of those data, and thus better analyses will lead to future advances.

### Measuring Air-Sea Fluxes

A major recent advance in the observational data base is the routine production of all the surface fluxes and flux parameters by the NWP centres such as NCEP and ECMWF. These products represent almost all the relevant observations, assimilated under the dynamical constraints of an atmospheric physical model. They are available on a regular horizontal grid, 4 times daily from the early 1970s to the present, so sampling issues are not limiting. However, because the analysed fluxes depend on uncertain parameterisations and do not satisfy global constraints, corrections - sometimes major - are needed. To advance, these corrections should be based on regional comparisons with independent observations. The use of the fluxes themselves effectively locks in the model SST, albedo and method of computing fluxes, and loses information on the atmospheric state, and complicates merging different data sets. It may therefore be preferable to use bulk formulas together with the flux parameters, which allows for greater flexibility in applying corrections. For example: locally, with adequate data, it seems possible now to determine surface heat fluxes to better

than  $\pm 10 \text{ Wm}^{-2}$  (Weller and Anderson, 1996) if the atmospheric state is known well enough. The major problems with surface flux estimates are systematic errors in the NWP products and inadequate observations in some areas. Since those are not a concern of NWP, it is up to CLIVAR to deal with it by determining the regional biases in the NWP flux parameters, such as near surface temperature, humidity, and wind velocity.

CLIVAR will also need to determine the best solar and long-wave radiation data sets and to establish any necessary corrections. Previous experience suggests that the parameter corrections are much larger than uncertainties in the bulk formulas that are used to transform them into fluxes. Therefore, the programme need not concern itself with the turbulent transfer coefficients. Fortunately, a great deal of data exist with which to attack the bias problem. Over the last several years an unprecedented number of wind speeds and velocities have been observed from satellites. These can be used to transfer standard wind measurements and to hence determine biases in NWP winds globally on scales of a few degrees. The analysis of weather observations from a select subset of North Atlantic volunteer observing ships (Kent et al., 1993) have been successful at identifying biases in the reported ship data, which can now be used to correct the NWP products. In addition, the data from field programmes with excellent meteorological measurements, such as FASINEX and Subduction, are available for this purpose. Because these verification data span a number of years, it will be most advantageous to correct the reanalysed NWP products, and so avoid complications due to changing operational models and procedures.

In addition to addressing the large scale heat flux and budget issues just discussed, CLIVAR requires focused process studies directed towards improving the understanding of the physical processes of air-sea coupling. These must address

- (i) the marine boundary layer of the atmosphere; the associated convective and baroclinic eddy processes that distribute heat and moisture vertically in the troposphere; their relation to SST and ocean thermal anomalies; and their impact on the large-scale tropospheric flow and, concomitantly,
- (ii) the upper boundary layer of the ocean; the cycle of mixing and restratification; the manner in which SST and the associated thermal anomalies are created by air-sea interaction; and quantification of, as a function of time-scale, the role of the ocean in the advection and transfer of heat to and from the surface, through subduction, Ekman layers, geostrophic eddies etc.

From analysis of existing data, and with a design that evolves through the implementation of D1, a 'skeleton' long-term measurement network for the Atlantic Ocean needs to be put in place so that the evolution of key oceanographic indicators can be tracked. Many requirements will be met through the implementation of CLIVAR sustained observations. North Atlantic enhancements for D1 will be required. Some additional possibilities are presented in the following sections.

#### 5.4.2 A DecCen "NAO Array"

Cayan (1992 b, c) showed that the pattern and amplitude of Atlantic winter heat flux is to a large extent driven by the NAO. Kushnir (1994) then demonstrated that winter SSTs in the subtropical and subpolar gyres were warmer during a 15 year period of relatively low atmospheric NAO index (1950-1964) than during a subsequent 15 year period of relatively high NAO index (1970-84). Hansen and Bezdek (1996) and Sutton and Allen (1997) later showed that Kushnir's warm and cold periods involved propagating warm and cold SST anomaly patches that move from year to year downstream along the gyres' circulation pathways. McCartney et al. (1997) explained the recurrence of these propagating SST anomalies by describing them as the surface expression of deep-seated anomalies formed by winter convection and mode water formation, and these processes, in turn, are controlled and orchestrated by the NAO (Dickson et al., 1996). The current wisdom is therefore that warm and cold SST anomalies track McCartney's "warm water transformation pathway" from the western subtropical gyre around the subpolar gyre to the Labrador Sea, reflecting anomalies of the heat content of deep winter mixed layers.

The process appears to begin with the advection of anomalously warm or cold western subtropical waters into the subpolar transformation pipeline. These advected heat anomalies are sequestered in the mode water, exposed to the atmosphere in winter, isolated by the seasonal thermocline during the warmer seasons, but reappear in subsequent winters, advected downstream (Alexander and Deser, 1995). Kushnir's warm and cold periods are thus revealed as periods of relatively warm and cold temperatures in the mode water along the transformation pipeline. When the warm water transformation pathway runs warm or cold, the end product of the transformation - Labrador Sea Water (LSW) - runs warm or cold also, resulting in an anomalously thin (warm) or thick (cold) LSW layer. These variations in LSW thickness have been found to impact the density structure of the western subtropical gyre with a time lag of 5-10 years (Curry et al., 1998).

There are potential feedbacks in this system. (1) By one theory, an increased southward transport of LSW in the DWBC may cause a southward shift of the Gulf Stream which "leaves behind" a large body of warm water in the subpolar gyre - an alternative origin for the warm water which sets the pipeline running warm in the first place. As the LSW becomes depleted, (taking, say 5-10 years to bleed out in the DWBC), the Gulf Stream returns to a more northerly path and the process reverses. (2) Interaction between thermohaline and wind-driven flows may have other effects. For example, the southward propagation of LSW thickness changes and their degree of entrainment into the deep Gulf Stream are thought to have an impact on the stability characteristics of the western boundary current with effects on its downstream intensity (Spall, 1996). (3) The baroclinic expression of the ingestion of SST and heat anomalies by the subpolar gyre is a potential energy anomaly difference between the subtropical and subpolar gyres which should also effect a change in the eastward upper-ocean transport along the gyre:gyre boundary. For this reason, McCartney refers to the upper ocean potential energy anomaly difference between Bermuda and BRAVO as an "Oceanic NAO Index" (updated in Fig. 5.5) and notes that it appears to lag the atmospheric NAO signal by a few years.

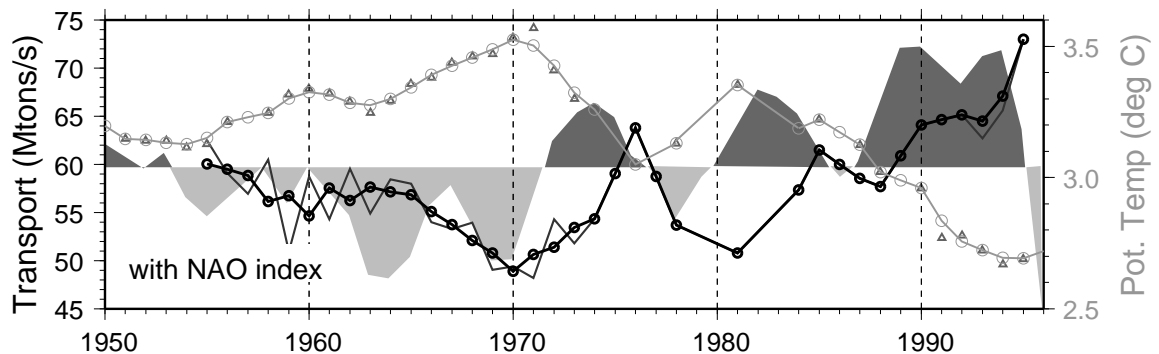


Fig. 5.5: Ocean temperatures and transports related to the NAO: A low-passed winter NAO index (Hurrell, 1995, dark gray=high, light gray=low) is plotted against the variation in the temperature of deeply convected water in the Labrador Sea (light grey line, right scale). Also plotted is the variation in eastward baroclinic transport of the Gulf Stream/ North Atlantic Current, as indexed (heavy black line, left scale) by potential energy anomaly differences between the Labrador Sea and Bermuda (an oceanic analogue of the atmospheric NAO index). The warming temperatures before 1970 (low NAO index) and cooling thereafter (high NAO index) are also reflected in subpolar SST. These changes are the underlying cause of the Cold Ocean part of the "Cold Ocean - Warm Land" (COWL) pattern (Wallace et al., 1996) in the Atlantic sector in the past 25 years. Oceanic transports appear to lag the NAO by 4-5 years, and decline with the warming Labrador Sea (and general subpolar SST) and declining NAO index of the 1950's and 1960's. The oceanic transports rise again with the cooling Labrador Sea (and general subpolar SST) and strengthening NAO index of the 1970's, 1980's and 1990's (until the abrupt shift of winter 1996). The 0.8°C temperature range of this large pool of subpolar water, and the fluctuation range of more than 30% in circulation intensity are some of the indications of a powerful participation of the ocean in this North Atlantic Atmosphere-Ocean Oscillation (from McCartney et al., 1997, see also Kerr, 1997).

### III. The CLIVAR Principal Research Areas

Other variants and theories certainly exist - e.g. the westward and southward propagation of SST anomalies by topographic and/or planetary waves (Greatbatch and Peterson, 1996). However, the “oceanic NAO index” and the evidence connecting SST history to warm water transformation through winter mode-water convection encompasses much of our present evidence/ideas, and indicates a monitoring strategy.

XBT programmes have much value, but are ultimately limited in utility: Mode water convection often exceeds the depth range of even the 760m version of XBTs so that although they can provide a good measure of mode water temperature, such measurements do not reach the thermocline and thus cannot comment on the baroclinicity of the thermocline beneath the mode water. Additionally, salinity variations are believed to exert a significant control on buoyancy-driven convection. Thus temperature alone is insufficient and this will be particularly true in the case of the highly-variable thermocline T-S relation in the eastern Atlantic where the warm subtropical waters sweep into the subpolar gyre. GOOS might eventually help to establish an upper ocean Atlantic climatology, and the WOCE ACCE experiment is already experimenting with a large deployment of PALACE floats as one means of supplementing XBTs to provide improved space- time coverage of upper ocean hydrography.

An alternative approach is to provide high time-resolution full-depth (not available from PALACE floats) hydrography at a few key locations, analogous to the old OWS's (or the continuing Bermuda and OWS M time-series) to supplement the sparser time resolution of XBTs, profiling floats and intermittent hydrographic sections. Given the slow covariant evolution of ocean signals, described above, we suggest that a sparse inter-gyre network of moored deep-parked profiling CTDs (such as the WHOI Moored Profilers, prototypes of which have been tested off Bermuda and now in the Labrador Basin), can assess the evolution of temperature and salinity content in the mode water and thermocline, as well as describe the seasonal capping of the system.

Analogous to Fig. 5.5, pairs of such moorings can simultaneously provide indices of baroclinic advection between key points in the transformation pipeline. We suggest a total of seven deep-moored profiling CTDs (illustrated in Fig. 5.6, though in strongly-sheared regimes, as some of these are, the spatial variability may need to be determined before a representative monitoring site can be chosen):

- (i) The existing BRAVO site in the central Labrador Sea. Though this site lies east or southeast of the maximum winter heat flux (da Silva et al., 1994), the merit of extending an existing long time-series is the deciding factor in a study which depends so strongly on identifying decadal change.
- (ii) Assuming Bermuda (Station S) continues to be ship-based, we would pair it with a second moored profiler on the Slope north of the Gulf Stream (say in 4000m southeast of Woods Hole). This would simultaneously monitor the evolution of the deep water brought south in the DWBC and provide a direct measure of the expected response (Spall, 1996) in terms of the changing dynamics and stability of the eastward flowing Gulf Stream jet.
- (iii) A third moored profiler at the offshore side of the DWBC south of Cap Hatteras to investigate the phase-lag of DWBC signals, and the waxing and waning of the LSW signal for comparison to that north of the Stream.
- (iv) A ship-based Canaries series to couple with the Bermuda site (also ship-based) to provide a subtropical gyre index, a record of subducting watermass changes in the eastern subtropics, and a measure of the expansion and contraction of LSW influence on Upper North Atlantic Deep Water.
- (v) Since the circulation bifurcates at the tail of the Banks, the subtropical gyre east of Newfoundland does not track the GS well. To monitor the split between the Gulf Stream recirculation and the Azores Current versus the northward then eastward North Atlantic Current (NAC), we propose two further moored profilers, one in the central Newfoundland basin (Worthington's mythical Dram Bouie Island!) the other near the Grand Banks. Again, analogous to the Bermuda-Slope pairing ((ii) above), this would provide an NAC Index as well as recording watermass property changes in the southward-flowing DWBC.

## A tentative NAO Array

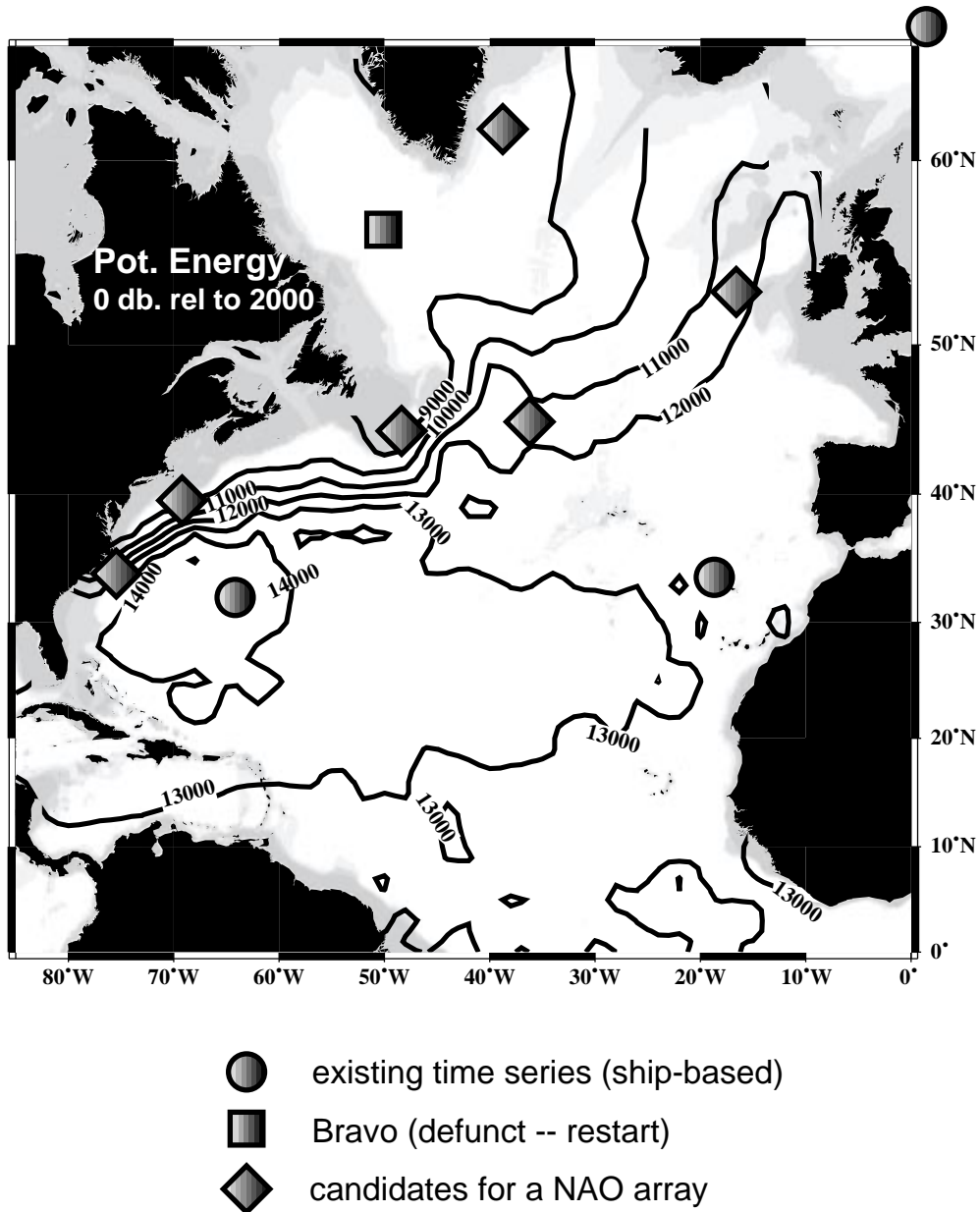


Fig. 5.6:

Potential energy anomaly 0 - 2000 db for the climatological average North Atlantic, a baroclinic transport streamfunction for that layer relative to 2000 db. The positions of a DecCen "NAO Array" of moored profiling CTDs are indicated by different symbols. In Fig. 5.6 the time history of baroclinic transport from time-series at two of these locations is shown. A complete array would add tropical subtropical sites south of 30°N to include the whole ocean decadal variability implied by the coherent SST whole-ocean fluctuations described by Kushnir (1994, 1996) and Sutton and Allen (1997), and be co-ordinated with the CLIVAR Programme on American Monsoons (G3) and Tropical Atlantic Variability (D2).

### III. The CLIVAR Principal Research Areas

- (vi) A further moored profiler is suggested for the Rockall area of the Eastern Atlantic, to index the baroclinic gyre between there and BRAVO and to characterise the warm water flowing north in the transformation pipeline west of Ireland.
- (vii) The final moored profiler is suggested to lie at the East Slope of Greenland, placed to sample the Irminger Current as the watermass entrained by the Denmark Strait overflow.

Other pairings of these sites may of course turn out to have value. Together they should reveal the time lags of propagating warm water disturbances such as the warm anomaly of the 1950's and 1960's, or the southward return to the subtropical western boundary regime of the transformed products, as in the case of the recent southward invasion by a very cold and thick LSW layer. This "NAO Array" should therefore be directly aimed at the central question that links NAO to CLIVAR - whether (and how) the ocean temperature field might feed back to encourage recurrent behaviour in the NAO.

Compared with the single Bermuda-BRAVO pairing available at present, the greater redundancy provided by this network will also be of value. Since there is no single spectral peak in the NAO, there might in fact be more than one feedback process involved. Further unknown processes are the draining of Labrador Sea Water from the centre of the Labrador gyre by horizontal exchange processes (the Labrador Current is observed to vary with the NAO; Myers et al., 1989), the role of deep narrow boundary currents in transmitting the convective water mass signals into the oceans interior, and the fluxes of fresh water from run off and sea ice from the high latitudes. Most of these processes are not well captured in coupled models, and must be covered in our fieldwork.

We suggest that the evolution of temperature and salinity content in the mode water and thermocline that our "NAO Array" is designed to monitor should be supplemented by one or both of two large-scale process experiments:

- a revived and updated CAGE experiment, in which a large volume of atmosphere and ocean (the North Atlantic) is cordoned off in attempt to budget its total heat content, and
- a lagrangian study which would enter the CAGE to follow mode waters around McCartney's transformation pipeline over a succession of winters, evaluating their subduction, obduction and transformation directly.

#### **5.4.3 Water mass conversion processes in the subpolar North Atlantic: A Lagrangian process study**

To investigate the mechanisms for converting warm subtropical waters into cold subpolar water masses and to understand the propagation of persistent sea surface temperature (SST) anomalies around the North Atlantic, a series of wintertime convection experiments will attempt to follow SST anomalies around the subpolar gyre. Each year, an Eulerian array would measure the evolution of upper ocean temperature and salinity profiles throughout the winter at the centre of an SST anomaly (using, for example, a moored CTD profiler) and the air-sea heat and freshwater exchanges over the anomaly from surface buoy measurements. After the first and subsequent winters, the Eulerian array would be moved to follow the SST anomaly so that a Lagrangian profile of the conversion processes over the pathway of the SST anomaly through the subpolar gyre would be built up. If an SST anomaly can be followed over five winters, such a combined Eulerian-Lagrangian experiment should contribute toward understanding what determines the trajectory and the persistence of SST anomalies that play such a large role in North Atlantic climate variability.

For each year's experiment the central question is to delineate how the strength and depth of oceanic convection during each winter depend on the entrainment of the thermocline stratification below and on the intensity of air-sea exchanges due to atmospheric wintertime climate and storms. Over five years, the SST anomaly should be sampled from its entrance into the south-east subpolar gyre, around its counterclockwise trajectory, ultimately to the region of deepest convection in the Labrador Sea leading to an understanding

of how the temporal and spatial variations in thermocline stratification and atmospheric exchanges break down or enhance the anomaly and of how the SST anomaly affects the atmospheric circulation and climate as a function of its position within the subpolar gyre.

How to follow the propagation of an SST anomaly is the critical issue for there is little understanding at present of what property an anomaly tracks. After the first winter's measurements, an estimate for next winter's location of the anomaly might be initially made on the basis of Hansen and Bezdek's analysis of past events. Development of coupled model studies including anomalies should also help to define what path the anomaly might travel. For example, the SST anomaly might follow surface currents, or the advection speed of water masses at the base of the deepest wintertime mixed layer, or the barotropic Sverdrup circulation velocity, or the advection - propagation speed of a thermocline anomaly say in potential vorticity. Floats and tracers would be injected into the anomaly at the end of the first (and subsequent) winter's experiment in order both to test the model predictions and also to develop an observational basis for understanding the eventual trajectory of the anomaly.

#### 5.4.4 Repeat CTD-tracer sections

To supplement the "NAO array" described above, the occupation of a number of relatively short repeated hydrographic stations is recommended. They cross the western and eastern boundary currents and have been occupied during WOCE. They could be worked in conjunction with the servicing of the DMPCs and would provide useful opportunities for float and drifter deployments.

The initial recommendations are:

- (i) Carolinas to Bermuda (WOCE AR3)
- (ii) Nova Scotia to Bermuda (WOCE AR3)
- (iii) Grand Banks eastwards (Western end of WOCE A2/AR19)
- (iv) Rockall to Greenland (WOCE AR7E)

Several of these form parts of existing long range transocean CTD-tracer sections which we recommend to continue in CLIVAR. These are after all the means by which we have hitherto tracked the trans-Atlantic spreading of the products of deep convection. However, repeat transocean research vessel sections are expensive, and we restrict ourselves to 3 which already have multi-year records and lie at critical locations to address the aims of both the thermohaline circulation and the NAO in CLIVAR.

The 3 transocean sections of prime importance are these:

- (i) WOCE Section A2/AR19 or similar. A section to determine the exchanges between the subpolar and the subtropical gyres of the North Atlantic, and to monitor the export of North Atlantic Deep Water along the deep western boundary. This section (WOCE section A2) runs from the English Channel to the tip of the Grand Banks. About 7 transects will have been carried out when WOCE is terminated, and its western end has had good hydrographic coverage over past decades, revealing significant decadal circulation variability. Hence, we have a good basis for optimising the design of future repeat workings in CLIVAR. This section also meets requirements for D3.
- (ii) WOCE Section A1E/AR7E or similar. A section across the subpolar North Atlantic at 55-60°N for monitoring the source regions of NADW and the spreading LSW plume. It would cut through the deep boundary currents east of Greenland and east of the Midatlantic Ridge that are fed by the overflows, and in the East Atlantic, transects the north-flowing NAC, thus covering the warm water flowing into the subpolar gyre west of Ireland in the mid-section of the mode-water transformation pathway.



- (iii) A transect through the centre of the Labrador Sea from the Labrador Coast through the location of BRAVO to Cape Farewell, A1W/AR7W.

Similar to the old Ice Patrol section, and so with long records of good quality data to comment on decadal changes. Extends the BRAVO series in passing and sets it into its regional context. The LSW is the end-point of the transformation pathway, the greatest source of deep decadal change accessible to the open North Atlantic, exerts a major influence on density structure and circulation of the subtropical gyre, and is closely linked to the NAO in terms of the depth and intensity of LSW production.

To an unknown extent, these few sections might be reinforced using vessel of opportunity (VOS) sections with deep XBT or XCTDs. The special focus of the “NAO array” on baroclinic transport suggests the occasional use of XCP’s from such vessels, preferably coupled to ADCP, to make infill estimates of the baroclinic transport and its changes to 1600m over key places and times.

#### 5.4.5 Inventories of deep and intermediate watermass changes

Inventories of hydrographic and tracer properties to assess volumetric changes and formation rates of the intermediate and deep waters of the Atlantic will be necessary to both the NAO study and the thermohaline circulation study within CLIVAR. From past individual sections, or for restricted areas of ocean such as the deep Greenland Sea, we have been able to determine that multiannual variations in mode water production do occur, and that regionally, their production may be co-ordinated by the NAO. But their three-dimensional nature could not be determined, and the link from intensified mode water production to a change in the intensity of the thermohaline circulation has yet to be made. Sampling intervals for such quantities may have to be shorter than 10 years and more intensive in space if this connection is to be demonstrated outside models.

#### 5.4.6 The Greenland Sea and its overflows

Though separated from the open North Atlantic by the Greenland-Scotland Ridge, changes in the convective centre of the Greenland Sea are still thought to exert a sufficient control on the T and S characteristics of the Denmark Strait and Faroer Bank Channel overflows to produce regional and inter-ocean changes in the thermohaline circulation. Since the convective changes in the Greenland Sea are thought to be a function of the NAO (e.g. Dickson et al., 1996), it becomes a part of the NAO study within CLIVAR to monitor both the source and the outflow.

To monitor the source, the German scientists F. Schott and J. Meinke plan to maintain a full depth multi-year mooring in the centre of the Basin at 75°N 2°W carrying multiples of Aanderaa current meters, an ADCP and SEACAT salinity sensors. To set the basin-wide context, the Institut für Meereskunde, Hamburg and the Alfred-Wegener-Institut, Bremerhaven will work an annually repeated CTD and tracers section across the basin along 75°N.

Monitoring for interannual and decadal changes in the transport and hydrographic character of the outflow will be carried out by direct long-term current measurements in the core of the near-bottom overflow from the Denmark Strait, on a single array normal to the E. Greenland slope off Angmagssalik. The initial deployment period is three years, but with the intention from the outset of extending to 10 years in order to capture the quite separate dynamics that are likely to operate over decadal time scales. The need to sustain this effort for a decade and the vigorous nature of the current dictated the use of a simple low-drag, near-bottom, six mooring array of three current-meters per mooring, supplemented by additional measurements of the thickness of the overflow plume using a combination of bottom-mounted Inverted Echo Sounders at 12 kHz and broad-band ADCP at 150 kHz. The work was initiated under the SIO-LDEO Consortium on The Ocean’s Role in Climate (CORC) and continues as a collaborative element of the MAST-III VEINS programme (Variability of Exchanges In Northern Seas), between three funding partners (B.

Dickson, MAFF, UK; J. Meincke, IFMH, Germany; and P. Malkki of MRI, Finland). Seasonally-repeated CTD-tracer sections by S. Malmberg, IMR, Reykjavik, will monitor changes in the hydrographic characteristics of the overflow and its local entrainment. The long-term measurement of these exchanges, their variability and the forces which control them is of central relevance to climate over a range of time- and space-scales.

Overspill of SF6 from the 1996 deliberate tracer release experiment in the Greenland Sea under the ESOP-II (European Subpolar Ocean Programme) initiative of MAST III will for a while act as a link between the two sites.

### 5.4.7 The Arctic response to NAO forcing

The case for including an Arctic Ocean component in this section of the CLIVAR plan is clear. First, as already described (Section 5.1.2), a significant fraction of the hemispheric warming trend appears to be associated with an amplification of the NAO in recent decades and there is considerable activity in ACSYS sorting out the role of the NAO on Arctic climate variability. Second, a range of models predict that the warming effect of anthropogenic forcing will be maximal in the high Arctic (e.g. IPCC, 1996, their Fig. 8.12), especially in winter (IPCC, 1996, Fig. 6.10). Third, the Arctic Ocean lies squarely within the domain of the NAO (Hurrell, 1995, his Fig. 1b, 3b). If these three facts do not yet form a seamless argument, it is largely through our ignorance of their connective processes.

Fourth, the NAO appears to exert a significant control on the export of ice and freshwater from the Arctic to the open Atlantic, which with other more localised effects further south, are thought to promote significant changes in the “headwaters” of the global thermohaline circulation (thermohaline circulation; see Chapter D5). During the extreme low-index conditions of the 1960s, for example, characterised by an intense northerly airflow along the eastern flank of a record Greenland Ridge, an extra 2000 km<sup>3</sup> of ice and freshwater were brought south from the Arctic Ocean in a swollen East Greenland Current (Aagaard and Carmack, 1989), convection in the Iceland Sea became capped (Dickson et al., 1988), and convection in the Greenland Sea reached to record depths (>3500m; Dickson et al., 1996), all essentially from the same cause and all with potential knock-on effects on the Denmark Strait Overflow and hence on the production and characteristics of North Atlantic Deep Water.

Identification of a time-dependent NAO response in the Arctic Ocean should concentrate on two main tasks:

1. Repeat Trans-Arctic Sections: The first modern trans-Arctic CTD-tracer section worked by Canadian and US icebreakers in 1993-94 revealed considerable differences in watermasses, circulation, exchange and ventilation rates between the four sub-basins, and compared with earlier transects, showed spectacular interannual changes, particularly to the mid-depth temperature field. Over the Lomonosov Ridge, Atlantic Layer temperatures had risen by 0.5°C since 1991, and the extent of the warmest Atlantic-derived waters had clearly broadened (Swift et al., 1997; see also Carmack et al., 1995; McLaughlin et al., 1996; Kolatschek et al., 1996 and Carmack et al., 1997). Such changes are plainly relevant to our understanding of global-change impacts in this climatically sensitive zone, but their large-scale nature precludes monitoring at a point or points. Repeat multi-tracer trans-Arctic sections at intervals of a few years seem the most cost effective way of building this understanding.
2. Monitoring the Fram Strait Ice-flux: The flux of ice and freshwater through Fram Strait is a key CLIVAR/ACSYS variable, reflecting the net production of ice in the Arctic Ocean, integrating (we suppose) the effect of a range of climatic impacts in the Arctic, quantifying an important component of the Arctic Ocean heat budget (due to the heat of fusion lost during freezing) and producing changes in the hydrography of the Northern Gyre and possibly of the thermohaline circulation downstream. Monitoring the ice-flux with modern techniques has proved possible since 1990 (Vinje et al., 1998), and its two main component tasks should be maintained and supported throughout CLIVAR. These are:

- *Upward Looking Sonar (ULS)*: Following the first successful year-long trials in 1987-88, regular annual series of ice draft observations have been obtained from the Fram Strait since 1990 using moored Norwegian (ES-300, CMR, Bergen; 300mHz), US (ULS Mk2, APL, Seattle) and Canadian (IOS, Sidney) instruments. These provide frequent point measurements of ice-draft, floe size and velocity, and are equipped to correct for changes in the depth and tilt of the sonar head. Ice draft is related to ice thickness using a constant factor based on nearly 400 drillings in the Fram Strait in 1981-84 and subsequently, and should be typical for ice from the Arctic ocean (Vinje et al., 1998). As point measurements, however, a cross-channel ULS array is required to capture the spatial and temporal variability of ice-draft in an area as dynamic as the Fram Strait.
- *Remote sensing of drift speed*: The conversion of monthly mean ice-thickness into volume flux requires supplementary data on ice stream-width from ice maps, and mean ice velocities from SAR observations. Ice extent and ice concentration maps derived from satellite microwave radiometer data have been available for more than 20 years and are expected to continue in the outlook 10 to 20-year period - albeit at a resolution of 25 km. This should improve to 5 km resolution under plans for the forthcoming AMSR system on ADEOS II, thus helping to resolve the drift velocities of large floes. In the next decade the availability of satellite radar data is also expected to continue. The present RADARSAT may still function over the next five years. In its ScanSAR mode with a swath of 500 km, it covers the Fram Strait daily in a single pass at 100m resolution. From late 1999, ENVISAT with its Advanced Synthetic Aperture Radar (ASAR) is expected to have a performance exceeding that of RADARSAT and the present ERS AMI (Active Microwave Instrument), and will have a design-life of 5 years. And finally, there are plans for a RADARSAT 2 that may materialise early in the next century. Thus it seems the necessary instruments will be in place to contribute to the monitoring of Fram Strait ice-flux in CLIVAR/ACSYS, but present trends towards the commercialisation of data reception, processing and dissemination may yet mean that long-term monitoring such as we envisage here may be a costly exercise.

## 5.5 LINKAGES WITH OTHER ELEMENTS AND PROGRAMMES

### 5.5.1 Other elements of CLIVAR

- close links exist with focus D3 (Atlantic Thermohaline Circulation) because of the control of deep convection by the NAO and the contributions made by the products of convection to the DWBC, hence to the intensity of the abyssal limb of the thermohaline circulation/MOC. By affecting the character of the entrainment, changes made by the NAO in the near surface hydrographic characteristics of the Irminger Sea are also relevant to the fate of the Denmark Strait Overflow component.
- An obvious link exists between the NAO and D2 (Tropical Atlantic Variability). We take particular note that CEOF SLP analysis by Barnett (1985) shows a substantial subtropical signal following the NAO SLP march, while SST analyses with subsidiary SLP fields by Kushnir (1994, 1996) and Sutton and Allen (1997) show that on decadal time scales there is whole-ocean covariance, extending through the critical zone of northern tropical hurricane genesis to the equator, and in Kushnir's analysis, well south into the subtropical South Atlantic.
- some links exist also with A2 (prediction of climate change), for five main reasons. The NAO spectrum is showing increasing signs of organised multi-decadal behaviour; it is a major contributor to a major global climate trend (NH warming); the detailed study of storm-surface interactions (Sections 5.3.2 and 5.3.3 above) should directly guide model development; we are in prospect of a 1000 year proxy to NAO wintertime behaviour, which could indicate whether and how often the amplification of low-frequency NAO variability has happened before (i.e. whether it is likely to be natural or anthropogenic in origin); and the field plan should inform models on the key question of whether the surface temperature field can force protracted behaviour in the NAO.

- In its new draft Implementation Plan (ACCP, 1997), the Atlantic Climate Change Programme ACCP describes itself as part of CLIVAR. Certainly its aims, scientific rationale and the priority of its field objectives are synonymous with those of CLIVAR; the new report contains one of the clearest and most detailed expressions of the scientific case, an honest assessment of uncertainties, and a major and modern fieldwork plan which are all of primary relevance to CLIVAR.

### **5.5.2 Other WCRP programmes**

- The World Ocean Circulation Experiment (WOCE) has established a sound and modern observational base for determining the present state of the ocean circulation and properties, and will continue to inform CLIVAR during its Analysis, Interpretation, Modelling and Synthesis (AIMS) phase.
- There are currently about 20 ULS's monitoring ice draft in the Arctic Ocean under the WCRP Arctic Ice Thickness project (see section 5.4.5).

### **5.5.3 With European Union projects**

- Under the VEINS programme (Variability of Exchanges In Northern Seas) started in April 1997, 16 institutions from 7 nations will attempt to measure the ocean transport through all four of the gateways to Nordic Seas and over a long enough period to assess means and variability (up to a decade). VEINS 1, 2, 3, and 4 will cover respectively the Faroer-Shetland inflow, the Barents Sea throughflow, the Fram Strait throughflow, and the Denmark Strait overflow.
- The ESOP-II initiative aims to understand the thermohaline circulation of the Greenland Sea, its sensitivity and impact on the global ocean circulation, and includes a deliberate release of SF<sub>6</sub> into the convective centre of the Greenland Sea. Convective activity there is governed by the NAO, and the spreading of this tracer may be of value in the VEINS Denmark Strait component and downstream.
- The ECLAT Project, based at Climate Research Unit of the University of East Anglia (Norwich, UK), will provide an interface between individual EU climate change scenarios and observed climate data
- The EC-funded Arctic Radiation and Turbulence Interaction Study (ARTIST) will study boundary-layer phenomena in the Fram Strait using aircraft and satellite data and a wide spectrum of instruments, from 1997 to 2000-01.
- The Mile Clim EU project will study the climate variability over the North Atlantic and western Europe over the last millennium.

### **5.5.4 With other ongoing or planned national programmes**

- Process studies on Labrador Sea deep convection and its integral effects on water mass transformation are carried out by the USA, Canada and Germany during 1996-98.
- The major 5-year SHEBA project (Summer Heat Budget of the Arctic) of NSF-ONR aims to develop, test and implement models of arctic ocean-atmosphere-ice processes that demonstrably improve simulations of the present day arctic climate, including its variability using GCM's. It has therefore much in common with the aims of the CLIVAR modelling component.

### *III. The CLIVAR Principal Research Areas*

- The Central Greenland Ice Sheet Project (GISP-2) and GRIP continue to provide a proxy for long-term NAO behaviour based on the time-dependence of a suite of stable isotopes, including deuterium excess which may reflect the impact of regional changes in ocean conditions
- The NOAA funded SIO-LDEO Consortium on the Ocean's Role in Climate continues its 1994-97 science plan, albeit at a reduced level of funding, including partial support for monitoring the Denmark Strait outflow. Its aims of understanding decadal and abrupt climatic change are synonymous with those of CLIVAR.
- The Eulerian/Lagrangian Experiment described in Section 5.4.3 was first discussed at a UK CLIVAR meeting and the development of a prototype experiment will be part of a UK CLIVAR initiative now being developed.
- The German Sonderforschungsbereich (SFB) 460 "Dynamics of thermohaline circulation variability" is a multi-year study of convection, overflows and resulting water mass formation in the subpolar North Atlantic; its various observational and modelling components - changes in air-sea fluxes, their relation to large-scale atmospheric patterns (such as the NAO), water mass modification and upper ocean variability monitored by repeat sections, repeat convection moorings and a repeat tomography array in Labrador Sea are directly relevant to the questions of NAO forcing and modelling in D1. It started in summer 1996, with funding by Deutsche Forschungsgemeinschaft (DFG).

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## 6. TROPICAL ATLANTIC VARIABILITY (D2)

### 6.1 SCIENTIFIC RATIONALE

Extensive research in the last thirty years indicates a strong link between various climate-related disasters that occurred in countries surrounding the tropical Atlantic Basin and sea-surface temperature anomalies (SSTAs) in the tropical Atlantic Ocean. The well-known droughts of Northeast Brazil, for example, have been shown to be closely related to anomalously warm/cold SSTAs in the tropical north/south Atlantic Ocean (Hastenrath and Heller, 1977; Chu and Hastenrath, 1981; Moura and Shukla, 1981; Hastenrath, 1984a; Lough, 1986; Rao et al., 1993; Enfield, 1996; Harzallah et al., 1996). Droughts in sub-Saharan Africa are often found to be associated with a broad band of negative/positive SST. As across the tropical north/south Atlantic (Lamb, 1978 a, b; 1983; Hastenrath and Lamb, 1977a, b, and 1978; Folland et al., 1986). Rainfall variability in the Central American/Caribbean region appears to be related to tropical north Atlantic SST fluctuations (Hastenrath, 1976, 1984a; Enfield, 1996). The SST conditions in the tropical Atlantic can also have an impact on fisheries. For example, a dramatic decrease in alongshore pelagic fisheries in 1995 was found to be connected with the anomalously warm SST. Extensive bibliographies pertaining to devastating climatic phenomena in the tropical Atlantic and their major social, economic, and environmental consequences can be found in the monograph by Hastenrath (1985).

Considerable efforts have been made to identify preferred periodicities in the regional rainfall variability and the associated large-scale circulation, in part motivated by the desire for long-range prediction through spectral extrapolation. A preference for variability at quasi-biennial time scales appears to exist in many climatic elements and areas. The Brazil-tropical Atlantic sector is one of such regions where both the surface circulation and rainfall variability exhibit a quasi-biennial frequency peak (Hastenrath and Kaczmarczyk, 1981; Chu, 1984). A marked preference for variability around 13 years has also been indicated (Hastenrath and Kaczmarczyk, 1981; Chu, 1984). Additionally, there is an indication of a concentration of spectral power in rainfall around 27-28 years (Markham, 1974). In contrast, spectral peaks in sub-Saharan Africa rainfall variability are less pronounced. However, the persistence of drought and flood regimes is remarkable.

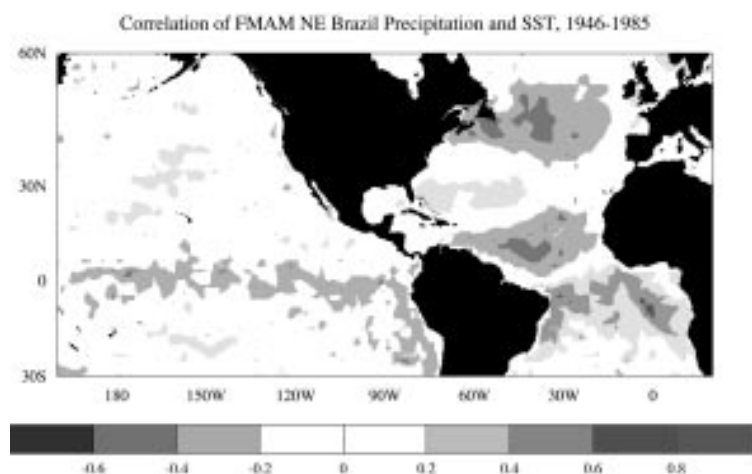


Fig. 6.1: Correlation between average February through May precipitation in northeast Brazil and sea-surface temperature. Shading indicates regions in which above-normal sea surface temperatures tend to be observed in conjunction with above (below) normal rainfall in Northeast Brazil. The strongest correlations are on the order of 0.5. Northeast Brazil rainfall tends to be more strongly correlated with Atlantic sea surface temperatures than with Pacific sea-surface temperatures. (From "Pan American Climate Studies: A Scientific Prospectus").

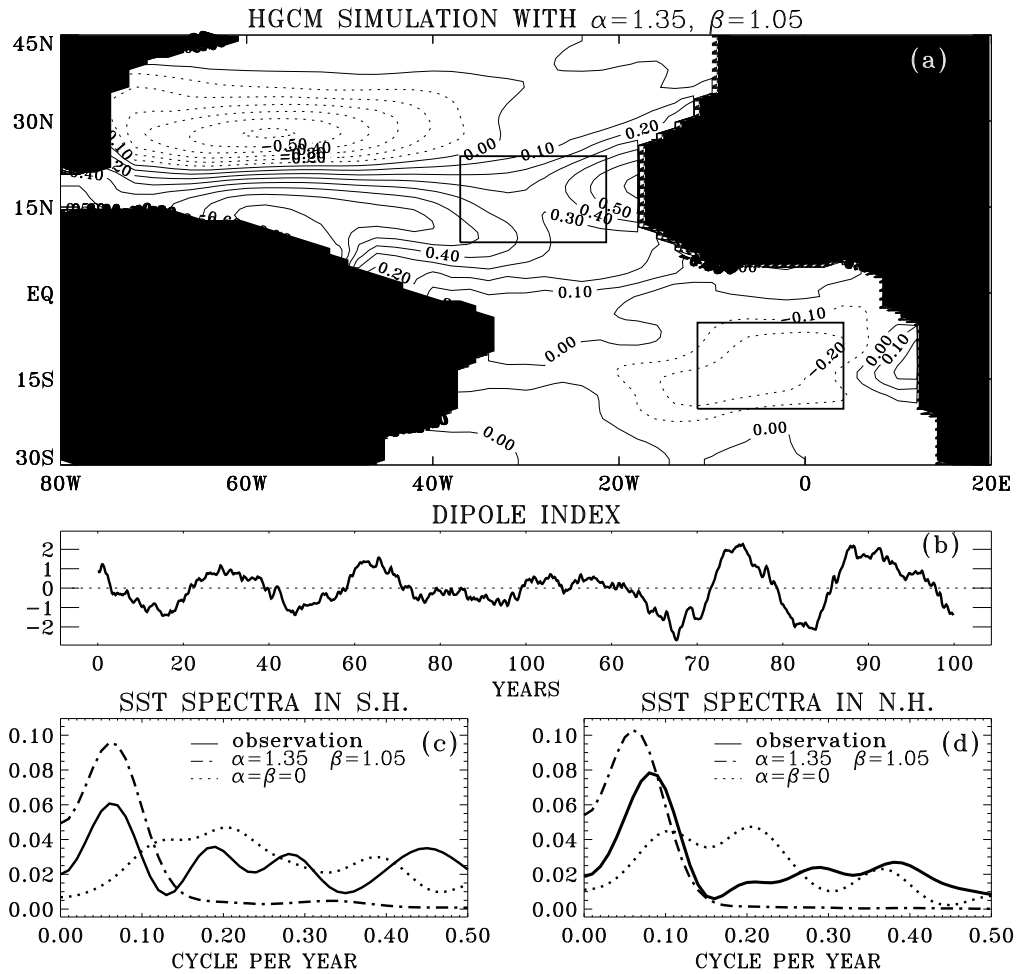


Fig. 6.2: SST fields simulated by a hybrid coupled general circulation model forced with wind-noise with both dynamic and thermodynamic coupling ( $a=1.35, b=1.05$ ). The dipole pattern shown in (a) was generated using a regression analysis with a dipole index shown in (b) derived by differencing the model SSTs averaged over a  $15^\circ \times 15^\circ$  area in each hemisphere indicated by two rectangles. The dipole pattern is insensitive to the choice of the index. The two areas were chosen because of the best availability of the 100-year SST observations in these regions. The 100-year (1890-1990) observed monthly mean SST time-series were derived based on the UK Meteorological Office Main Marine Data Bank by area-averaging over the two regions. The observed SSTs were compared with similar SST time-series derived from model simulations via a spectral analysis. The SST spectra in the Southern and Northern Hemispheres are shown in (c) and (d), where solid lines are for observations, dash-dotted and dotted lines are for simulations with  $a=1.35, b=1.05$  and  $a=b=0$ , respectively. The SST spectra were estimated using the Hanning window with a bandwidth  $M=240$  months and were normalised by their own variance. The standard deviations of the observed SST in the Northern and Southern Hemispheres are about  $0.5^\circ\text{C}$ . Similar values for the simulated SSTs are about  $0.3^\circ\text{C}$  for  $a=1.35, b=1.05$  and are less than  $0.1^\circ\text{C}$  for  $a=b=0$  (after Chang et al., 1997).

Of particular importance to the rainfall in Northeast Brazil and, to some less extent, the rainfall in the Sahel region of Africa is the variation of the interhemispheric SST gradient. Many empirical studies in the past have consistently shown an intimate relationship between Northeast Brazil rainfall and the surface circulation/SST anomalies in the tropical Atlantic. The composite of anomalously wet years minus the composite of anomalously dry years in Northeast Brazil yields a dynamically consistent picture: The Intertropical Convergence Zone (ITCZ) is displaced southward; south equatorial Atlantic surface waters are anomalously warm, while waters in much of the tropical north Atlantic are anomalously cold; positive/negative sea level pressure departures in the north/south tropical Atlantic drive a counterclockwise anomalous

surface circulation, weakening southeasterly trades south of the equator and strengthening Northeasterly trades north of the equator (Hastenrath and Heller, 1977; Markham and McLain, 1977; Moura and Shukla, 1981; Hastenrath, 1984a; Lough, 1986). More recently, Harzallah et al. (1996) and Enfield (1996) present evidence that Northeast Brazil rainfall is influenced by two different dynamical processes: on interannual time scales El Niño related SST anomalies in the tropical Pacific exert a strong “remote” influence on Northeast Brazil rainfall; on decadal time scales the variation of the interhemispheric SST gradient in the tropical Atlantic dominates rainfall dynamics. Fig. 6.1 shows correlation between average February through May precipitation in Northeast Brazil and sea-surface temperature anomalies in the eastern tropical Pacific and Atlantic. Consistent with the empirical analyses described above, the pattern in the tropical Atlantic Ocean exhibits a “dipole” with positive correlation values south of the thermal equator and negative values on the opposite side. It is obvious from Fig. 6.1 that Northeast Brazil rainfall tends to be more strongly correlated with Atlantic sea surface temperatures than with Pacific sea-surface temperatures. Furthermore, the pattern of alternating sign correlations extends from the tropics into the north Atlantic region. Namias (1972) pointed out that increased cyclonic activity in the Newfoundland area is statistically associated with positive rainfall anomalies in Northeast Brazil, suggesting a linkage between the “North Atlantic Oscillation (NAO)” and tropical Atlantic climate variability. Nobre and Moura (1984) find a standing wave train in the upper-air circulation over the Atlantic sector accompanied by Northeast Brazil rainfall anomalies. In summary, the coexistence of preferred time scales of variability in the tropical Atlantic and rainfall variability in surrounding continents is remarkable. The cross-equatorial SST gradient plays a key role in determining the regional climate variability surrounding the tropical Atlantic basin. However, the origin of the SST variability is not yet understood and has been the subject of considerable debate in recent years.

Two competing hypotheses have been put forward to explain the variability of the cross-equatorial SST gradient. One hypothesis postulates that decadal variations of the interhemispheric SST gradient stem from regional ocean-atmosphere positive feedbacks involving primarily SST and wind-induced latent heat flux (Chang, 1997; Carton et al., 1996). Although it is generally expected that air-sea heat exchange will be important in generating SST anomalies off the equator, Carton et al. (1996) demonstrate quantitatively that the wind-induced latent heat flux acts to enhance SST variability both north and south of the equator in the tropical Atlantic Ocean. Chang et al. (1997) further suggest that there is a mutual interaction between the wind-induced heat flux and SST in that the SST anomalies maintain the anomalous wind pattern and thus the surface heat flux anomalies, while ocean processes set the slow time scale of variability. Coupled model experiments indicate that in a realistic parameter regime the cross-equatorial SST gradient oscillates on a time scale around 13 years (Fig. 6.2) (Chang et al., 1997). Dynamically, this mechanism is consistent with the relationship between the rainfall variability and surface circulation revealed by the empirical analyses (Hastenrath and Heller, 1977; Markham and McLain, 1977; Moura and Shukla, 1981). It is noteworthy, however, that although this air-sea interaction hypothesis assumes that the circulations on both sides of the equator are related, it does not require that SST changes in each hemisphere must be simultaneous as in a perfect SST dipole. What is fundamentally important is the variability of the interhemispheric SST gradient.

The other hypothesis views that the development of SST anomalies on either side of the equator is dynamically independent and controlled by processes in each hemisphere (Houghton and Tourre, 1992; Enfield and Mayer, 1997; Mehta, 1998). Although principal component analysis indicates a dipole-like SST mode with a preferred time scale around 13 years (Hastenrath, 1978; Servain, 1991; Mehta and Delworth, 1995; Mehta, 1998) (Fig. 6.3), Houghton and Tourre (1992) argue that the SST “dipole” structure is not stable, because it can separate (under rotation) into modes where the explained variability is heavily weighted on one side of the equator or the other, suggesting a true SST “dipole” does not really exist. Recent studies indicate that tropical Atlantic SST and wind fields are regularly affected by Pacific ENSO on an interannual time scale (Hastenrath et al., 1987; Hameed et al., 1993; Nobre and Shukla, 1996; Enfield and Mayer, 1997). In particular, Enfield and Mayer (1997) show that the ENSO-induced Atlantic SST fluctuations lag their Pacific counterparts by 4-5 months and that the ENSO impact appears to be strongest in the western flank of the tropical north Atlantic. Mehta (1998) suggests that decadal SST anomalies travel into the tropical Atlantic from the extra-tropical Atlantic along the eastern boundaries of the basin. Penland and Matrosova (1998) present evidence that the tropical Atlantic dipole is a real phenomenon, but that the influence of the Pacific often disrupts the northern branch so that the dipole structure is “unstable”. Taking the viewpoint that SST anomalies occur independently on either side of the equator, the variation of interhemispheric SST gradient may not have preferred time scales. Therefore, this hypothesis postulates that variability of the cross-equatorial SST gradient is largely stochastic in nature.

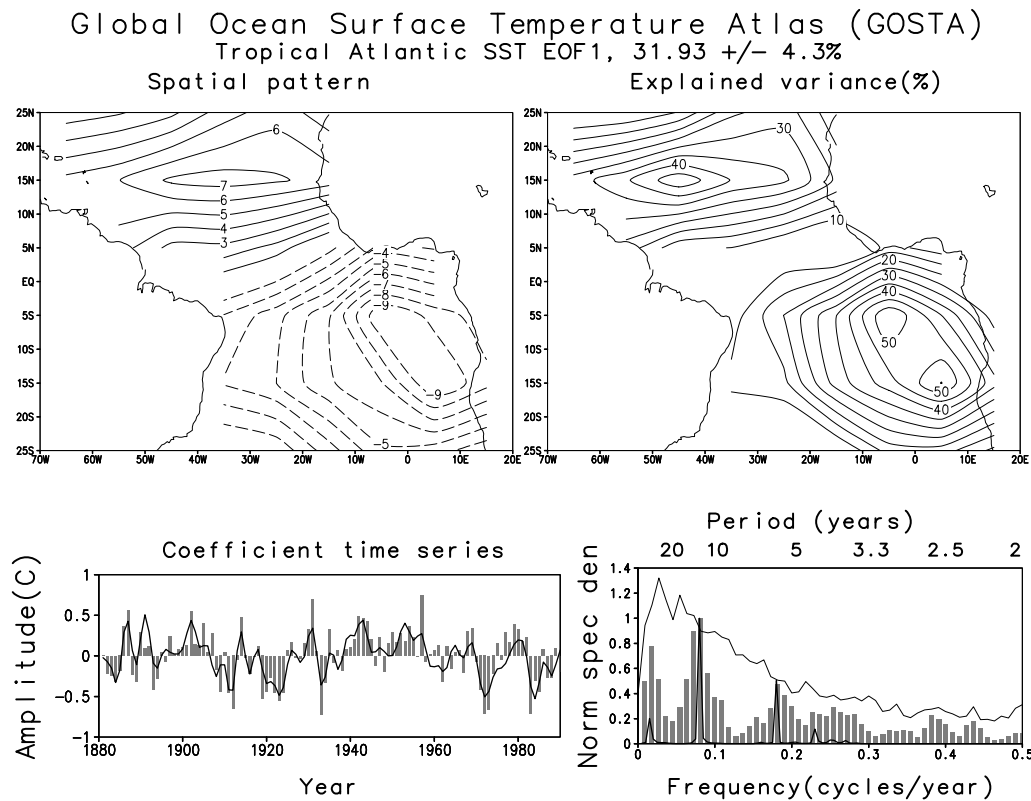


Fig. 6.3: Empirical Orthogonal Function (EOF) analysis over the domain 30°S - 30°N. Annual-average sea surface temperature anomalies from the GOSTA were used. (a) First EOF multiplied by 10 (contour interval one unit). (b) percent of the total variance “explained” by PC1 in each grid box (contour interval 10%, interval between thick and thin contours 5%), (c) first Principal Component (PC) amplitude (C) time-series, and (d) estimated normalised Fourier spectrum (bars) of the first PC amplitude time-series, the 95% confidence level (light line) for the Fourier spectral peaks obtained with the Monte Carlo technique, and the normalised maximum entropy spectrum (heavy line) of the SSA-filtered PC time-series (Mehta, 1998).

In addition to interhemispheric SST anomalies, a mode of variability similar to the Pacific ENSO has also been identified in the tropical Atlantic Ocean (Covey and Hastenrath, 1978; Philander, 1986; Zebiak, 1993 and Carton and Huang, 1994). Although it is much weaker than its Pacific counterpart, the Atlantic equatorial SST anomalies can have an effect on rainfall in the Gulf of Guinea (Wagner and da Silva, 1993). As in the Pacific, equatorial waves and remote wind forcing play a significant role in the generation of SST anomalies on the interannual time scale (McCreary et al., 1984; Hirst and Hastenrath, 1983 a, b). However, the Atlantic ENSO mode appears to be stable (Zebiak, 1993), as expected from delayed oscillator theory (Battisti, 1988). Hence, the Atlantic ENSO variability is likely to be forced by external stochastic forcing. Delecluse et al. (1994) suggest that the Pacific ENSO provides one possible source of external forcing for interannual SST variability in the eastern equatorial Atlantic.

Gu and Philander (1997) hypothesise that exchange between extratropical and tropical water masses through thermocline ventilation can cause decadal changes in the equatorial thermocline depth which in turn can modify ocean-atmosphere interactions and give rise to decadal SST variability. Hansen and Bezdek (1996) presented observational evidence of anomalous SST variability on decadal scales extending into the tropical Atlantic along the preferred path of the subtropical gyre. However, the full extent to which these tropical-extratropical ocean exchange processes affect Atlantic SST variability is unknown.

While air-sea interactions may be instrumental in determining the origin of the interhemispheric SST anomalies and rainfall variability in Northeast Brazil, other positive feedbacks involving processes over land may also play a role in the persistence of anomaly rainfall regimes in Sub-Saharan Africa and other

regions. Charney (1975) and Charney et al. (1977) propose a “biogeophysical feedback mechanism” in which deterioration of the vegetation cover over land can lead to a reduction of surface net radiation, which in turn enhances subsidence and reduces cloudiness and precipitation. The decreased rainfall would further diminish the vegetation cover and so on. Courel et al. (1984) present evidence of decreased albedo during dry season in the Sahel which is consistent with changes in plant cover. These land feedback processes need to be further examined in a fully coupled system.

Forecasting studies of the Atlantic climate variability are in their infancy, although a limited investigation has been made into the possibility of predicting rainfall (Hastenrath, 1984b, 1990; Ward and Folland, 1991; Folland et al., 1991; Hastenrath and Greishar, 1993; Graham, 1995) and of predicting tropical Atlantic SSTs (Chang et al., 1998; Penland and Matrosova, 1998). The rainfall prediction studies suggest that seasonal rainfall variability in Northeast Brazil is predictable a few seasons in advance when combined SST anomalies from both the tropical Pacific and Atlantic are used (Fig. 6.4). However, the Atlantic anomalies appear to have stronger impacts on the skill of these forecasts than the Pacific anomalies (Hastenrath, 1984b, 1990; Hastenrath and Greishar, 1993; Graham, 1994), confirming the importance of regional SSTs in the tropical Atlantic climate variability. Preliminary prediction studies using a regional coupled ocean-atmosphere model of the tropical Atlantic have indicated that the low-frequency SST variability in the subtropics of the northern Atlantic Ocean is predictable several years ahead, albeit at modest levels of skill (Chang et al., 1998) (Fig. 6.5). The results suggest that atmosphere-ocean interactions enhance predictability of the decadal SST variation beyond the persistence time, strengthening the air-sea interaction hypothesis. Penland and Matrosova (1998) and Chang et al. (1998) further argue that the remote influence of the Pacific, primarily due to ENSO, enhances the predictability of SST in the north Atlantic at short lead times ( $\leq 1$  year), whereas local ocean-atmosphere interactions dominate the predictable dynamics at longer time scales. Although these studies show promise for decadal climate forecast in the tropical Atlantic basin, the robustness of these results needs to be further examined. More importantly, it remains to be shown whether or not the prediction of decadal SST variability can improve seasonal rainfall forecasts.

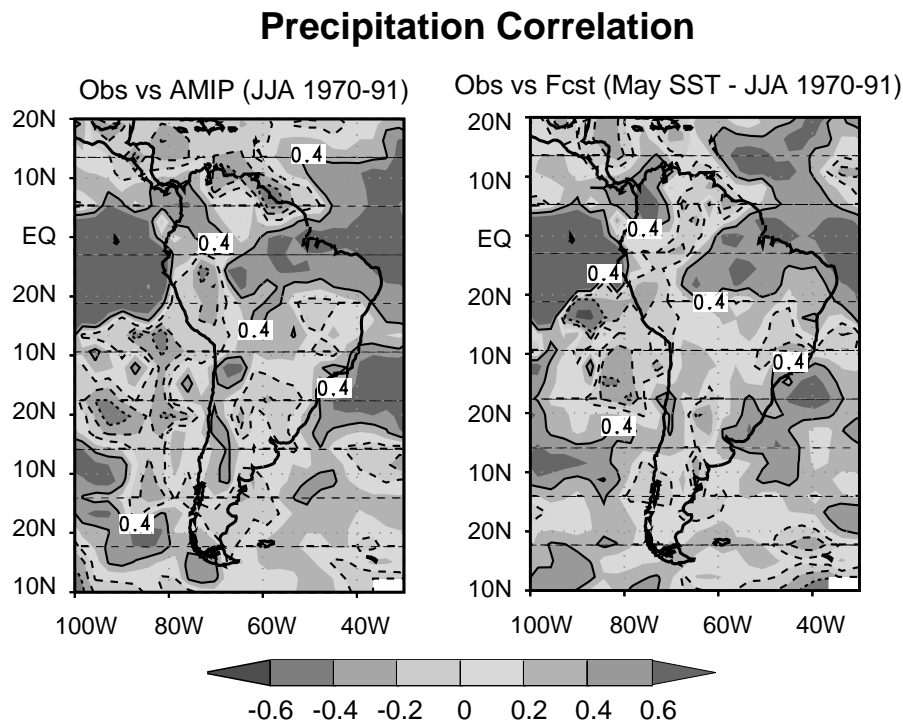


Fig. 6.4: Correlations between observed and simulated precipitation (upper) and between observed and predicted precipitation (lower). The simulated precipitation is based on an ensemble average of 5 runs of ECHAM3 GCM (T42L19) forced with the observed SST for JJA 1970-91. The predicted precipitation is based on the same atmospheric GCM using persisted May SSTs (Graham, 1994).



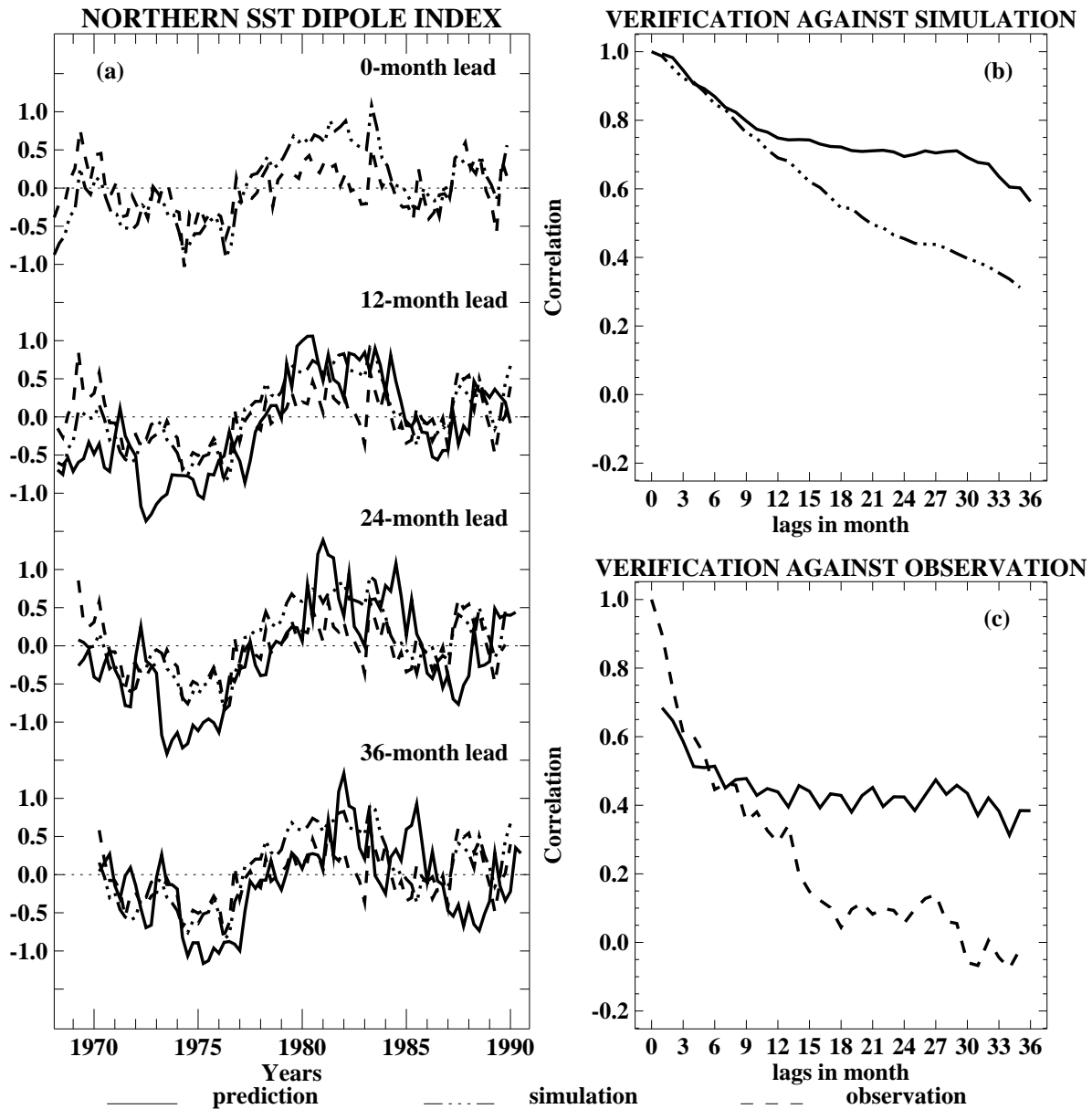


Fig. 6.5: Time-series of observed (solid), simulated (dash-dotted) and predicted (dotted) northern SST dipole index. The index was derived by spatially averaging SSTAs in a cross-basin latitudinal band between 6°N and 24°N and represent the variability of the northern component of the Atlantic SST dipole. The simulation and prediction were carried out by the same hybrid coupled model shown in Fig. 6.2. The indices are shown at lead time 0, 12, 24 and 36 months in units of °C for a 23-year prediction period (a). Correlations errors between predicted and simulated and between predicted and observed northern dipole SST index are shown in (b) and (c), respectively. Solid lines are predictions and dash-dotted lines are persistences. Results were based on 96 seasonal forecasts between 1967 and 1989 (Chang et al., 1998).

In summary, climate variability in the tropical Atlantic Basin and surrounding continents represent a well-defined climate problem in terms of the large-scale circulation and ocean-atmosphere-land interactions, that has an extraordinary economic and social impact. Considerable research effort in the past have offered some prospects of climate prediction in the tropical Atlantic region. However, many fundamental questions remain unanswered:

- (i) What are the physical mechanisms that cause the variability of the interhemispheric SST gradient? What is the dynamical relationship between the SST anomalies on either side of the equator? If these anomalies are independent modes of variability, what are the physical processes responsible for each of them, and do these anomalies interact? If so, how do they interact?
- (ii) What are the feedbacks among surface heat fluxes, winds, heat content and SST that attribute to low-frequency SST variabilities, especially the interhemispheric SST anomalies? What is the role of the ocean dynamics in off-equatorial SST variabilities? In particular, what is the relative importance between horizontal heat transport and vertical mixing/subduction processes? How important are cross-equatorial and cross-gyre exchanges? What is the relative importance between western boundary current transports and interior Ekman transports? What is the relation between SST and thermocline variability off the equator? Do oceanic waves play an important role in determining SST fluctuations in the tropical Atlantic Ocean?
- (iii) How important are “remote” influences versus “local” air-sea interactions in the genesis and evolution of the tropical Atlantic SST anomalies? If “remote” influences are important, where are their origins and through what physical processes do they exert their influences on the tropical Atlantic? Are there mutual interactions between the tropical Atlantic variability and NAO? What is the relative importance between the large-scale, low frequency “remote” influences and the random “weather” phenomena in the tropical Atlantic SST variability?
- (iv) What are the influences of continental heat sources on the tropical Atlantic SSTs? What is the role of land feedback processes, such as Charney's “biogeophysical feedback mechanism”, in the tropical Atlantic climate variability? How do these feedback processes affect ocean-atmosphere interactions in the tropical Atlantic?
- (v) What are the interrelations among the interhemispheric SST variability and the equatorial SST variability? What are the interrelations between interannual-to-decadal climate variability and the tropical annual cycle? Do they strongly interact with each other, and if so, how?
- (vi) Can we forecast decadal SST changes in the tropical Atlantic basin? Does the predictability of the Atlantic SST depend on the seasonal cycle? To what extent is the predictability of the interhemispheric SST anomalies affected by the equatorial variability and “remote” influences? Furthermore, can decadal prediction of SST improve rainfall and other climate forecasts?

## 6.2 MODELLING AND PREDICTION

Modelling studies in the tropical Atlantic Ocean, particularly coupled model studies, are limited at present. There are some stand-alone atmospheric and oceanic GCM studies in the tropical Atlantic basin (e.g. Moura and Shukla, 1981; Palmer, 1986; Philander and Pacanowski, 1986; Blanke and Delecluse, 1993; Carton and Huang, 1994; Carton et al., 1996). Intermediate and hybrid coupled models have been recently developed. Numerical experiments with these models show that these models are capable of capturing certain salient features of observed Atlantic SST variability (Zebiak, 1993; Chang et al., 1997, 1998). Long-term coupled global GCM simulations also reveal evidence of dipole-like SST variabilities in the tropical Atlantic Ocean (Mehta and Delworth, 1995), but physical mechanisms responsible for these variabilities are not fully understood. A general consensus emerging from modelling investigations is that surface heat flux is a major contributing factor to the SST variability off the equator, whereas wind forcing is the main source of the equatorial SST variability. However, there are many unresolved issues concerning generation and evolution of low-frequency SST variabilities in the tropical Atlantic that require further modelling studies. Modelling investigations in CLIVAR will be crucial in addressing important scientific questions such as:

1. What is the relative importance between regional air-sea interactions and remote influences?
2. Where are the origins of the interhemispheric SST anomalies?

### *III. The CLIVAR Principal Research Areas*

3. Can the tropical Atlantic SST variability be better described as a self-sustained oscillator due to unstable air-sea interactions or as a stable dynamical system driven by stochastic processes?
4. How do the tropical Atlantic SST anomalies influence the regional and global atmospheric circulations?
5. What are the factors that control air-sea fluxes, convection, and SSTs, especially the physical mechanisms that link anomalous SST with anomalous rainfall?
6. How important are land processes in determining rainfall variability?
7. What are the dominant oceanic processes that regulate low-frequency SST fluctuations in the tropical Atlantic?
8. What are the interrelations between the interhemispheric and equatorial SST variability, and how do they interact with the seasonal cycle?

Various modelling approaches are envisioned, with stand-alone atmospheric and oceanic models, as well as coupled models. For example, atmospheric experiments in which the evolving pattern of SST in different basins of the oceans is prescribed must be conducted to examine the atmospheric linkages between the tropical Atlantic and other ocean basins. Of particular interest is the examination of the atmospheric response to interhemispheric SST perturbations and its relation to rainfall variability in Northeast Brazil. These experiments will be crucial to improve our understanding of the underlying dynamics determining the surface circulation, surface heat flux and atmospheric connections between tropical and extra-tropical climate variability in the Atlantic. Oceanic experiments in which different forms of atmospheric forcing are specified in the tropical and extra-tropical Atlantic Ocean must be carried out to gain an understanding of oceanic processes that govern SST evolution and the importance of gyre exchange processes on tropical SST variability. Special emphasis should be placed on understanding the role of ocean dynamics in off-equatorial SST variability. A rigorous evaluation must be carried out to understand the oceanic conduit between high latitude processes and tropical SST variability. The extent to which thermocline ventilation in extra-tropical regions involving detrainment or subduction of mixed layer water and horizontal advection of the water along isopycnal surfaces may remotely influence the tropical thermocline must be carefully examined. Coupled model experiments must be performed with and without the influence of remote forcing to evaluate relative importance of regional air-sea interactions and the impact of SSTs in other ocean basins on tropical Atlantic SST variability. External forcing must include the deterministic forcing associated with climate anomalies, such as ENSO teleconnected into the Atlantic basin, and the stochastic forcing associated with dynamical instabilities internal to either the atmosphere or ocean. Co-ordination of these efforts with the CLIVAR NEG panels should prove to be beneficial and important.

Seasonal prediction of rainfall variability over Northeast Brazil has been carried out using both statistical and dynamical models (Hastenrath, 1984b, 1990; Ward and Folland, 1991; Folland et al., 1991; Rowell et al., 1992; Semazzi et al., 1993; Hastenrath and Greishar, 1993; Graham, 1994). These studies indicate that the rainfall variability in this region is predictable a few seasons in advance provided that accurate SST information in both the tropical Atlantic and Pacific Oceans is given. It is further shown that the skill of the rainfall forecasts depends more strongly on the Atlantic SST than its Pacific counterpart, suggesting the importance of the regional SST influences. Although operational SST forecasts are now being made routinely in the tropical Pacific, few attempts have been made to predict the Atlantic SST variability. However, recent forecast experiments using a coupled dynamical model of the tropical Atlantic Ocean and a statistical model show promise of decadal SST prediction in the tropical Atlantic Ocean (Penland and Matrosova, 1998; Chang et al., 1998). Prediction efforts within CLIVAR should be built upon current successes to further address issues such as:

1. How predictable are the interhemispheric SST anomalies, and how predictable is the equatorial Atlantic SST variability?

2. How can interannual-to-decadal prediction of SST in the tropical Atlantic improve seasonal rainfall and other climate forecasts?
3. What are the major factors that limit the climate prediction on seasonal-to-interannual and decadal time scale, and how do they differ?
4. To what extent is the predictability of the interhemispheric SST anomalies influenced by the equatorial SST variability and the seasonal cycle?
5. What impacts do the remote and stochastic processes have on the predictability of a climate system of the tropical Atlantic?
6. What observational data are needed for initialised coupled prediction models? How sensitive is the predictive skill of the coupled system to errors in initial conditions, and how can initialisation procedures be improved to minimise these errors?

Most present climate forecasting schemes in the tropical Atlantic are statistical (Hastenrath, 1984b, 1990; Ward and Folland, 1991; Hastenrath and Greishar, 1993; Penland and Matrosova, 1998). These statistical models have demonstrated respectable skills in seasonal rainfall forecast and have much to offer at present. Since these models use different variables than the dynamical models, they provide another view of the data which enhances our understanding of predictability. Furthermore, they set a measure of prediction against which dynamical forecast must be tested. Although dynamical models may ultimately prove superior for long-term climate forecasts, they are far from being perfect at the moment. Therefore, it is highly desirable to use dynamical approaches in conjunction with statistical methods. For example, a coupled-model prediction of tropical Atlantic SST might be used as input to a statistical procedure for forecasting seasonal rainfall over Northeast Brazil and the Sahel region of Africa. The feasibility of such a two-tiered approach (Bengtsson et al., 1993; Hunt et al., 1994; Graham and Barnett, 1994) needs to be explored for the tropical Atlantic climate prediction.

### 6.3 SPECIAL OBSERVING NEEDS

For the past 10-15 years, developing an observing system in the tropical Pacific Ocean for monitoring and predicting El Niño-Southern Oscillation has been a major focus of the international community (McPhaden et al., 1998). In contrast, the tropical Atlantic has received less attention. The most comprehensive observational study that has been conducted in the tropical Atlantic since the early 80s is the French-American FOCAL/SEQUAL experiment between 1982-84. The objective of that experiment was to improve our understanding of the seasonal cycle of the equatorial Atlantic Ocean. During the FOCAL/SEQUAL, intensive measurements of surface winds, subsurface thermal structure and currents were made along the equator for two years. Although these observations have played a vital role in advancing our understanding of the seasonal response of the tropical Atlantic Ocean to surface forcing (Philander, 1986; Katz et al., 1986; Katz, 1987; Richardson and Walsh, 1986; Richardson and Reverdin, 1987; Weisberg and Colin, 1986; Weisberg and Weingartner, 1986; Merle and Arnault, 1985), they are inadequate to address broad scientific issues concerning Atlantic climate variability because of their limited spatial and temporal coverages. Due to lack of sufficient long-term observations, there has been only a very limited number of quantitative studies of physical processes related to the low-frequency Atlantic SST variability. As a result, we do not completely understand how various atmospheric and oceanic processes contribute to changes in the tropical Atlantic SSTs and the associated air-sea fluxes.

The present suite of observations for the tropical Atlantic Ocean consists of

1. a volunteer observing ship (VOS) programme providing surface observations (SST, pseudo wind stress and surface salinity) and subsurface temperature observations (XBTs);

### III. The CLIVAR Principal Research Areas

2. coastal and island tide gauge stations which monitor sea level changes in certain regions of the tropical Atlantic Ocean;
3. satellite observations of sea surface temperature, topography, and wind velocity;
4. a small number of drifting buoys which give estimates of SST and surface current velocity.

These observations are required as part of the CLIVAR system of sustained observations. The observations that are presently being obtained are now being incorporated into quasi-operational assimilation systems for the tropical Atlantic Ocean in both the US and France. However, there are many problems with the existing observations. The VOS programme collects data only along well-defined shipping routes, leaving large data gaps between observations. The number of tide gauge stations are limited by the few islands in the tropical Atlantic Ocean and many of them are not optimally located for climate studies. Most drifting buoys exist north of 20°N, thereby providing little or no information near or south of the equator.

In the past several years there has been an important increase in the amount and quality of remotely-sensed observations of the tropical Atlantic basin. Satellite data products for the region include SST retrievals from NOAA/AVHRR, Meteosat, and ERS/ATSR. Sea surface topography information is available going back to the mid 1980's from the GEOSAT radar altimeter, and more recently from the ERS 1-2 and high precision TOPEX/Poseidon altimeters. Such measurements of sea level variability are expected to continue with the forthcoming launches of the GEOSAT Follow-On and TOPEX Follow-On (JASON) altimeter missions. Sea surface wind speed measurements have been available since 1987 from the passive microwave SSM/I sensor. Active microwave sensor, i.e. scatterometer, measurements of surface wind velocity are available from the AMI on board ERS 1-2 and from the NSCAT instrument launched on board ADEOS in August 1996. Remotely sensed measurements of ocean colour are now available, albeit with limited coverage, from the OCTS sensor on ADEOS, and more comprehensive basin-scale coverage of ocean colour is expected from the SeaWiifs satellite to be launched in 1997. These observations should prove useful for monitoring changes in oceanic primary production induced by the physical climate system and for delineating ocean circulation features such as the retroflexion of the north Brazil Current. Space-based estimates of precipitation at low latitudes become available after the launch of the Tropical Rainfall Measurement Mission in November, 1997.

Satellite observations, though providing estimates of some key surface variables with adequate spatial and temporal resolution, are incapable of providing direct measurements beneath the ocean surface. Moreover, *in situ* validation of these observations is often woefully inadequate. As a result, there are severe limitations with the existing observational data base in the tropical Atlantic Ocean which makes it inadequate to fully address important climate issues in this region. The lack of a sufficient observational data base in the tropical Atlantic will be partially addressed by a newly proposed observational programme, called PIRATA (Pilot Research Moored Array in the Tropical Atlantic). The objective of this programme is to improve our understanding of the seasonal-to-interannual climate variability in the Atlantic coupled system. The programme is intended to run from 1997-2000 with the full array being in place in the latter part of 1999. The moored array is an extension of the TAO Array in the tropical Pacific Ocean used to study ENSO (McPhaden, 1995). It will consist of 12 moorings, including one zonal mooring section along equator and two meridional mooring sections, one along 38°W between 4°N - 15°N and the other along 10°W between 10°S - 2°N (Fig. 6.6). The array will provide well-resolved time-series measurements of surface heat and moisture fluxes, SST and salinity, subsurface thermal and current structures up to 500m. These measurements are crucial to our understanding of contributions of various oceanic and atmospheric processes to Atlantic climate variability and for validation of remotely-sensed observations in the region. A more detailed description of the PIRATA array and present status of the tropical Atlantic observing system can be found in the Science and Implementation Plan for PIRATA (PIRATA, 1996). Obviously, this 4-year pilot study cannot address decadal climate variability in the tropical Atlantic Ocean, but it can provide a basis for a longer term monitoring system in that region. Therefore, it is highly recommended that PIRATA be used to assess the composition and feasibility of a more permanent observational effort within CLIVAR for the tropical Atlantic region. It is important for CLIVAR establish an observing system in the tropical Atlantic to meet D2 objectives after 2000 and it is considered likely that the PIRATA array will be part of that system and perhaps expanded to provide a wider coverage of regions of special interest. Specifically, the two me-

ridional mooring sections should be extended to higher latitudes (say 30°S - 40°N), in order to study the interactions between the tropical and extra-tropical oceans. If feasible, observations in the western Atlantic basin off the equator should be enhanced as these are the crucial regions where not only anomalous warm waters get stored preceding warm events in the Atlantic, but also the equatorial ocean circulation and the subtropical gyres mutually communicate. The enhanced observations will allow us to gain understanding of the relative importance of low-latitude western boundary current transport and interior Ekman transport in Atlantic SST variability. Last but not least, there is an urgent need for more high-quality observations in the southern hemisphere because analyses of atmospheric and oceanic observations in that region are presently notoriously bad. Adding more TAO-style moorings in the southern hemisphere would dramatically improve the estimates of winds, SST and particularly air-sea fluxes, which are crucially important for understanding and predicting low-frequency SST variability in that region.

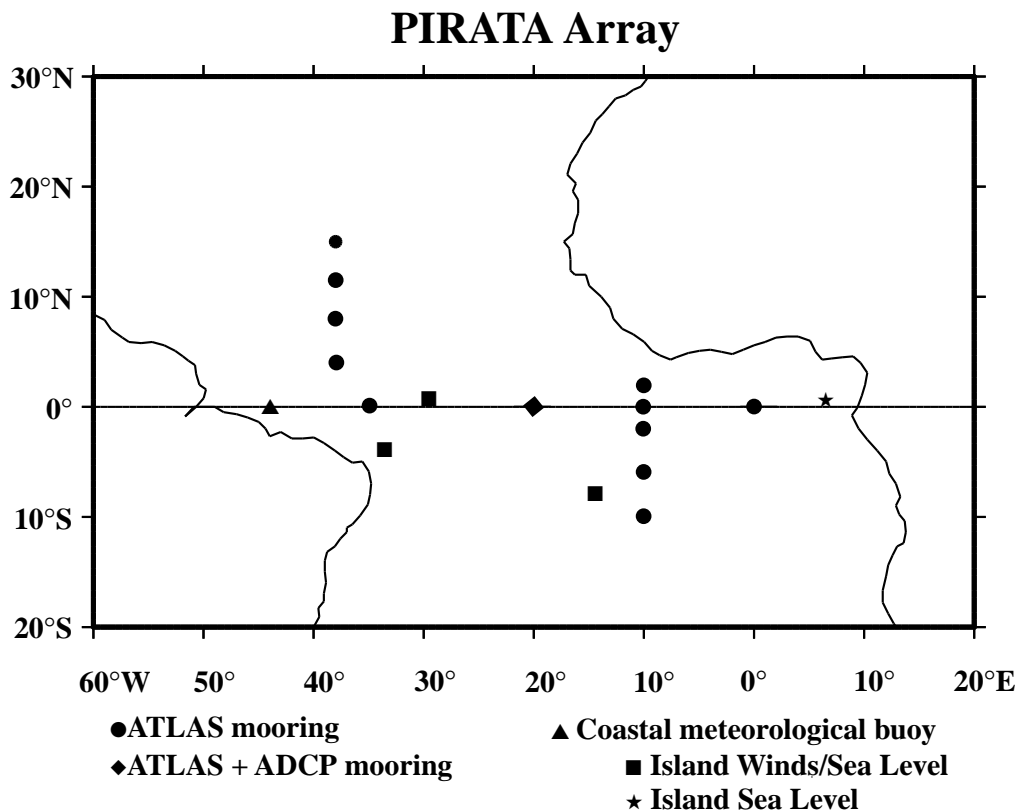


Fig. 6.6: The proposed PIRATA array in the tropical Atlantic Ocean (PIRATA, 1996).

## 6.4 FOCUSED RESEARCH PROJECTS

The CLIVAR process study projects in the tropical Atlantic Ocean should give the highest priority to the processes that govern SST variability in the off-equatorial regions that have large impacts on rainfall over the Northeast Brazil and Sahel region. These projects should elucidate the complicated physical processes in the coupled system and contribute to improved modelling of the coupled climate system in the tropical Atlantic region. The process experiments should include enough oceanic and atmospheric observations to support future model development and validation. The following are some specific physical processes pertinent to Atlantic dipole variability, and which are also important for a number of principal research areas that ought to be addressed by process experiments in connection with the modelling of atmosphere-ocean interactions:

1. Air-Sea exchanges processes

An accurate description of surface flux variability is crucially important for understanding and predicting SST fluctuations in off-equatorial regions. Neither COADS nor operational atmospheric models provide spatially complete and accurate surface flux fields. On the other hand, it has been shown that the surface heat flux can be measured *in situ* under most conditions with an estimated error of less than  $10 \text{ Wm}^{-2}$ . Combining accurate *in situ* observations of surface fluxes with measurements of upper ocean variables, such as temperature and salinity can help us to improve the parameterisation of surface fluxes on the one hand, and identify important air-sea feedback processes on the other hand. If feasible, process experiments should include a critical mass of atmospheric and oceanic observations to improve the description of the planetary boundary layer structure from the equator to subtropics.

2. Oceanic surface mixed layer processes

Most information about ocean-atmosphere interactions is stored in the upper ocean which is highly diabatic with strong mixing and transport processes occurring in both the surface mixed layer and thermocline layer just beneath. These processes determine not only how the ocean interacts with the atmosphere, but also how SST anomalies are regulated in the ocean. At present, there are large uncertainties in the implementation of boundary layer physics in many coupled ocean-atmosphere models for climate simulation and prediction. Developing a more realistic ocean mixed-layer model in ocean-atmosphere coupled systems for climate prediction requires a detailed description and knowledge about upper ocean boundary layer physics. A focused research effort in the off-equatorial region of the tropical Atlantic may be of particular importance to understand the role of ocean in Atlantic climate variability.

3. Interactions between the ocean surface mixed-layer and thermocline

Thermocline ventilation in extra-tropical regions involving detrainment or subduction of mixed layer water and horizontal advection of the water along isopycnal surfaces may remotely influence the tropical thermocline. Conditions in the tropical thermocline may influence local surface conditions that in turn affect the atmospheric circulation. It is possible that this variability of the tropical thermocline and associated changes in heat content may be a key element of decadal SST variability. However, the extent to which this tropical-extratropical ocean exchange process affects Atlantic dipole variability is unknown. Process experiments in conjunction with high-resolution ocean model simulation may be instrumental in addressing this issue.

## 6.5 DATA SET DEVELOPMENT, DIAGNOSTICS AND EMPIRICAL STUDIES

Development of reliable historical data sets is of vital importance not only for empirical studies, but also for model initialisation and verifications. It is thus critical for CLIVAR to support a comprehensive, long-term data set development effort. This effort in the tropical Atlantic should be prioritised according to its ability to improve 1) our understanding of low-frequency SST variability, 2) initialisation and verification of coupled model predictions: Follow up efforts that may be most beneficial to the study of Atlantic climate variability:

1. continuing the development of the Comprehensive Ocean Atmosphere Data Set, particularly SST, winds and surface heat flux;
2. consolidating various oceanic observational data sets for the Atlantic Ocean, such as, XBT, CTD, current meters, drifters, and tide gauges;
3. developing a comprehensive surface atmosphere and upper ocean data set in the tropical Atlantic Ocean based on PIRATA moorings and future expanded moorings;

4. compiling long-term rain gauge observations over Central and South America;
5. gathering various proxy data sources, such as corals, tree rings, and ice cores, for paleoclimatic reconstruction of variability in many aspects of tropical Atlantic climate.

The sparse long-term observations, especially in the oceans, impose severe limitations on applications of historical data sets to climate studies. Diagnostic analyses are essential to provide interpolation between, and extrapolation from, observations in order to provide estimates of climate system. One effective approach is to assimilate various historical data sets into a numerical model. An Atlantic Ocean assimilation system has been running in a quasi-operational mode at the NCEP. A retrospective analysis of XBT and SST observations for 1980-89 has been generated using COADS surface winds and heat flux. Future improvements of the system are planned, including a more sophisticated mixing parameterisation, and an updated assimilation system allowing the assimilation of satellite altimetry observation. Similar assimilation efforts in the Atlantic Ocean should be supported by CLIVAR. A strategy should be developed to assess advantages and drawbacks of the various assimilation techniques, as well as effectiveness of various observations in estimating the state of the ocean. Data assimilation may also be vital in preparing initial conditions for climate predictions in the tropical Atlantic. An optimal interpolation has been used to fill the data gap in the observed SST dated back to 1856 (Kaplan et al., 1997). Such a century long data set is invaluable for the study of decadal climate variability. Further studies are needed to assess the reliability of the interpolated data sets.

Instrumental data alone may not be enough to provide information about decadal climate variability because of its limited time span. Paleoclimate data can offer views into the past unavailable from other sources and provide a test-bed for numerical models of the ocean and atmosphere. The combination of instrumental, paleoclimate, and modelling approaches can offer substantial new insights into tropical climate variability. There is a new PAGES-CLIVAR initiative on Annual Records of Tropical Systems (ARTS) that promotes the synthesis of paleoclimatic with instrumental and modelling perspectives to address significant uncertainties in our understanding of tropical climate variability (Cole, 1997). There are some sources of paleoclimate data available in the tropical Atlantic sector, including coral, tree rings, varved sediments and ice cores. Most coral data which offer records of tropical SST variability are in Caribbean/Gulf of Mexico region. A few scattered tree-ring and varved sediment records also exist in Africa. A focused effort on the analysis of existing records is under way to determine the needs and priorities of future sampling. Since paleoclimatic reconstructions provide the only source of information on long-term changes in the tropical climate variability and its teleconnections, it is very important to further expand the paleoclimatic data base in the tropical Atlantic sector. Approaches need to be explored to integrate paleoclimatic and instrumental data sets into climate models.

Empirical studies based on historical data sets can provide important clues about how various parts of climate system are internally linked and interact. For the tropical Atlantic climate variability, the empirical analyses should be focused on issues such as

1. relationships between the northern and southern component of the Atlantic dipole, tropical Atlantic and Pacific SSTs, and tropical and extratropical Atlantic SSTs;
2. relative importance of the tropical Atlantic and Pacific SSTs' influence on rainfall variabilities over America and Africa;
3. linkages between SST, winds and surface heat flux near and off the equator;
4. oceanic and atmospheric processes that control cross-equatorial SST gradient variability;
5. interrelations among Atlantic dipole, equatorial modes and the seasonal cycle;
6. potential links between the SST variability of the dipole mode south of the equator and the changes to the South Atlantic Convergence Zone (SACZ).



New and innovative statistical analysis techniques should be explored to identify positive feedbacks in ocean-atmosphere-land coupled system and their roles in Atlantic climate variability.

## 6.6 LINKAGES WITH OTHER ELEMENTS AND PROGRAMMES

The tropical Atlantic climate variability is likely to be linked to other climatic phenomena in the global coupled system. The SST anomalies over the Caribbean and the tropical north Atlantic, for example, are shown to be connected to the Pacific/North American (PNA) pattern which is associated with the Pacific ENSO. The north Atlantic Oscillation (NAO) may also exert certain influences on the Atlantic dipole and equatorial variability, possibly through tropical-extratropical exchanges in the ocean. Furthermore, the SST and rainfall patterns over the tropical Atlantic may influence and interact with monsoon precipitation over the Americas and Africa. Therefore, it is very important to co-ordinate properly the tropical Atlantic research effort with other elements within CLIVAR to maximise available resources. The following research areas within CLIVAR are likely to be most closely related to the study of Atlantic dipole:

1. G1: ENSO: Extending and Improving the Predictions
2. D1: North Atlantic Oscillation
3. G3: Variability of the American Monsoon Systems (VAMOS)
4. G4: African Climate Variability
5. D4: Pacific and Indian Ocean Decadal Variability

Several programmes that either exist already or are now under way or planned are also highly relevant to CLIVAR's tropical Atlantic research. One of such programmes already mentioned is the PIRATA. Others include GCOS, GOOS, IAI, LBA, PACS, ACCE, ECLAT, Satellite & Climate, REVIZEE. A brief summary of these programmes are as follows:

- VAMOS Variability of American Monsoon Systems (CLIVAR focus G3): with goals to describe, model and understand the mean and variable aspects of the American Monsoon Systems, to investigate its predictability and to make predictions to a feasible extent, and to prepare products in view of meeting societal needs. As such, there are some important areas for synergy between the Tropical Atlantic Variability component of CLIVAR and VAMOS.
- LBA (Large-Scale Biosphere-Atmosphere Experiment in Amazonia): A multidisciplinary programme to understand general functioning of Amazonia and its interaction with the Earth system.
- PACS (Pan American Climate Studies): A U.S. programme to gain understanding of climate variabilities over the Americas and the adjacent tropical oceans.
- PIRATA (Pilot Research Moored Array in the Tropical Atlantic): A 4-year (1997-2000) joint programme between Brazil-France-US to develop an observing system in the tropical Atlantic Ocean. PIRATA is designed to become a component of CLIVAR.
- IAI (Inter-American Institute for Global Change Research): A programme sponsored by 16 countries in the Americas to improve understanding of climate variabilities and their societal impacts.
- ACCE (Atlantic Climate and Circulation Experiment): A U.S. programme to focus on Atlantic's thermohaline circulation and its impact on global climate.

- ECLAT (Etudes Climatologiques dans l'Atlantique Tropicale) and Satellite & Climate: Two French programmes to become the French contribution of CLIVAR in the tropical Atlantic.
- REVIZEE (Avaliação do potencial Sustentavel de Recursos Vivos na Zona Economica Exclusiva): A Brazilian programme to obtain fisheries and physical data from CTD and XBT stations in the southwestern tropical Atlantic.
- GCOS (Global Climate Observing System): An international programme to develop a global observing system which provides a global data set for monitoring and predicting climate variability and change.
- GOOS (Global Ocean Observing System): An international programme to develop a global ocean observing system for monitoring and predicting oceanic variability.

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### *III. The CLIVAR Principal Research Areas*

## 7. ATLANTIC THERMOHALINE CIRCULATION (D3)

### 7.1. SCIENTIFIC RATIONALE

The oceanic heat transport in the Atlantic Ocean has an obvious and well-known impact on climate. Most of the heat transport in this basin is a consequence of the warm-to-cold water conversion associated with the thermohaline circulation. Fig. 7.1 shows the main northward flowing warm water routes and the cold deep southward return flows that form the North Atlantic thermohaline circulation. To the extent that variations of the thermohaline circulation on decadal-to-centennial time scales lead to changes in SST and ocean heat transports, they are therefore of direct interest to CLIVAR DecCen. Furthermore, as the transport of carbon by the Atlantic thermohaline circulation plays a significant role in the global carbon budget, thermohaline circulation variations may contribute to changes in the oceanic carbon transport and hence indirectly affect the atmospheric CO<sub>2</sub> content.

While the generation mechanisms for DecCen variability involving the thermohaline circulation are not well understood, several of the principal mechanisms listed in the CLIVAR Science Plan can be of potential relevance in connection with thermohaline circulation variations.



Fig. 7.1: An oceanic roundabout. As warm ocean currents in the subpolar gyre gradually cool, they warm Europe and may trigger seesaws in climate (McCartney et al., 1996).

#### 7.1.1 Sudden changes

Paleo-oceanographic data show that climatic changes have occurred in the geological past and were associated with changes in the thermohaline circulation (e.g. Fig. II.9, page 56). Some of these changes developed very rapidly. These sudden changes which are described in other documents (e.g. PAGES, 1996) may have taken place within a few decades. While their origin is unknown, there is indication that they were associated with substantial changes in the formation of North Atlantic Deep Water (NADW), and hence in the overall strength of the thermohaline circulation. Model results suggest that a collapse of the thermohaline circulation within less than ten years is indeed dynamically possible. The detailed conditions for such



an event are not well understood, it is however likely that a more or less complete collapse of the thermohaline circulation could be triggered by changes in surface conditions leading to fresher and/or warmer sea surface in high latitudes. Results of coupled models (Manabe and Stouffer, 1995) indicate that a substantial climate change, in particular over the North Atlantic and European regions, would follow a complete breakdown of the thermohaline circulation.

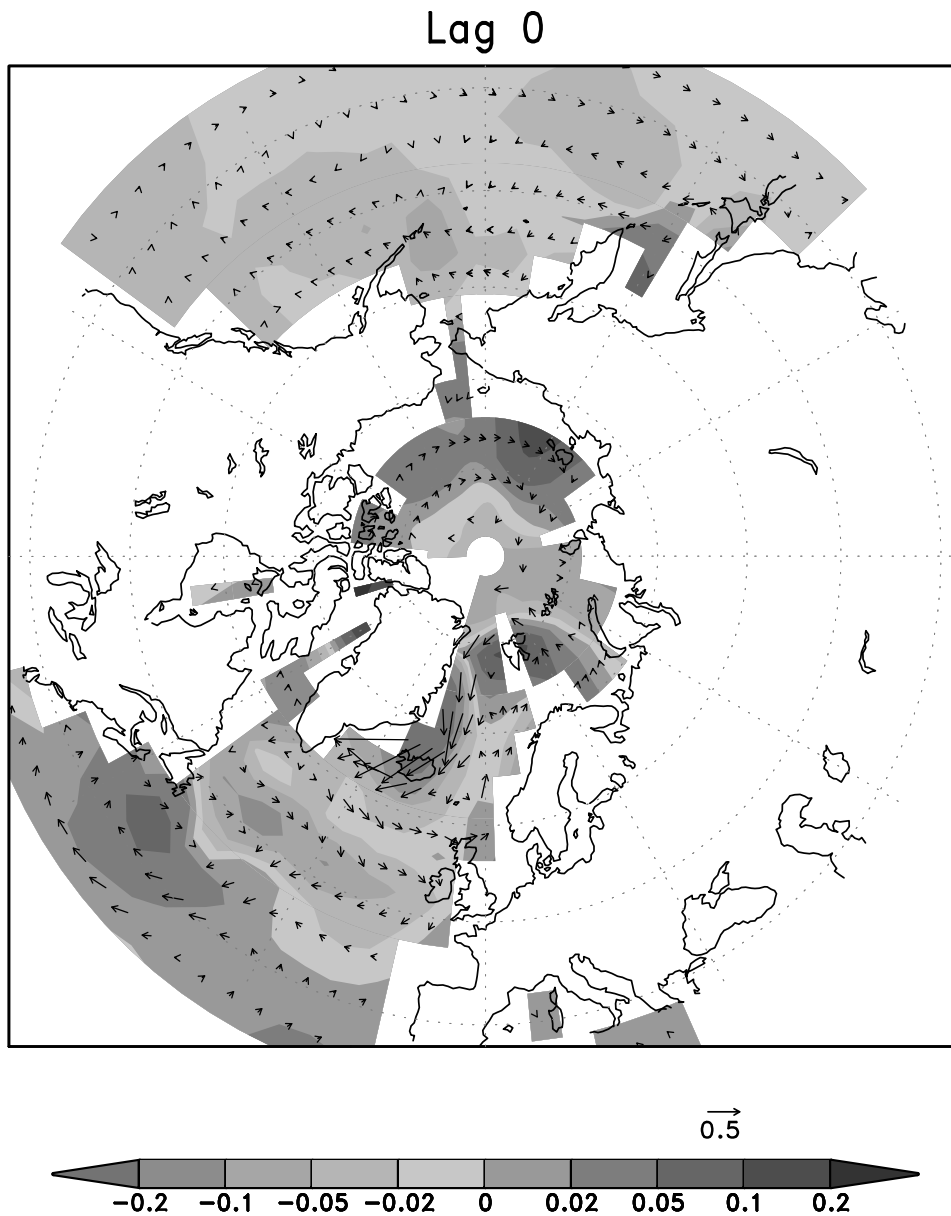


Fig. 7.2: Anomalous surface currents (vectors) and sea surface salinity (SSS; shading) at the time of coldest temperatures in the Denmark Strait. Prior to the phase of the oscillation depicted here, there was a buildup of fresh water in the Arctic. This fresh water then exited the Arctic through Fram Straits and the East Greenland Current, leading to an anomalously fresh Greenland Sea. Associated with this was a strengthening of the model East Greenland current (Delworth et al., 1997).

### 7.1.2 Internal oceanic variability

Results from ocean-only models under idealised (constant) atmospheric boundary conditions indicate that long-term fluctuations in the overall strength of the thermohaline circulation may result as a consequence of internal oceanic processes. The variability seems to occur predominantly at centennial and even millennial time scales, and the latter being outside the scope of CLIVAR-DecCen. However, the variability can include both a collapse of the thermohaline circulation as well as a sudden onset of the thermohaline circulation, with the transitions between fundamentally different states of the thermohaline circulation taking place within decades. It is unknown to which degree those oscillations are modified by the atmosphere, but it is virtually certain that a collapse or sudden onset of the thermohaline circulation would lead to a substantial atmospheric reaction.

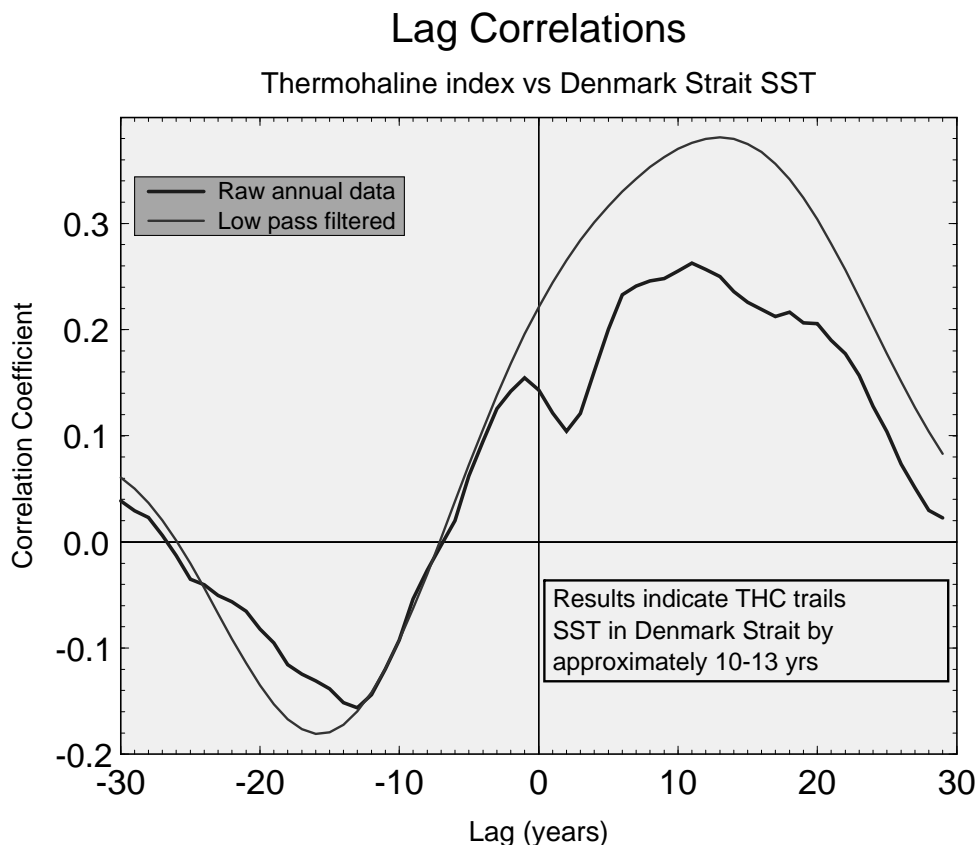


Fig. 7.3: Lagged correlations between the time-series of SST in the model Denmark Strait and the intensity of the thermohaline circulation in the model North Atlantic. The positive values at lag +10 indicate that the variations in the intensity of the thermohaline circulation trail the anomalous Greenland Sea SST and SSS anomalies by approximately 10 years. In the model, the surface fresh water anomalies propagate through the East Greenland current into the region of the Labrador Sea. There, the anomalous surface fresh water inhibits the convective exchange of heat between the atmosphere and the subsurface of the ocean, thereby weakening the thermohaline circulation (courtesy of T. Delworth).

### 7.1.3 Coupled modes

Results from coupled models indicate that multi-decadal thermohaline circulation variations of moderate amplitude have a feedback on atmospheric climate. In a multi-century integration with a coupled model, Delworth et al. (1997) found pronounced oscillations of oceanic temperature and salinity in the Greenland Sea. These oscillations, with a time scale of approximately 40-60 years, involve large-scale in-

interactions between Arctic fresh water and ice export, the intensity of the East Greenland current (Fig. 7.2), and fluctuations of the intensity of the thermohaline circulation in the model North Atlantic (Fig. 7.3). The mechanisms causing a feedback of thermohaline circulation variations to the atmosphere are however not well understood. In particular it is not known which pathways for propagation within the ocean are most relevant, and which factors determine the time scale of coupled oscillations.

Variability on a 10-20 year time scale seems to result from interaction between the wind-driven and the thermohaline circulation (Grötzner et al., 1998; Sutton and Allen, 1997), which is coupled to the NAO. It is unclear to which extent the thermohaline circulation is affected by similar variability in the Southern Hemisphere.

#### 7.1.4 Atmospheric forcing

Observations have shown that the water mass distributions in the subpolar North Atlantic change on decadal time scales. In particular, convection activity in the source regions for the deep thermohaline circulation has been observed to undergo substantial changes on decadal time scales. The most likely cause of this variability is atmospheric forcing associated with the North Atlantic Oscillation (NAO). SST-variability observed during the past decades has also been linked to variations in the thermohaline flow, although quantitative estimates of thermohaline circulation variability are lacking. While the response of the thermohaline circulation to atmospheric forcing would not automatically be of relevance to CLIVAR-DecCen, its study can serve to improve the ocean component of coupled climate models through comparison with observed thermohaline circulation changes.

The sensitivity of the thermohaline circulation to changes in atmospheric conditions is presently not well known, and different models disagree on this issue. Little can be concluded from observations as the instrumental record so far does not allow to infer variations in thermohaline circulation intensity. The observed correlation between the intensity in formation of Labrador Sea Water (LSW) and variations “downstream” in the subtropical North Atlantic is however indicative of a role of the thermohaline circulation: variability of the LSW thickness is followed with a time lag of about 5 years by mid-depth cooling anomalies in the Sargasso Sea near Bermuda. Most climate models predict a substantial change of atmospheric conditions towards warming and freshening in high latitudes during the next decades, due to anthropogenic emissions of greenhouse gases. Therefore, a quantitative understanding of the dynamical response of the thermohaline circulation to changes in the fluxes at the sea surface is urgently needed.

Models and observations show changes in the thermohaline circulation which are forced by the atmosphere, but less understanding is available on how these ocean signals feed back to the atmosphere. For instance, does equatorial upwelling play an important role in bringing these signal to the surface, is interior basin upwelling important, what is the role of topographically induced vertical motions, etc.? At first this information must come from empirical, coupled and ocean-only models. When processes are identified, *in situ* process studies and monitoring efforts can be designed.

#### 7.1.5 Links to other oceans

The upper branch of the thermohaline circulation involves the spreading in the Atlantic of intermediate and subtropical mode waters originating from the Indian, Pacific and Southern Oceans (Gordon, 1986; Schmitz, 1995). Key links in this return flow seem to be the interocean exchange between the Pacific and Indian Oceans near Indonesia, the exchange between the Pacific and Atlantic through the Drake Passage, and the exchange between the Indian and South Atlantic Ocean through Agulhas leakage. It is unknown yet how sensitive the thermohaline circulation is to variations in the amount of interbasin exchange. Also the interaction between the thermohaline circulation and wind driven gyres and equatorial currents feature bifurcations in the circulation where the upper layer return flow might be easily modified, i.e. near North Brazil and Guyana (Stramma et al., 1995; Schott et al., 1995).

### 7.1.6 Overarching objectives

The thermohaline circulation is a phenomenon of basin-to-global-scale, but its dynamics and in particular its variability is controlled by rather small-scale processes associated with the formation and spreading of deep water, in particular convection, flow through narrow passages and past the equatorial zone, deep recirculating gyres, western boundary currents and the vertical mixing processes which cause warming and upwelling of the cold water in the interior abyssal ocean. It is absolutely critical that these processes are properly represented in the ocean component of climate models.

The main objectives of a programme investigating the role of the Atlantic thermohaline circulation in DecCen-variability should then be as follows:

1. to determine the space-time characteristics of past DecCen variability that may be related to thermohaline circulation variations, with a special focus on the last 6000 years, the time interval when glacial ice sheets had disappeared and when forcings were comparable to those acting today. This would allow to put the variability of the last millennium within a longer context which is necessary to encompass the time constant of the global ocean circulation which is larger than 1000 years;
2. to determine the sensitivity of the thermohaline circulation to changes in the surface fluxes;
3. to determine the conditions under which sudden transitions of the thermohaline circulation to another state may occur;
4. to understand those oceanic processes which are critical for the dynamics of thermohaline circulation changes;
5. to investigate the coupling mechanisms between the thermohaline circulation, the wind-driven gyres, and the atmosphere;
6. to establish the degree of predictability arising from the influence of thermohaline circulation variations on atmospheric climate;
7. to investigate the sensitivity to changes in interbasin exchanges.

These objectives should be achieved through a programme involving modelling, repeated observations, diagnostics of existing instrumental and proxy data sets, and specifically designed process studies, which is described in the following.

## 7.2 MODELLING AND PREDICTION

As described elsewhere in this plan (Section II 2.3), the main tools for modelling decadal climate variability are global coupled ocean-atmosphere models. These models have achieved a certain degree of realism, and in principle also include the dynamics of the thermohaline circulation, albeit in a rather coarse resolution. It has however been recognised that the continuing use of ocean-only models with a sufficient representation of atmospheric feedbacks is still necessary, in particular for studies to investigate the sensitivity of the thermohaline circulation and for long-term integrations, but also because of severe limitations in the ocean component of climate models. Ocean-only models represent feedbacks involving the atmospheric heat transport in a rudimentary way, either through ‘mixed’ boundary conditions or (preferably) through explicit inclusion of an atmospheric feedback component. The use of high-resolution ocean models will initially be limited to process studies. In order to understand and quantify the role of thermohaline circulation variations, it will be necessary to focus CLIVAR modelling activities on several aspects of the thermohaline circulation dynamics which are listed below.

### III. The CLIVAR Principal Research Areas

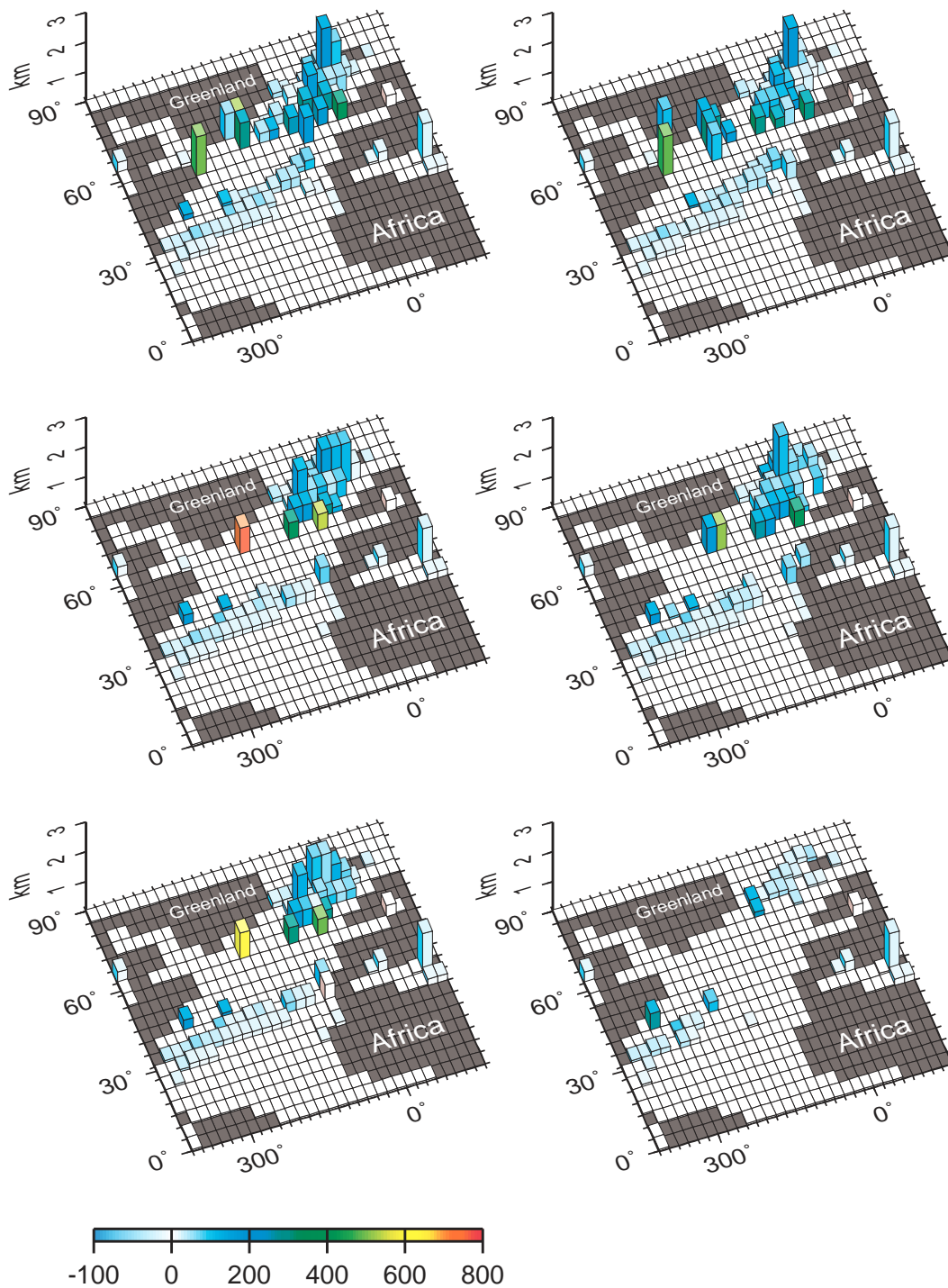


Fig. 7.4: North Atlantic convection patterns for six equilibrium solutions (all except bottom left having identical surface forcing) of the global ocean model by Rahmstorf (1995) which has been coupled to a highly simplified model of atmospheric heat transport. The height of the column indicates the depth of convection, and the shading indicates the amount of heat (in  $\text{Wm}^{-2}$ ) lost by the ocean during convection. The upper two states have convection in the Labrador Sea, and a meridional overturning of 20 Million  $\text{m}^3 \text{s}^{-1}$ .

The middle two panels have no convection in the Labrador Sea, and a reduced meridional overturning of 16 Million  $\text{m}^3 \text{s}^{-1}$ . The bottom right panel shows a state without deep convection where the overturning circulation is collapsed  $> 3$  Million  $\text{m}^3 \text{s}^{-1}$ .

### 7.2.1 Sudden transitions

Changes of the thermohaline circulation occurring within a decade can be induced by rather local processes inhibiting or starting convection ('convective' mechanism), and lead to a changed pattern of water mass formation with corresponding changes in the thermohaline circulation intensity. Recent results from both coupled as well as from coarse-resolution ocean-only models indicate that e.g. shutting on or off the convection in the Labrador Sea would involve thermohaline circulation changes of 3–4 Sv, and lead to considerable regional changes in surface temperature over the Atlantic and western/northern Europe. On the other hand, from experiments with high-resolution ocean models it has been concluded that the Labrador-Sea convection may have less influence on the thermohaline circulation. These high-resolution models are however limited in other respects, e.g. by short integration times and restoring at boundaries to represent climate conditions.

The convective mechanism can also induce a 'polar halocline catastrophe' where the thermohaline circulation would collapse almost completely within 10 years. In coupled models, such an abrupt breakdown has been simulated as a consequence of a large surface freshwater input, and found to induce strong cooling over the North Atlantic (basin-averaged 2°C, regionally more than 5°C) and European regions. Likewise, the establishment of a strong thermohaline circulation from a state with weak or absent NADW formation, a situation which resembles the behaviour deduced from high-resolution proxy records, has occurred in a coupled model within 30 years. A systematic investigation of the conditions under which sudden changes can occur is however lacking, as well as the simulation of sudden changes with high-resolution models.

### 7.2.2 Multiple equilibrium states

Adjustment of the thermohaline circulation to changes in forcing or initial conditions can also be brought about through a slow 'advective' mechanism which involves a steady change of the thermohaline circulation over several hundred years. A steady decline of the Atlantic thermohaline circulation to very low values has e.g. been predicted to occur within 200 years in calculations with coupled models simulating a global warming as a result of the increase of greenhouse gases, the details depending on the scenario of greenhouse warming (Manabe and Stouffer, 1994). Once the thermohaline circulation is stopped, hysteresis effects may prevent its onset even when the forcing is brought back to normal conditions. Models suggest that the thermohaline circulation can have multiple equilibrium states under identical forcing conditions; the structure of these states both in ocean and atmosphere is, however, not well established. Fig. 7.4 shows the convection patterns for several different equilibrium states of the coarse-resolution ocean-only model by Rahmstorf (1995). While it appears plausible that transitions between these different states play a crucial role for DecCen variability, it is unknown to what degree patterns of this type exist in coupled models or in models of higher resolution.

### 7.2.3 Sensitivity to atmospheric fluxes

The sensitivity of a model's thermohaline circulation to changes in atmospheric fluxes depends strongly on the type of model used. Coarse-resolution ocean-only models using mixed boundary conditions tend to be unrealistically sensitive to freshwater inflow in the convection areas. Both coupled models and ocean-only models that include a representation of atmospheric heat transport are much less sensitive, and agree reasonably well with each other when the same ocean model is used. Some models suggest that the present thermohaline circulation state may be close to a transition point (Tziperman et al., 1994). Furthermore, sensitivity of the thermohaline circulation appears to depend strongly on model parameters such as heat and salt diffusion, models with less diffusion being more sensitive. The model resolution potentially has also a significant impact on model sensitivity, and high-resolution ocean models with a proper representation of deep overflows have been found to be less sensitive. The dependence of the thermohaline circulation sensitivity on critical model parameters and on the mean climate state is of crucial importance.

#### 7.2.4 Resolution and parameterisation of climate-relevant processes

The insufficient resolution in the ocean component of current climate models constitutes a principal problem for climate modelling involving thermohaline circulation-variations. It leads to a lack of realism in the reproduction of the complex and small-scale processes involved in the formation, modification, spreading and mixing of intermediate and deep water masses, and might severely affect the models' ability to simulate the dynamics of the coupled ocean-atmosphere system on interdecadal time scales. Parameterisations of these processes which are implemented in models are usually of an ad-hoc nature. So far, the apparent improvements of high-resolution basin-to-global-scale ocean models in recent years have been utilised for oceanographic applications only; due to their typical limitations, e.g. in integration times, direct comparisons with coarse-resolution climate models have usually not been attempted.

A systematic assessment of the impact on climate dynamics of the representation of key physical processes in ocean models differing in resolution, parameterisation or numerical schemes is lacking, hampering progress in the development of more realistic ocean model components for climate research. The JSC/CLIVAR Working Group on Coupled Modelling has concluded that a specific effort to foster the improvement of ocean circulation models for use in climate research is urgently needed. That effort should include both the WOCE-related ocean modelling community as well as the groups working with the oceanic part of global coupled climate models.

#### 7.2.5 Predictability

As the atmosphere has a very short memory, any predictability in the coupled system can only arise from an influence of the oceanic state on atmospheric parameters. The influence of moderate thermohaline circulation oscillations on decadal to interdecadal time scales appears to be weak. Nevertheless, there are recent indications that variations of the dominant SST patterns in the North Atlantic which have been associated with climate changes over Europe and Eurasia can indeed be predicted over a decade and longer, provided that the state of the thermohaline circulation is monitored with adequate accuracy (Griffies and Bryan, 1997). Establishment of the degree and the limits of predictability is a main objective of DecCen.

A modelling programme to determine the role of the thermohaline circulation for DecCen climate changes should include the following elements:

1. Long integrations (order 1,000 years) with coupled models in realistic geometry should be performed in order to study the space-time characteristics of the models' internal variability. The model results would also contain information on possible mechanisms of DecCen variability, and would thereby provide indication what to look for in observed data sets. Particular attention should be directed at the processes that cause variations in the thermohaline circulation, and couple these variations back to the atmosphere in these integrations. Are there preferred modes of thermohaline circulation variability, or are the oscillations merely response to a noisy atmosphere? How well can the thermohaline circulation be specified by other parameters that are easier to observe, e.g. such as sea level? Moreover, results from such integrations sets may also be useful for comparison with proxy data, in particular if some proxy parameters (as e.g.  $\delta^{13}\text{C}$ ) were included in the prognostic calculations.
2. Determination, through a series of integrations both with coupled and ocean-only models, of the sensitivity of the ocean-atmosphere system to changes in boundary conditions, and on the conditions which facilitate the possibility of rapid transitions of the thermohaline circulation.
3. A programme to improve and test the ocean component of climate models in the light of observations is required. Here co-ordinated experiments with various ocean models which may differ in resolution, parameterisation or other aspects, are envisaged. The sensitivity to model parameters should also be systematically investigated, a task for which e.g. adjoint models can be fruitful. Models should be driven by appropriate atmospheric fluxes, and be compared with observed char-

acteristics of thermohaline circulation variability and of thermohaline circulation-relevant processes. As a first step, a set of well-defined oceanic fields should be identified, including the thermohaline circulation response to external forcing variations on decadal time scales, that all models (both those existing and those under development) should strive to simulate, and that could eventually lead to an organised ocean modelling intercomparison project.

4. Very long integrations (order 20,000 years) with suitable ocean-only models, in order to determine some aspects of sudden transitions which may occur sporadically after long intervals, as a result of internal ocean processes. In particular, the dependence of this type of variability on the parameterisation of diapycnal mixing and on the mean climate state needs to be investigated.
5. Investigation of the predictability of climate parameters over decadal time scales based on the dynamics of thermohaline circulation variations, through series of repeated integrations with coupled models extending over a few decades with different initial conditions.

### 7.3 OBSERVING NEEDS

A large observational programme in the Atlantic has been carried out and is still continuing in the context of WOCE and results should be evaluated, also in comparison with coupled model results, before a CLIVAR strategy is proposed. Following are some preliminary recommendations that may need to be modified subsequently. The observational programme to meet D3 requirements will have considerable common elements with that for D1 and joint planning and implementation of the field programme is essential.

#### 7.3.1 Watermass and current sections at crucial latitudes

Determining thermohaline circulation variability implies monitoring the changes of watermass parameters and currents along some crucial Atlantic cross-basin sections. Of prime importance are:

- A section to determine the exchanges between the subpolar and the subtropical North Atlantic, in particular to monitor the export of North Atlantic Deep Water (NADW). This latitude is also an extremum in the meridional freshwater transport. The section, WOCE section A2/AR19, runs from the English Channel to the tip of the Grand Banks. About 7 transects will have been carried out when WOCE is terminated, and its western end has had good hydrographic coverage over the past decades, revealing significant decadal circulation variability there. Hence, a good basis for designing such a repeat section exists.
- A section to close off the South Atlantic; to determine the variations in inflows of southern source waters, the contributions of inflows from the Drake Passage or from the Indian Ocean, respectively, and the exit of northern source waters. WOCE section A10 or A11 serves this requirement which is also a requirement for D5.

Further sections that would significantly contribute to the objectives are:

- A section across the subpolar North Atlantic at 55 - 60°N for monitoring the source regions of NADW. It would cut through the deep boundary currents east of Greenland and east of the Midatlantic Ridge that are fed by the overflows, and near the surface through the North Atlantic Current that is near - meridional in that latitude range.
- The 24°N section, WOCE section A5/AR1 located near the heat flux maximum, where decadal changes in watermass salinity and temperature has been documented in observations of 1957, 1981 and 1991.



### III. The CLIVAR Principal Research Areas

- A section across 10°S, or a WOCE section to the north or south to determine the exchange of the equatorial zone with the southern subtropical Atlantic, in particular the variability of southern warm water export into the Northern Hemisphere and the net export of northern deep water.

Furthermore, methods have to be developed on the basis of WOCE experience to augment or replace expensive research vessel transects by a combination of

- vessel of opportunity (VOS) sections (with XCTDs, ADCP),
- PALACE float arrays, preferably including salinity observations,
- satellite altimetry,
- end-point monitoring arrays.

#### 7.3.2 Northern ice and freshwater import

The ice import has been shown in both modelling and analysis of the climate record to be of pre-eminent importance for the interannual to decadal variability of deep convection and water mass transformation. Ice and fresh water transports need to be monitored in Baffin Bay and through Fram Straits. Ice thickness observations using upward-looking sonars are required. These observations are of equal importance for ACSYS and a joint programme is indicated.

#### 7.3.3 NADW export array

The export of NADW out of the subpolar North Atlantic needs to be monitored on a decadal basis. The narrow western basin between the tail of the Grand Banks and the Mid-Atlantic Ridge would be a suitable choke passage, and it would be located along the western end of the 48°N section (see above). Past moored and shipboard observations as well as high resolution model fields indicate, however, that this is an area with extremely high mesoscale variability, both transient and topographically trapped. This may require covering the entire western basin with a “picket-fence” moored array, at least for an initial intensive observational phase, until the correlation patterns of the most energetic features are determined and coverage can be restricted to resolving the dominant modes of deep circulation variability. At that later stage of a reduced array, spatially integrating instrumentation can be used for interpolation between current meter moorings.

#### 7.3.4 Inventories of deep and intermediate water changes

Inventories of hydrographic and tracer properties to assess volumetric changes and formation rates of the intermediate and deep waters of the Atlantic will be necessary. From past individual sections significant variations of the large-scale deep water masses were detected, but their three dimensional nature could not be determined. For example, in the state of high NAO there is intense LSW formation. Yet we do not have any indication whether this represents a general intensification of the MOC or a switch in the formation intensity from one component to another. Sampling intervals for such quantities may have to be shorter than 10 years, based on present knowledge of this variability.

Besides selected “standard” sections (see above) a full D3 field programme may require:

- additional research vessel sections to resolve the variability structures;
- repeated deployments of profiling floats, including salinity measurements when feasible;
- acoustic tomography arrays for basin-wide determination of water mass variations;
- time-series stations at key locations for monitoring thermohaline circulation water mass variability.

Some monitoring of deep convection and water mass variability upstream from the overflows, i.e. in the Iceland and Greenland Seas, will also be required.

### **7.3.5 Inventories of intermediate and subtropical mode water changes**

Inventories of hydrographic and tracer properties to assess volumetric changes and spreading rates of Antarctic Intermediate Water (AAIW) and Subtropical Indian Mode Water (SIMW) in the South Atlantic will be necessary. Past individual sections and inverse calculations yield strongly contradicting estimates of the amount and type of interbasin exchange (Schmitz, 1995). Recently the BEST (Benguela Sources and Transports) programme has highlighted the variability of the spreading of SIMW within the Benguela Current (Garzoli et al., 1996). It is still unclear, to which extent AAIW first recirculates within the Indian Ocean before it spreads northward within the South Atlantic (Gordon et al., 1992), to which extent Agulhas Rings contribute to the thermohaline circulation, or only mix their water masses within the South Atlantic wind driven subtropical gyre (Garzoli and Gordon, 1996) and which processes control the spreading of SIMW in the South Atlantic, and in particular, what is the role of the wind forcing herein (Shannon et al., 1990).

### **7.3.6 Flux fields**

To determine the atmospheric forcing of thermohaline circulation variability, data sets for the fluxes at the sea surface are required. It is envisioned that the fields in relation to D3 research will result from re-analysed atmospheric model products (Section 7.5).

### **7.3.7 Documentation of climate change response**

The propagation of anthropogenic signals (in particular CO<sub>2</sub>) through the thermohaline circulation needs to be documented to obtain a data base for model intercomparison. This objective will to a great deal be covered by the section and inventory observations described above, but it may require additional dedicated activities.

## 7.4 FOCUSED RESEARCH PROJECTS

### 7.4.1 Water mass transformation and relation to thermohaline circulation variability

Deep convection in the Labrador Sea is the source of renewal of upper NADW, and its intensity is known to vary on decadal time scales, possibly in antiphase with deep renewal of the Greenland Sea (Dickson et al., 1997). While it has recently been found that the small-scale plumes in deep-mixed regimes act as mixing agents rather than causing mean downward motions, meaning that their net mixing effect is sufficiently well represented by the convective adjustment schemes of existing numerical models, the physics and time scales of the lateral exchanges are still poorly understood. Process studies on the integral effects of deep convection and resulting water mass transformation need to be carried out to test and possibly improve eddy flux parameterisations for these exchanges with the stratified environment.

There are indications for large-scale recirculation of LSW throughout the subpolar North Atlantic, before these waters become exported by the Deep Boundary Current, implying a buffer role of the subpolar North Atlantic between the variability of surface flux fields and thermohaline circulation variability. The physical mechanisms of such recirculations that do not seem to be represented realistically even in high-resolution models, are not yet understood (see also chapter D1 on NAO variability).

Overflows over the sills between Greenland, Iceland and Scotland are the source of the deeper cores of NADW. Overflows and resulting entrainment are notoriously poorly represented in thermohaline circulation models, and process studies for improved parameterisation are required. Several studies of national groups on deep convection and overflows are presently under way (Section 7.6), and progress may be forthcoming.

Deep recirculation gyres are another mechanism that may impose an extended time scale on thermohaline circulation variability and make model time scales of climatic change unrealistic, if not properly represented. Indications for such deep gyres have been found near 24°N, in the tropical North Atlantic and under the Gulf Stream south of Newfoundland. Process studies to infer their dynamics and role in response time scales are required.

### 7.4.2 Role of equatorial zone in interhemispheric communication of thermohaline circulation variability

The equatorial regime is still a very poorly understood part of the global ocean, although a main thoroughfare for climate-relevant ocean signals. What little we do know suggests that the equatorial ocean acts as a kind of a buffer zone for the meridional exchanges of water masses and introduces specific time scales that need to be understood to be able to properly model the role of the ocean in the decadal to centennial variability.

Recent work has shown that both the upper-layer western boundary flow and the deep western boundary currents are discontinuous within 10 degrees south and north of the equator, making wide excursions into the interior with transformations along the way. Almost nothing is known about the fate of low-frequency deep off-equatorial disturbances when reaching the equator. Some hints are given by model results: when inflow conditions for the lower NADW at the overflow sills are changed, anomalies propagate southward along the western continental slope as a topographic Kelvin wave. When arriving at the equator they get trapped and the further development is very much in analogy to an ENSO event: an equatorial Kelvin wave travels eastward leading to reflected equatorial Rossby waves and poleward Kelvin waves at the eastern side of the basin which in turn generate mid-latitude Rossby waves that propagate westward again. That can lead to decadal variability in the deep interior.

A reliable observational base against which to test the top-to-bottom circulation of GCMs does not exist, neither for the mean nor for the variability. Yet, as suggested by the large detours of mean circulation pathways and by model experiments, the equatorial zone may be an important buffer for the propagation of

decadal variability. The following issues need to be addressed to better understand the role of the equatorial zone for thermohaline circulation variability and assess the realism of GCMs in representing it:

- Determine mean pathways of warm and cold water transfer past the equatorial zone, between 10°S and 10°N.
- Determine nature of seasonal to longer variability, in particular role of equatorial wave processes in cross-equatorial exchange variability; interaction of DWBC variability (topographic waves?) with equatorial belt; effect of upper-layer equatorial variability on cross equatorial exchanges.

A combination of field studies and numerical modelling is required to address these objectives.

### 7.4.3 Deep to surface layer water mass modifications

Processes that control the transfer of deep ocean signals to the surface layers need to be defined. For example, the relative roles of interior, equatorial, and boundary upwellings in bringing deep anomalies to the surface are unknown. Budget studies using basin-wide sections and intense upper layer monitoring arrays (XBT, floats) should be used to define these water mass modification processes.

### 7.4.4 Subgrid-scale processes for improved parameterisation

Because of the coarse grid used in climate models, there is strong need for parameterisations of sub-grid-scale processes. There are numerous processes that one needs to take into account, usually under the category of “mixing”.

- eddy-induced transport

The representation of the eddy-induced mixing and advection has been shown to have a significant impact on various long-term simulations. This needs to be explored in more detail and quantified. Ultimately, the issue may be addressed through the use of eddy-resolving models.

- spatial variability in deep diapycnal mixing

The interaction of tidal currents or of longer-period, deep-reaching ocean current variability with the deep topography can result in large gradients of near-bottom mixing. This in turn can cause horizontal pressure gradients and corresponding geostrophic deep circulations that may differ significantly from presumed circulation patterns under constant mixing assumptions, and may also affect the overall thermohaline transport on longer time scales.

- double diffusive effects

Salt fingering has been shown to be able to completely change the results of thermohaline oscillator models. In the observed distributions of the western tropical Atlantic warmwater sphere, significant cross-isopycnal transfers are known to exist due to salt finger effects. Diffusive layering may also play an important role for the preconditioning of convection in the Greenland Sea.

#### 7.4.5 Interbasin exchange

The spreading of AAIW and SIMW merges where the South Atlantic Current (SAC), the Benguela Current and the Agulhas Retroflexion meet. Gordon et al. (1992) have shown that the cold and warm water route can merge in the Southwest corner of the Indian Ocean to enter the South Atlantic Ocean via the Benguela Current. Recent work has shown that the amount of AAIW and SIMW that constitute the NADW return flow might be variable, and that especially the interbasin flux of SIMW is highly intermittent (Garzoli et al., 1997). It is still unknown to which extent the ratio between cold and warm water route changes across a range of time scales and which processes would determine such variability. It has been proposed, however, that interdecadal variations in the gyre-scale wind field play an important role in inducing interdecadal variations in interbasin exchange of SIMW. The following issues need to be addressed to better understand this variability:

- Determine the ratio between AAIW that is directly transported via the SAC and Benguela Current equatorward in the South Atlantic, and AAIW that is transported with the SAC and subsequently loops into the Indian Ocean before it enters the Benguela Current; the variability of this ratio and the processes that govern the variability.
- Determine the ratio between SIMW originating from Agulhas Rings and SIMW from direct Agulhas leakage; its variability and the processes that govern the variability.
- Determine the watermass transformation and mixing processes taking place within SIMW and AAIW spreading in the South Atlantic, together with the spreading paths of SIMW and AAIW. Determine the ratio between SIMW and AAIW in the Benguela Current; the variability of this ratio and the processes that govern this variability.
- Determine the role of interbasin exchange variability in inducing variability in the transfer of Southern Hemisphere properties into the North Atlantic and the process of NADW formation.
- Determine the role of variability in the wind driven gyres, western boundary currents (North Brazil Undercurrent) and equatorial currents in inducing changes in interhemispheric exchange in the Atlantic.

### 7.5 DATA SET DEVELOPMENT, DIAGNOSTICS AND EMPIRICAL STUDIES

#### 7.5.1 Data sets on water mass and thermohaline circulation variability

Data sets need to be developed from observational programmes that can be used in model assimilations or inversions. The methodology is presently being developed within the context of WOCE (see 7.6.1), and it should be decided at an early stage of CLIVAR which elements of the WOCE data handling and storage capacity should be transferred into CLIVAR.

#### 7.5.2 Reanalysis of the instrumental record

Although the data base from the subsurface of the Atlantic is sparse in space and time and strongly biased toward near-surface observations, recent analyses have provided new insight into the propagation of water mass anomalies. Further progress in our understanding of decadal variability in the climate record will come from the continuation of such analyses by applying novel techniques to determine spatial and temporal characteristics of long-term variability in the ocean and its coupling with atmospheric variations, in particular the NAO (see focus D1). There are still old data reappearing that help to establish multidecadal trends in water mass parameters.

### 7.5.3 Model analysis

Due to the paucity of observations of decadal variability it is important to diagnose variability patterns from long-term integrations with coupled models in order to understand the underlying mechanisms relating thermohaline circulation and climate variability, and with ocean-only models to understand mechanisms causing long-period auto-oscillations of the thermohaline circulation (see Science Plan, (WCRP, 1995)).

### 7.5.4 The paleoclimatic record

Coral records, tree rings and (Greenland) ice cores provide proxy records for determining past climate variability at decadal periods when sampled at sufficient resolution. The objective is to extend the climate record back by about a millennium. Such records are available only from a few locations, and regional-specific transfer functions have to be determined to calibrate the proxy data sets. Next, quantitative results on water mass and thermohaline circulation variability have to be derived from proxy variations by applying inverse techniques and assimilation into coupled models. For intercomparison with the paleo records, model output time-series of relevant parameters like  $\delta^{18}\text{O}$  have to be generated.

The paleoceanographic record of the North Atlantic Ocean reveals phenomena that may be related to changes in surface salinity much larger than the Great Salinity Anomaly in the 1970s during both interglacial conditions. These changes were closely correlated with sea surface temperature variations and resulted in reduced convection in the North Atlantic at times of low temperature and low salinity. High resolution records of the variability of sea surface temperature and salinity in the North Atlantic and the thermohaline circulation during the last millennia have to be derived with a centennial resolution or better to be compared with other proxy records for determining past climate variability at decadal periods. Rapid climatic variations in areas other than the North Atlantic have been evidenced and should be better documented to understand the teleconnections between the high latitudes of the Northern Hemisphere and the global climate.

## 7.6 LINKAGES WITH OTHER ELEMENTS AND PROGRAMMES

### 7.6.1 Other elements of CLIVAR

- Close links exist with focus D1 (NAO variability), because of the relations found in observations and models between North Atlantic surface atmospheric and oceanic properties (where the NAO is the dominant mode of variability) and the intensity of the thermohaline circulation (thermohaline circulation).
- Global models also suggest a relation between the southern ocean variability and overturning variability of the North Atlantic (loop oscillations); hence a relation to research area D5.
- Understanding the physics of thermohaline circulation variability, including documentation of observed penetration of the anthropogenic tracer signal into the deep ocean, has bearings on all three of the Anthropogenic Climate Change foci, in particular it is related to A1.

### 7.6.2 Other WCRP programmes

- The modern observational base for determining the present state of the global ocean circulation is being established by the World Ocean Circulation Experiment (WOCE). In its Analysis, Interpretation, Modelling and Synthesis (AIMS) phase, the various kinds of observations are being combined for determining the overturning circulation of all oceans as one main objective.

The overflows from the Nordic Seas into the Atlantic are monitored during a multiyear experiment since 1996 by groups of investigators from adjacent nations under “Nordic WOCE”. In the final field phase of WOCE (1996-98), the Atlantic Circulation and Climate Experiment (ACCE) is focusing on the subpolar North Atlantic, where a combination of profiling floats and ship sections will be used for determining the variability of water mass distribution and circulation; basin-wide upper layer, heat and salt budgets using an array of PALACE floats and VOS; and intergyre water mass exchanges, using arrays of subsurface floats to study transfers between the tropical and subtropical and subpolar gyres.

- The central objective of the Arctic Climate System Study (ACSYS) which is directed at understanding the interaction between the Arctic Ocean circulation, ice cover and the hydrological cycle, has direct relevance for the aims of focus D3 since the fresh water import anomalies from the Arctic appear to be of major importance for variability of the Atlantic thermohaline circulation.
- It is anticipated that the Global Energy and Water Cycle Experiment (GEWEX) will provide data on the global energy and freshwater fluxes that at a minimum benefit should serve as constraints for the determination of flux variability associated with thermohaline circulation variations. And the ocean observations proposed for focus D3 will in turn be beneficial for GEWEX objectives.

### **7.6.3 IGBP programmes**

Determining the role of thermohaline circulation variations in climate variability is a major aim of the Past Global Changes (PAGES) programme. The EC-funded programme “Climate Variability: How unusual is the Holocene” aims to understand the climate variability of the last 10,000 and the role of thermohaline circulation changes in the reconstructed variations in the absence of any continental ice volume variation. The reanalysis of the paleo record proposed for focus D3 is therefore of direct relevance to CLIVAR.

### **7.6.4 Other ongoing or planned programmes**

Several national research programmes of the coming pentad focus on aspects that are relevant for understanding thermohaline circulation variability. Process studies on Labrador Sea deep convection and its integral effects on water mass transformation are carried out by the USA, Canada and Germany during 1996-98. An EC programme (VEINS) will determine the pathways and circulation branches connecting the Arctic Ocean and the subpolar North Atlantic.

### **7.6.5 The Global Ocean Observing System (GOOS)**

GOOS which is co-sponsored by several international organisations, has a climate module with objectives largely parallel to CLIVAR /DecCen. Through GOOS, governmental organisations with seagoing capabilities might become involved in an observational network to monitor thermohaline circulation variability.

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*III. The CLIVAR Principal Research Areas*

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## 8. PACIFIC AND INDIAN OCEAN DECADEAL VARIABILITY (D4)

### 8.1 SCIENTIFIC RATIONALE

#### 8.1.1 The Pacific and Indian Ocean: general considerations

The decadal climate variations in the Pacific and Indian Oceans involve all latitudes. They include a modulation of ENSO, which is the largest global interannual signal (see components G1 and G2), and also lower frequency variations and possible trends (Trenberth and Hoar, 1996). It is not clear how the mid-latitude and tropical decadal variability are related - that is, whether the decadal variability is inherently ENSO variability, or whether the mid-latitudes, including the Indian and Southern Oceans as well as the Pacific, independently undergo decadal variability or affect ENSO variability. The evidence suggests some of both.

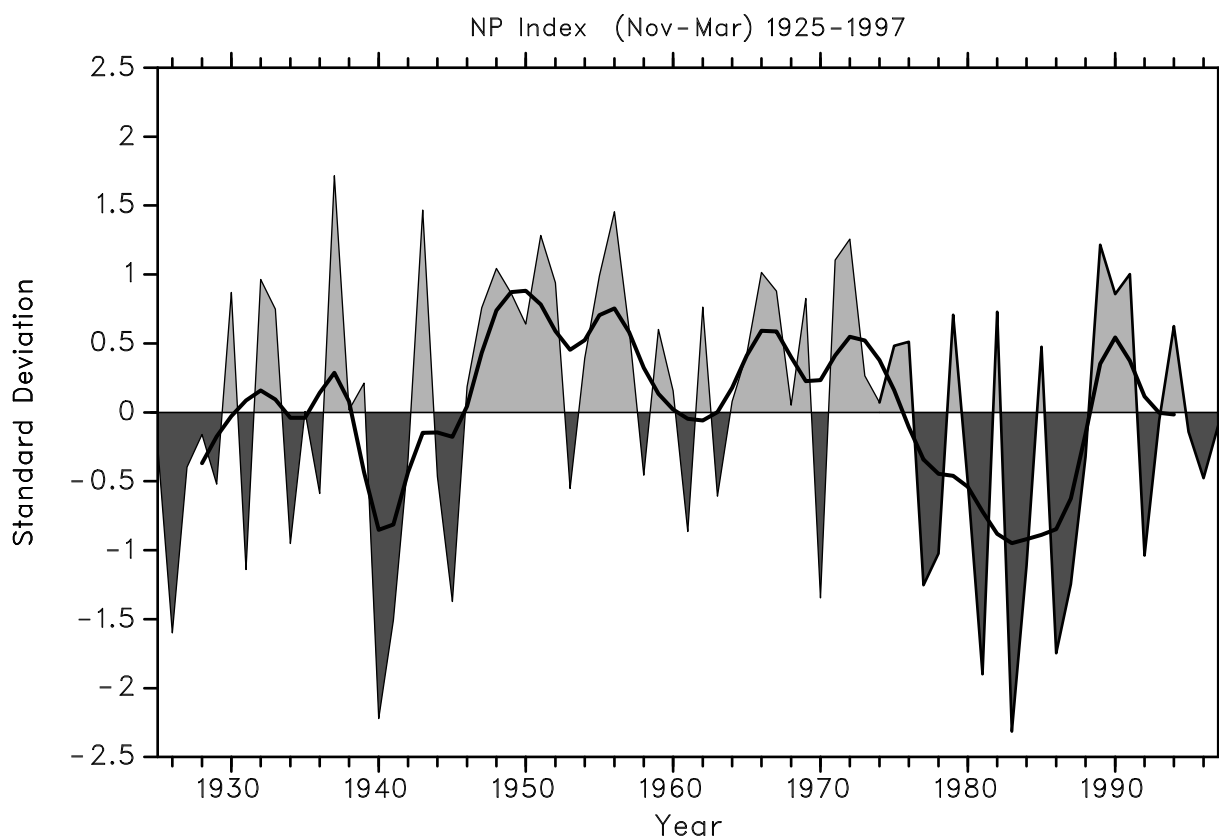


Fig. 8.1: The North Pacific (NP) Index is the area-weighted sea level pressure over the region 30°N-65°N, 160°E-140°W and shows a high level of decadal time scale variability (after Trenberth and Hurrell, 1994).

Because the observational records are short, determination of decadal and interdecadal variability cannot be pinned down precisely, but indications, described below, are beginning to appear. For instance, variability on decadal and longer time scales that modulates the interannual variability is clearly present in the North Pacific (Fig. 8.1), such as seen in the North Pacific (NP) sea level pressure index (Trenberth and Hurrell, 1994). Long-term variability in the Pacific and Indian Oceans must be dominated by variability of the upper ventilated portions of these oceans, where the circulation is primarily wind-driven, unlike the Atlantic which has a substantial *in situ* source of deep water and hence a major thermohaline component. Shallow thermohaline overturning associated with the wind-driven circulation is likely implicated in the variability in the Pacific and Indian Oceans. The current state of understanding is perhaps somewhat analogous

III. The CLIVAR Principal Research Areas

to that at the beginning of TOGA: phenomena are evident but are insufficiently defined and poorly understood, yet they have important climate and societal impacts. The prospects for filling the knowledge gaps and eventually learning to predict decadal variability is the motivation for this D4 programme.

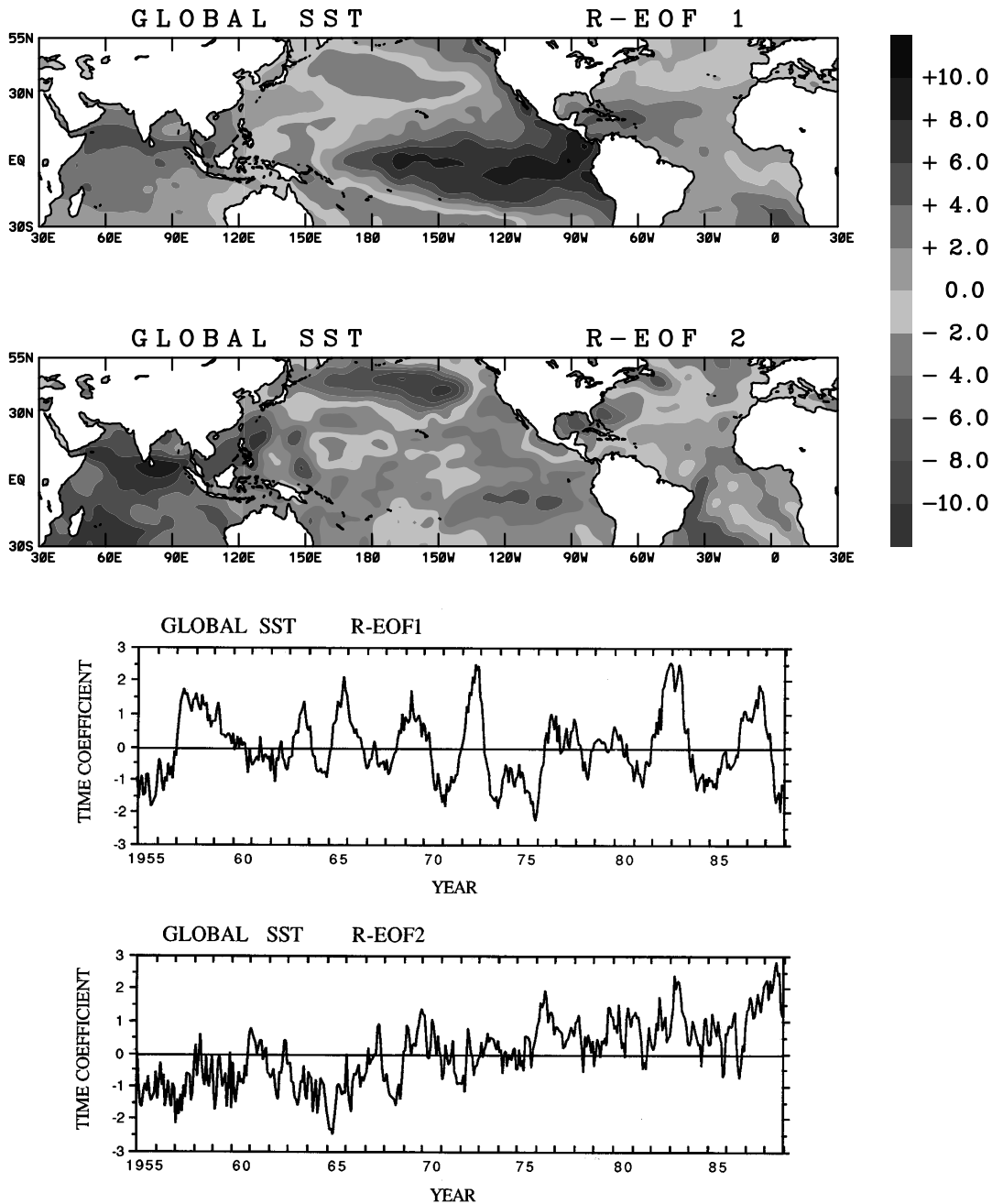


Fig. 8.2 a) (upper panel): Spatial patterns of the leading two R-EOF modes of monthly mean global-scale SST anomalies based on data for 34 years from January 1955 to December 1988, derived from the R-EOF analysis. Contour interval is 2.0 in relative units.

b) (lower panel): Time coefficient (i.e. factor scores) of the first two R-EOF modes over 34 years from January 1955 to December 1988 (Kawamura, 1994).

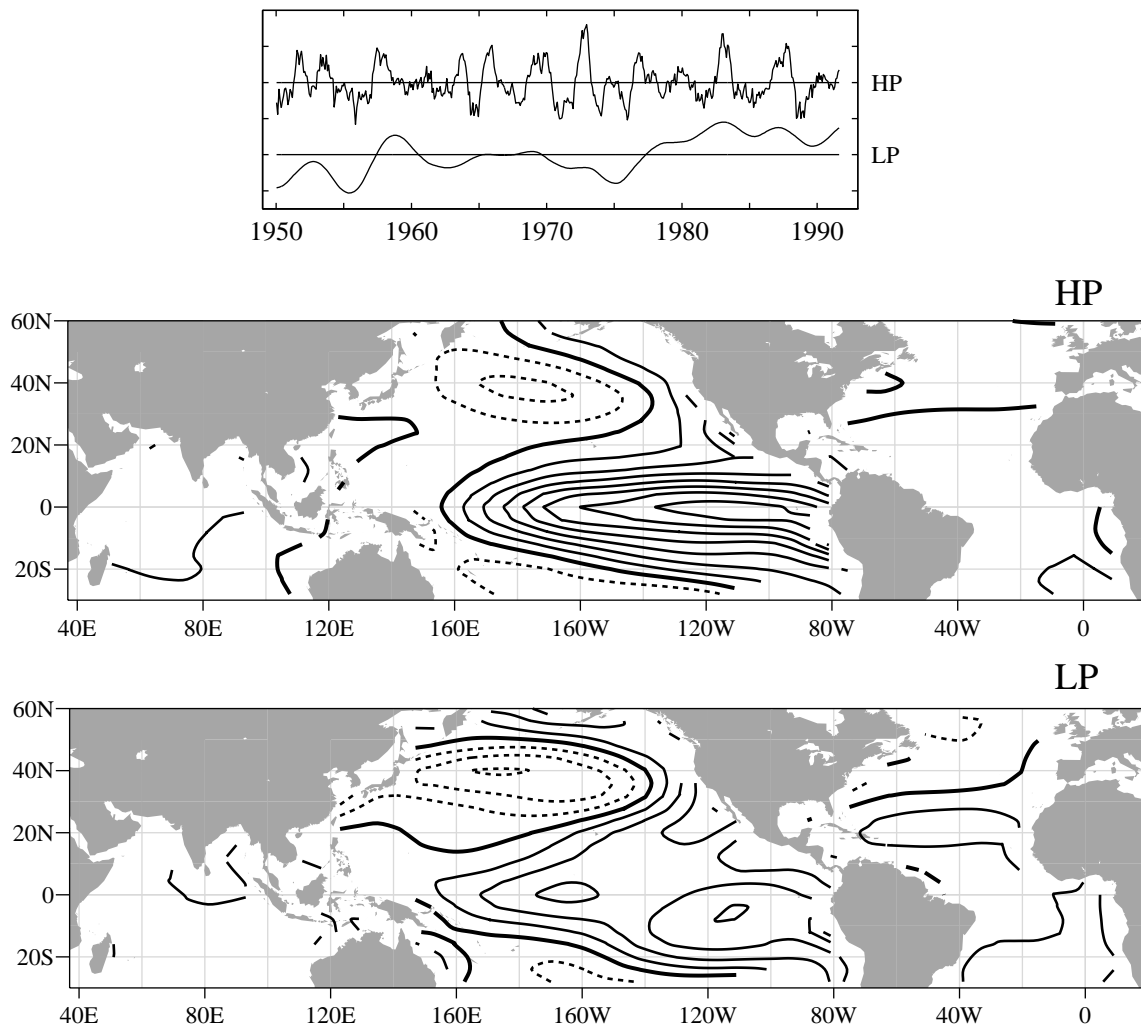


Fig. 8.3: The leading (normalised) Principal Components (PCs) of 6-yr. highpass- (HP) and lowpass- (LP) filtered SST over the Pacific domain shown together with the associated regression patterns for global SST. The interval between tick-marks on the vertical axis of the top panel corresponds to 1.0 standard deviation, and the spacing between the curves is arbitrary. Contour interval 0.1 K per standard deviation of the expansion coefficient time-series. Negative contours are dashed; the zero line is thickened (from Zhang et al., 1997).

## 8.1.2 Observed variability in the Pacific and Indian Oceans

### 8.1.2.1 Large-scale variability

Distinctly different patterns for interannual and longer-term variability are seen in global sea surface temperature (Fig. 8.2 (Kawamura, 1994)), showing rotated empirical orthogonal functions (EOFs), and Fig. 8.3 (Zhang et al., 1997), showing non-rotated EOFs, similar to those found by Nitta and Yamada, 1989). The North Pacific SST anomaly is stronger for the pattern of decadal and longer-term variability than for the interannual variability, which is dominated by ENSO. The decadal pattern in the North Pacific extends to the Indian Ocean although the out-of-phase relationship between the North Pacific and southern Indian Ocean is enhanced by the rotation of the EOFs, as seen in a comparison of Fig. 8.2 with Fig. 8.3.

The decadal mode contains the strong variability of North Pacific SST that correlates most strongly with the PNA teleconnection pattern, while the interannual variability of SST characteristic of ENSO correlates with a more zonal atmospheric pattern, as is apparent in Zhang et al.'s (1997) regression of the 500 hPa height first on ENSO (as measured by an equatorial Pacific Cold Tongue Index (CT)) and then on a pattern that gives the decadal SST pattern (as measured by GR, a global residual that basically consists of the global SST less the interannual variability characteristics of ENSO) (Fig. 8.4). Analyses of North Pacific SST by itself (Mantua et al., 1997) show similar results and indicate that the decadal variability associated with the strength of the Aleutian Low, has an impact on a range of environmental variables such as fish stocks.

The time scale or period of “decadal” variability is an issue: The records used in Kawamura and Zhang et al. (cited above) are too short to infer a time scale. Minobe (1997) looked at a number of different indices around the Pacific (including a three hundred year record of North American tree rings) to infer a dominant time scale of 50-60 years for the variability. Mantua et al. find that the Pacific Decadal Index is roughly consistent with this (their Fig. 1) while Latif and Barnett (1994,1996), on the basis of mid-Pacific SST simulations and observations, argue for something more like 25 years. Deser et al. (1996) indicate that all these time scales are present with shorter time scales dominating near the surface and longer ones at depth in the ocean (Fig. 8.5).

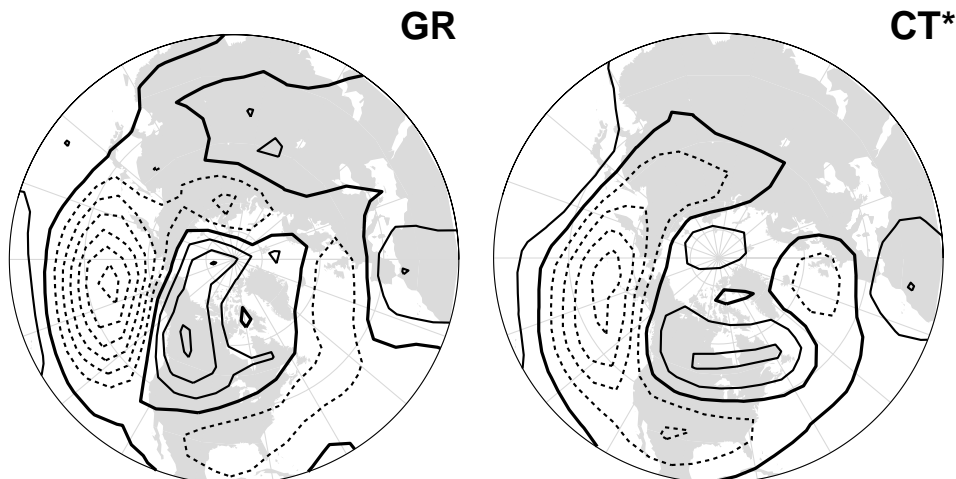


Fig 8.4: Cold season (November through April) 500-mb height field for the period of record 1946-93 regressed upon GR (residual of the global time-series after the least square best fit to the CT\* time-series) and CT\* (6-yr. high pass filtered cold tongue index time-series), as indicated. Contour interval  $5\text{m (std)}^{-1}$ ; negative contours are dashed; the zero contour is thickened (Zhang et al., 1997).

### 8.1.2.2 Pacific Ocean variability

We have seen that there are two global SST patterns which have dominant seasonal-to-interannual behaviour and decadal-to-interdecadal behaviour (Fig. 8.2). When looked at for just the Pacific, the SST variability seems to indicate that the North Pacific expression of these two modes is different. Fig. 8.6 (Deser and Blackmon, 1995) shows that the decadal mode has a distinctly different character from the interannual mode. The decadal mode is predominantly a mid-latitude mode, has most of its amplitude along  $40^{\circ}\text{N}$  (which is both in the Kuroshio extension and under the Pacific storm track) and correlates with the Pacific North Atlantic Pattern (PNA) the same way as does the decadal mode of Zhang et al. (1997) and is successfully simulated by coupled GCMs (e.g. Yukimoto et al., 1996). Clearly all the analysis methods yield similar but intriguingly different results.

Trenberth and Hurrell (1994) showed that the decadal variability in the North Pacific is coherent with part of the variability in the tropical Pacific SSTs and in the Southern Oscillation (SO), and suggested that this variability is enhanced in the North Pacific as the extratropical gyres spin up on decadal time scales.

### 8.1.2.3 Indian Ocean variability

Because the data base for the Indian Ocean variability is poor, knowledge of decadal variability in and around the Indian Ocean is poor.

Initiation and continuation of time-series measurements for the foreseeable future is important so that reasonably complete descriptions of decadal variability will be possible eventually.

Data collected in roughly twenty year chunks show clear indications of interdecadal variability of southern summer atmospheric circulation, being correlated with the trade winds in the western Pacific (Allan et al., 1995).

How Pacific decadal variability is part of or interacts with decadal variability in the Indian Ocean and possibly also in the western Atlantic is not well known but should be explored. Its relation to a possible propagating mode of decadal variability in the Southern Ocean (White and Peterson, 1996) is also not clear.

An important climate phenomenon in the tropical Indian and western Pacific is the interannual variation of the monsoon. Decadal variation of the monsoon has not been studied, but it is likely that a concerted study of historical data would be fruitful.

### 8.1.2.4 Western boundary currents

Western boundary currents are of special interest for climate because they transport large amounts of water meridionally relatively rapidly. Poleward heat transport in the subtropical western boundary current is part of some of the hypothesised ocean feedback mechanisms, especially the one described by Latif and Barnett (1994, 1996) described below. The western boundary currents are of interest to the countries they bound and have been monitored for many years so their behaviours are generally known.

The Sverdrup relation, the most basic principle of oceanography, indicates that they will respond to decadal changes in wind forcing. In addition to their large-scale importance, western boundary currents also directly influence local regional climate. The Kuroshio transport affects the local meander state of the Kuroshio, which affects local air temperature. The southward Oyashio transports cold, nutrient-rich water southward to Japan; decadal changes in Oyashio strength and location have strong effects on local climate and fisheries. The East Australia Current transports affect upper ocean heat content and SST in the Tasman and Coral Seas, which in turn affect local precipitation and cyclone tracks. SSTs in the Agulhas and Mozambique regions and the positions of the current cores have demonstrated correlations with rainfall in southern Africa (see component G4). These special roles suggest additional emphasis on monitoring these regions.

The western boundary currents may be directly connected with the large-scale North Pacific decadal SST anomalies discussed above. These SST anomalies occur in a region crossed by the Kuroshio and Oyashio Extensions and contain the western parts of the subtropical and subpolar gyres. Large-scale temperature anomalies can be advected into the region and thence eastward by both western boundary currents, and can also propagate westward as large-scale waves on the potential vorticity structure of the mean state. Part of the North Pacific Intermediate Water originates in the Okhotsk Sea (Yasuda, 1996; Yasuda et al., 1996; Talley, 1991). Thus, the Okhotsk Sea water conditions influence the Oyashio water and possibly the SST near the east coast of Japan as well as the Aleutian Low formation (Honda et al., 1996).

The strength of the western boundary current in the South Pacific and SST in the south Indian Ocean's western boundary currents have been shown to be correlated with regional rainfall. If the Kuroshio can be demonstrated to be an integral part of the coupled climate system in the North Pacific, then it is reasonable to expect that the Southern Hemisphere analogues might also play some role in the coupled climate system as well. In addition, the Agulhas retroflexion provides the warm water connection between the Indian and South Atlantic Oceans; the eddies which are shed in the retroflexion have been postulated to be an important part of the global thermohaline circulation. Variability in the strength of the Agulhas and the numbers

of eddies could affect the thermocline of the South Atlantic and eventually the large-scale overturning cell. Statistically significant correlations between rainfall over southern Africa and SST anomalies in the adjacent oceans have been demonstrated (e.g. Walker, 1990; Mason, 1995; Jury, 1995). Further work has established mechanisms by which alterations in the atmosphere over these regions lead to adjusted atmospheric circulation patterns and hence to modified terrestrial rainfall patterns. Some of these studies are related directly to known oceanic circulation patterns. So, for instance, it has been shown that rainfall along the coast of southeast Africa is related directly to the offshore distance of the core of the Agulhas Current (Jury et al., 1993). Western boundary currents in the Pacific also may contribute to communication between the subtropical and tropical oceans.

### 8.1.2.5 Indonesian throughflow

The Indonesian throughflow provides the warm water connection between the tropical Pacific and Indian Ocean. The throughflow plume is clearly evident all across the Indian Ocean (e.g. in salinity - see Godfrey et al., 1993). Models suggest that variations in the throughflow can strongly affect Indian Ocean surface properties and Agulhas strength (e.g. Hirst and Godfrey, 1993, 1994), and hence rainfall in Australia and southern Africa.

The leakage of upper ocean waters from the western Pacific warm pool to the Indian Ocean through the Indonesian Passages acts as a major heat sink/source for the Pacific/Indian Oceans (Godfrey et al., 1995). Ocean general circulation modelling results (Hirst and Godfrey, 1994) show that closure of the passages or weakening of the throughflow results in a distinct pattern of SST changes that span both the South Indian and Pacific Oceans: a stronger throughflow gives higher surface temperatures in the Agulhas and Agulhas Extension (20-30°S), warmer temperatures off Western Australia (strengthened Leeuwin Current), a cooled Tasman Sea, South East Pacific and Equatorial Pacific. Similar patterns of Indian Ocean SST anomalies were found by Allan et al. (1995) in comparing 20 year epochs spanning 1900 - 1983 suggestive of a 'strong throughflow' state pervading since the 1940's.

The throughflow strength and variations should be monitored in CLIVAR, both in the Indonesian Passages and across the Indian Ocean.

### 8.1.3 Possible mechanisms

The CLIVAR Science Plan has already discussed the possible generic mechanisms for decadal variability and these have been reviewed in detail by Sarachik et al. (1996). The simplest idea ("null hypothesis") is that the decadal pattern is just a basic mode of the atmosphere stochastically acting on the ocean with no ocean coupling. Any feedback by the ocean to the atmosphere would tend to enhance the robustness of the variability and enhance its predictability. It therefore becomes crucial to know how the ocean feeds back on the atmosphere.

Trenberth (1990) and Trenberth and Hurrell (1994) drew attention to the North Pacific variability and links with the tropical Pacific, and further proposed a hypothesis for how this comes about through the influence of tropical SSTs on extratropical teleconnections, which is supported by modelling studies of Graham et al. (1994) and Lau (1997). The abrupt change in regime in 1976/77 and interdecadal variations are simulated in many experiments (e.g. Kawamura et al., 1997).

The recent work of Latif and Barnett (1994, 1996), however, has the SST in mid-latitudes strongly interacting with the mid-latitude atmosphere to give rise to a decadal mode. The mechanism goes something like the following: A warm (say) large-scale SST anomaly in the North Pacific grows through the interaction of SST with surface fluxes on long time scales. This growth arises because the SST anomaly weakens the local north-south SST gradient and reduces the strength of both the zonal winds and the storm tracks, thereby reducing the latent heating and allowing more net radiation through the surface of the ocean to en-

hance the original SST anomalies. As the zonal winds near the SST anomaly decrease, the wind stress curl decreases leading to a general spin down of the entire subtropical gyre on time scales of a decade or so. As the subtropical gyre spins down, the wind driven heat transport by the ocean decreases so that the original warm SST is cooled. The process therefore involves both the fluxes at the surface and the wind-driven ocean circulation in an essential way.

A completely different mechanism for decadal modes was given by Gu and Philander (1997) which has the tropics affecting the mid-latitudes through the atmosphere but the mid-latitudes affecting the tropics through the ocean. The zonally averaged circulation in the Pacific shows a shallow meridional overturning cell that connects the tropics and subtropics (e.g. Hirst et al., 1996). This overturning involves equatorial upwelling, poleward flow due to northward Ekman transport under the trade winds, subduction in the subtropics and equatorward return flow in the upper thermocline due to southward Sverdrup transport.

Forced thus by both direct and indirect effects of the winds and thermohaline fluxes (McCreary and Lu, 1994; Liu et al., 1996), this cell helps determine the equatorial SST, the amount of tropical heat exported to the subtropics and thermocline stratification throughout the region. Variability of all these processes is likely on all time scales; forcing at one latitude is eventually felt at another. Mean streamlines into the tropics appear to originate in the south central and eastern parts of the subtropical gyre (Talley, 1985; Fine et al., 1994; Gu and Philander, 1997; Blanke and Raynaud, 1996). The associated shallow overturning circulation is completed with upwelling in the tropics. The detailed pathways for this equatorward transport are not known; observations and GCMs show anomalous exchange in the central North Pacific (McPhaden and Fine, 1988) in addition to significant exchange along the western boundary (e.g. Fine et al. 1994, and Blanke and Raynaud, 1996, their Fig. 3). Although there have never been any direct velocity observations of this connection, direct inference of such a connection is given by Deser et al. (1996) where an anomalous cold blob of water is shown to travel roughly along isopycnals equatorward from 1977 to 1986 but never actually reaching the equatorial zone.

However, the decadal time scale is similar to ocean advection time scales. Several coupled ocean-atmosphere feedback scenarios (especially that of Gu and Philander, 1997) are based on subduction of subtropical temperature anomalies. Most of the feedback hypotheses for the Pacific involve the upper ocean, from the mixed layer through the thermocline, both in the establishment and maintenance of teleconnections, as well as the local modification of the atmosphere.

Ocean-atmosphere feedbacks purely within the subtropical gyre have been suggested as a mechanism. Strong westerlies cause a spin-up of the subtropical gyre and Kuroshio, resulting in injection of warmer water at mid-latitudes. The response to the mid-latitude positive SST anomaly is a reduction in strength of the westerlies which then reduces the gyre strength and eventually results in a negative SST anomaly.

Interaction of the tropics and subtropics is another potentially important means by which the upper ocean processes influence climate variability, possibly including the decadal modulation of ENSO. ENSO signals are propagated to the subtropics in eastern boundary Kelvin waves and through atmospheric teleconnections as well as the shallow overturning circulation mentioned previously. There are clear signatures of ENSO over North America but the ocean's role in propagating these signals is unclear.

We see that climate variability in the Pacific depends on a large number of processes and is not completely understood. The possibility of understanding and predicting Pacific decadal climate variations offers an opportunity for Pacific countries to ameliorate adverse climate conditions and take advantage of favourable climatic variations.



III. The CLIVAR Principal Research Areas

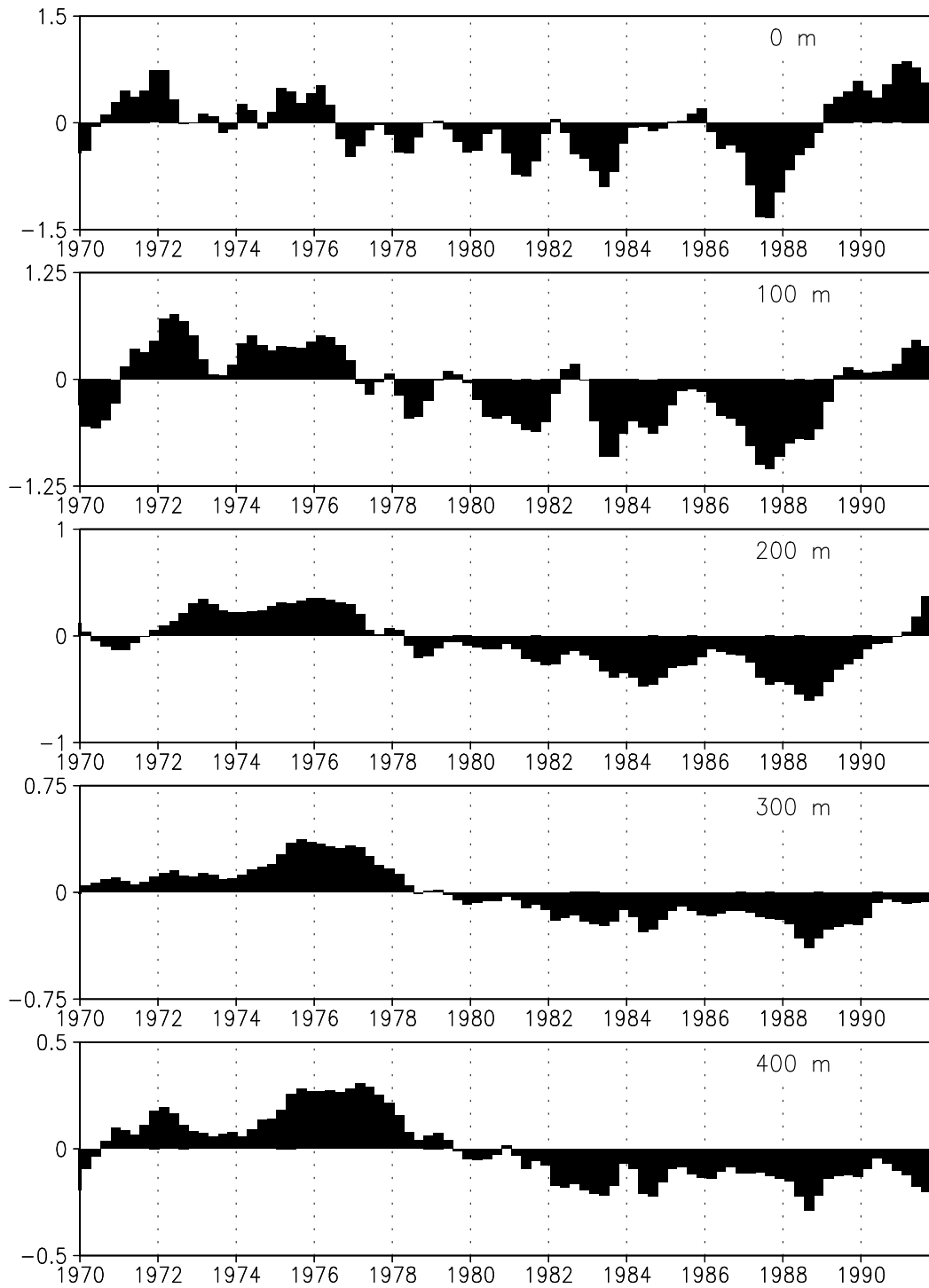


Fig. 8.5: seasonal temperature anomalies ( $^{\circ}\text{C}$ ) in the central Pacific region at selected depths. Note that the scale for the temperature anomalies is different for each depth (Deser et al., 1996).

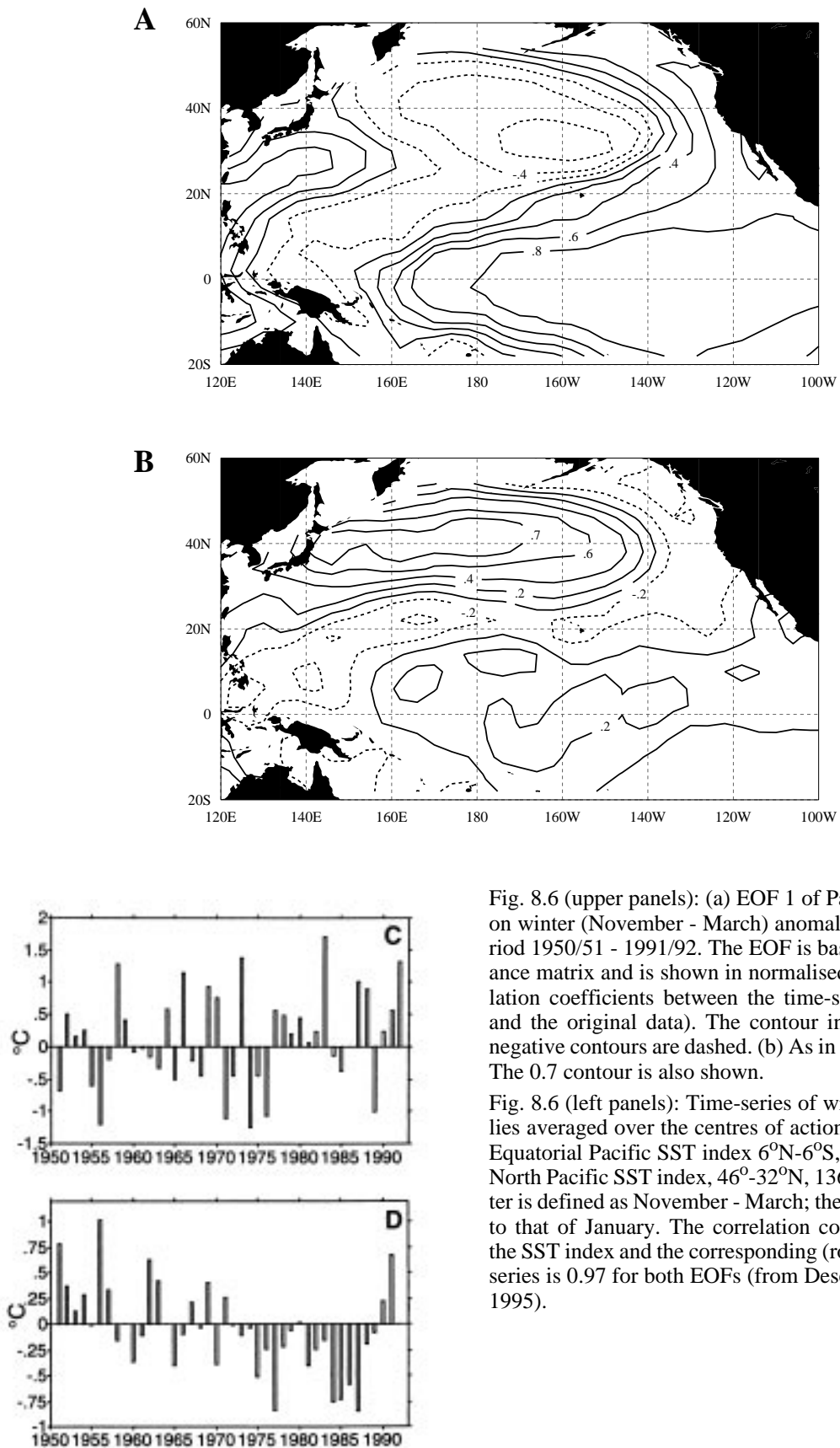


Fig. 8.6 (upper panels): (a) EOF 1 of Pacific SSTs based on winter (November - March) anomalies during the period 1950/51 - 1991/92. The EOF is based on the covariance matrix and is shown in normalised form (i.e. correlation coefficients between the time-series of the EOF and the original data). The contour interval is 0.2 and negative contours are dashed. (b) As in (a) but for EOF 2. The 0.7 contour is also shown.

Fig. 8.6 (left panels): Time-series of winter SST anomalies averaged over the centres of action of the EOFs. (c) Equatorial Pacific SST index  $6^{\circ}\text{N}$ - $6^{\circ}\text{S}$ ,  $178^{\circ}$ - $106^{\circ}\text{W}$ . (d) North Pacific SST index,  $46^{\circ}$ - $32^{\circ}\text{N}$ ,  $136^{\circ}\text{E}$ - $176^{\circ}\text{W}$ . Winter is defined as November - March; the year corresponds to that of January. The correlation coefficient between the SST index and the corresponding (rotated) EOF time-series is 0.97 for both EOFs (from Deser and Blackmon, 1995).

#### 8.1.4 Science questions

The basic question we wish to answer for the Pacific is:

*How can we better describe and understand decadal variability in the Pacific? To what extent is this variability predictable and what are the means to realise this predictability?*

Specific questions to answer are:

- What are the decadal time scales? Are the patterns of decadal variability identifiable as one or more modes of coupled atmosphere-ocean behaviour?
- To what extent is/are the atmospheric decadal pattern(s) in the Pacific affected by interactions with the ocean?
- To what extent does the tropical part of the decadal mode interact with ENSO? Is the decadal variability of ENSO due to the decadal mode or is there a separate dynamic?
- How will decadal and ENSO variability change with the addition of anthropogenic radiatively active constituents to the atmosphere?
- Can we differentiate between the hypotheses that are based on mid-latitude ocean/atmosphere feedbacks, and those based on tropical/subtropical feedbacks in which tropical SST drives atmospheric convection that drives the PNA with the tropics responding to the subtropics through shallow isopycnal circulation?
- To what degree does subtropical climatic SST variability result from upper layer processes like surface-layer entrainment and mixing, and how much results from internal readjustments that affect thermocline depth and structure?
- How must surface layer processes be parameterised to explain evolution of upper ocean temperature on seasonal, interannual and decadal time scales?
- How are decadal SST anomalies maintained through the annual cycle?
- How does the subtropical gyre maintain the tropical thermocline structure through subduction and subsequent advection along the shallow isopycnals? What role does western boundary current transports play in this exchange?
- Are low-frequency thermal anomalies propagated downwards by isopycnal advection in subduction processes or by vertical displacements driven by Ekman pumping forced by anomalous atmospheric circulation?
- What is the role of Kuroshio volume and heat transport in the climate-scale SST variability of the North Pacific? Does the Oyashio, which affects ocean conditions and climate in the western Pacific, have a role in the coupled variability?
- What are the pathways by which heat is exported from the tropical ocean to the extratropical North Pacific? How do wind and buoyancy forcing determine these pathways?

For the Indian Ocean, of which we have much less information, the key question is:

*To what extent can we better describe and understand decadal variability in the Indian Ocean and South Pacific, including monsoonal and mid-latitude variability? How is it related to the tropical/North Pacific mode? Is there a relation to the Southern Ocean propagating mode or to variability in the Atlantic? Is the decadal variability predictable?*

Specific questions are:

- Are there distinct decadal modes and do they interact with the Asian monsoon?
- Does the Indonesian throughflow provide an oceanic teleconnection for decadal variability?
- Is subduction just north of the Antarctic Circumpolar Current (primarily of thick layers of Subantarctic Mode Water) a factor in decadal time scales in the southern hemisphere, through sequestering of SST anomalies and mid-latitude feedbacks on the atmosphere?
- Is there a coupled ocean-atmosphere mode associated with the Antarctic Circumpolar Current on decadal or longer time scales?

### 8.1.5 Approach

The Indo-Pacific Decadal component of CLIVAR will proceed through a combination of modelling and observations, tied together through diagnosis of model results and observational analyses separately and together. The long time scales of the phenomena of interest present special observational problems and the active participation of the ocean requires special efforts to make ocean measurements.

Because the basic observational network for the tropical and North Pacific is well developed and has been for several decades, it has been possible to define the large-scale patterns of variability in these regions. The maintenance and augmentation of a sustained observation network in the atmosphere and in the ocean is crucial to future understanding of all decadal variability.

Full implementation of the global network is required, and it should be understood that it might be many years before robust decadal oceanographic signals are determined. The design should be such that future hypotheses can be tested. Proxy records are likely of special importance in the Indian Ocean. From a basic descriptive point of view, some regions of the Indian Ocean are so undersampled that basic knowledge of the current systems, their climatologically important mass and heat transport as well as their geographic extent, does not exist. This ocean basin may therefore be considered to be largely in an early stage of DecCen related research. Therefore basic exploratory work which would contribute the most to a better understanding of the climate system, and hence to CLIVAR, must be included.

Within the sustained global network are embedded two types of observational programmes: process studies that examine those poorly understood physical processes, which impede progress in understanding decadal phenomena, and Basin-wide Extended Climate Studies (BECS), with group measurements in and over a single basin so that the outcome of the measurements influence each other. Crucial to the BECS concept is the assimilation of all the data taken in a good model so that the output of the model may be considered the climate of the basin.

## 8.2 MODELLING AND PREDICTION STUDIES REQUIRED

Coupled models have reproduced decadal modes in the Pacific, like the ‘Latif-Barnett mode’ (Latif et al., 1994 (Fig. 8.7)) and the (North Pacific) mode (Yukimoto et al., 1996, 1998) shown in Fig. 8.2 and Fig. 8.3. It is vital to know what are the conditions for reproducing these modes in the models, in particular the resolution requirements for the atmosphere and the ocean components. Modelling is also required to elucidate the decadal variability of ENSO - competing theories are the nonlinear frequency doubling route to chaos (e.g. Tziperman et al., 1995), the devil’s staircase interaction of the annual cycle with the ENSO cycle (e.g. Jin et al., 1994), slow oceanic transport of subtropical anomalies to the tropics. (e.g. Gu and Philander, 1997), the interaction of the ENSO cycle with noise (Penland, 1995; Penland and Sardeshmukh, 1995) or simply modulation by the type of decadal fluctuations discussed above throughout the Pacific.

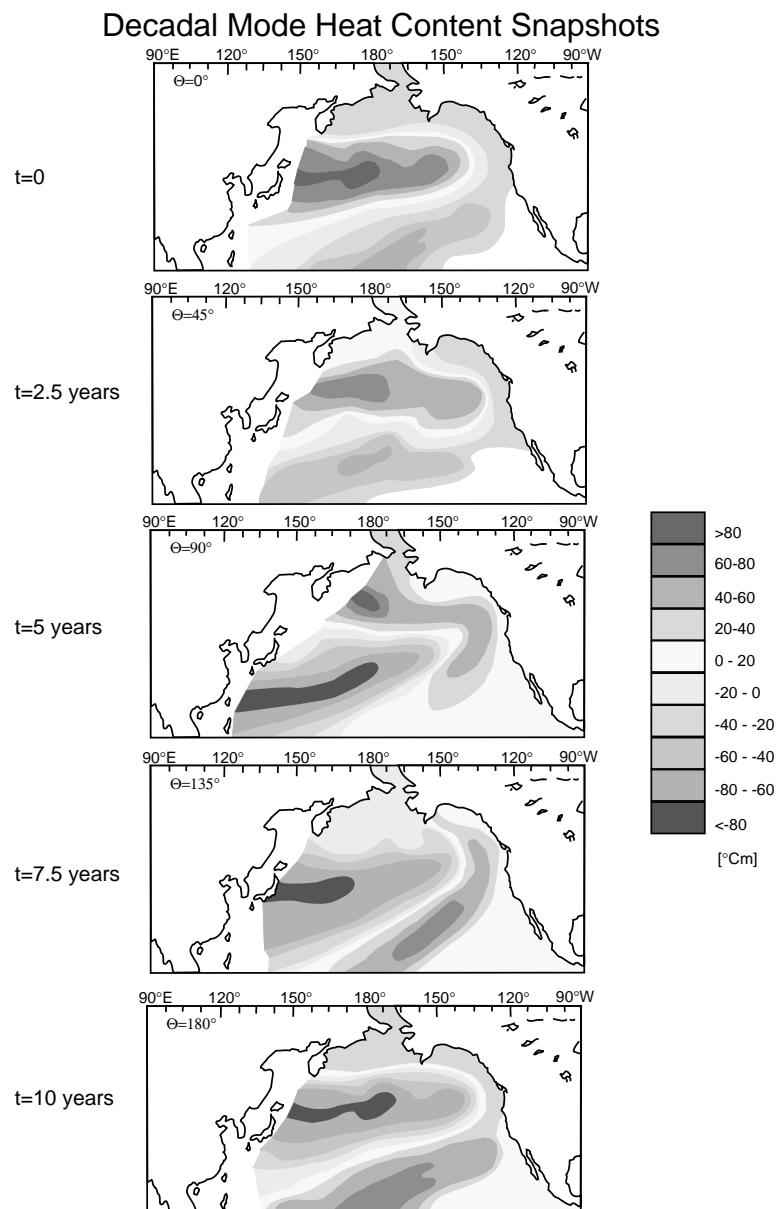


Fig. 8.7: Reconstruction of anomalous heat content from the output of a coupled model run in the Pacific Ocean. The individual panels show the progression of heat content anomalies at approximately 2.5 years apart (Latif et al., 1994).

The predictability of the Pacific decadal mode depends on the nature of its mechanisms. On the assumption that it is a coupled atmosphere-ocean mode, it is necessary to conduct simulated model experiments to determine: if predictability exists for SST and in what regions over what time scales; which regions are affected by the predictable SST variations; what is the ultimate limit of predictability; which data are the relevant data for initialisation; and what is an optimal measuring system for initialising the models.

A co-ordinated effort of observation and data-assimilation modelling is proposed. This involves substantial testing and development of dynamical models as well as development of assimilation methodologies.

### 8.3 OBSERVING NEEDS

Observing needs for description and modelling of the decadal to centennial climate in the Pacific and Indian range from thin global networks of sustained observations, to routine monitoring of important sites such as boundary currents and throughflows, to reconstruction of climate records from paleoclimatic data, to focused experiments comprised of observations and modelling to understand specific processes which govern climate variability.

This section describes the global network for the Pacific and Indian Ocean and monitoring and the paleoclimate programme. Section 8.4 describe the focused process experiments.

#### 8.3.1 Broad-scale and ongoing routine observations

The decadal and longer-term modes of variability in the Pacific and Indian Oceans are demonstrably of large-scale, covering the full extent of these basins including both hemispheres and the tropics. Much of what we know about the Pacific arises from routine measurements in the atmosphere and upper ocean. Atmospheric observations are made primarily for analyses in weather forecasting activities. Long period re-analyses convert the original weather record into as consistent a climate record as possible. Oceanic observations mostly come from ships of opportunity (sea surface temperature, sea level pressure, winds), routine XBT lines, from tide gauge stations, from the TAO/TRITON array in the tropical Pacific, from the drifter network, and from remote observations of SST and sea level height. Only the SST product is in the operational domain, the rest of the measurements are in the research domain. The XBT network in particular is declining.

The record is threatened by the decline of the upper air network and by the commercialisation of data in individual countries. It is vital to maintain these routine measurements in the atmosphere and the ocean into the future. Without them, the continuing analysis and diagnostics of evolving climatic variability becomes impossible.

All of the data sets used to characterise the variability thus far have been best supported and implemented in the tropical and North Pacific, primarily because they rely on shipping traffic. Thus the variability has been best characterised for these regions. Characterisation of ocean variation at decadal and longer time scales in the South Pacific and South Indian Oceans is still essentially at the stage of discovery. Over most of the area of these basins the historical instrumental record is not sufficient to unambiguously identify modes of variability. From a basic descriptive point of view, the current systems of the Indian Ocean, their climatologically important mass and heat transports as well as their geographic extent, have only begun to be described as a result of WOCE. Almost no information exists on their variability, and some regions are still in need of basic description.

For the future, sustained satellite measurements will provide for the first time a view of the expression of decadal modes at the surface. Building a sparse network that can monitor surface salinity changes, and expanding and maintaining a broad sampling array to monitor subsurface changes are the great challenges.

### III. The CLIVAR Principal Research Areas

*Broad-scale XBT network:* This provides subsurface observations for the upper ocean and is the source of information about subsurface propagation of thermal anomalies and changes in heat storage. In the Pacific the current level of observations should be maintained (U.S.A., Japan, France, and Australia). In the Indian Ocean the current level of observations should be maintained (U.S.A. and Australia).

*High resolution XBT network:* This is a sparse network of lines that span the gyres with eddy-resolving station spacing. It may be the only means of routinely monitoring heat advection and subsurface changes in gyre structure and transports, including the Indonesian throughflow. In the Pacific Ocean: Continuation of the quarterly network is recommended, with analysis of existing data to determine the minimum spatial sampling needed. In the Indian Ocean: Continuation of the throughflow line is recommended. Continuation of the subtropical IX15/IX2 section is encouraged.

*Salinity measurements:* These are important for regions where vertical stratification is dominated by major precipitation and runoff (subpolar and tropical); where evaporation is especially strong (subtropical gyres), vertical mixing may be affected by double diffusive processes. An appropriate programme should be designed for monitoring, including XCTD's, salinographs, drifter measurements. Regions in the Pacific are the western and central tropics, and subarctic; in the Indian the tropics (Arabian Sea/Bay of Bengal to 15°-20°S); in the southern ocean the Antarctic Circumpolar Current. The only currently reliable means of monitoring salinity on a basin scale is through salinographs installed on Volunteer Observing Ships (VOS). The current programme of VOS salinity monitoring should be continued and if possible expanded to include at least one meridional line across the Indian Ocean. Salinity monitoring on the IX1 XBT line from NW Australia to Java is under investigation. Where ship traffic is lacking (Southern Hemisphere), Sea Surface Salinity (SSS) monitoring will only be achieved through a different platform - specifically drifters in the near future, possibly satellites in the long-term.

*Surface drifters (SST, surface pressure, near-surface velocity, SSS):* Present levels of deployment with SST and SLP in the Indian and Pacific Oceans should be continued, and viable SSS measurements developed for southern ocean drifters. Deployment for purposes of surface temperature, pressure and, later, salinity measurements in southern high latitudes, where the VOS network is absent, should be encouraged and involves international co-operation. Surface drifters are the primary means of mapping the broad-scale near-surface velocity field including ageostrophic components, and as such monitor an important ocean response to changing wind forcing. For this purpose, broad-scale deployment throughout the ocean regions should be continued. An increase in the number of drifters will require new funds.

*Profiling subsurface floats ( $T(z)$ ,  $S(z)$ ):* This relatively recent technology has become an instrument of choice for profiling temperature and conductivity (salinity) especially in regions where ship traffic is infrequent or non-existent. Upon reaching the surface from their ballast depth, the floats report their temperature/conductivity profiles via satellite. The floats also provide velocity vectors at their ballast depth based on submergence and surfacing positions. Most of these floats are now deployed at about 1000 meters and are contributing to a large-scale picture of velocity and eddy energy at that depth. Continued and expanded broad-scale deployment of such floats is highly recommended.

*Altimetry (Sea Surface Height (SSH)):* This has rapidly and rightly become the principal means for monitoring circulation variability at the sea surface. The usefulness of altimetry for mapping subsurface temperature and dynamic topography requires continued calibration efforts and is strongly encouraged.

*Sea level:* These measurements will be supported. Evaluation of which records are useful is encouraged so that the continuation of these particular stations might be ensured.

*Shore stations:* Continuation of long records of proven relation to climate variations and pattern recognition is encouraged. Evaluation of which stations these are is encouraged. A specific recommendation for the Indian Ocean is the continuation of the French time-series at Kerguelen.

*TAO/TRITON array:* This will be continued and expanded into the western tropical Pacific. Funding is from the USA, Japan (TRITON), France, Korea, and Taiwan. Extension to buoys at about 30°N in the Kuroshio Extension area is encouraged.

*Repeat hydrography:* These data sets, which are collected by research vessels, are repeated at various intervals depending on their original and continued purpose. Those which have proven value to long-term climate change studies are most highly recommended; these tend to be records which are already the longest. Repeats of long hydrographic sections occur at much longer intervals than for the time-series listed here, and justification is based on monitoring tracer inventory changes and deep variability. Repeat hydrography recommended for continuation includes: Canada: Line P and Ocean Weather Ship (OWS) P; China: repeat hydrography in the Yellow, East China and South China Seas; Japan: routine lines; routine surveying by other coastal states: Australia, Chile, Peru, California, Alaska; Indonesian throughflow line (IR6 - Australia); USA: HOT station (Hawaii).

*Surface meteorological observations:* These observations are the back-bone of describing and understanding climate change as they provide the direct link between the ocean and atmosphere. Reanalyses efforts are already underway. Our specific recommendations, which are general, are: (1) strongly support continuing agency efforts to improve fluxes, including use of Numerical Weather Prediction (NWP) models; (2) endorse individual efforts to provide measurements to improve fluxes; (3) encourage atmospheric boundary layer studies.

*Boundary current monitoring:* The western boundary currents of the mid-latitude Pacific Ocean and to a lesser extent the Agulhas Current are monitored routinely. Somewhat lengthy records of their transport variability are available. Heat transport in the boundary currents affects local climate and may have important feedback effects for the larger scale. Continuation of routine monitoring is recommended where it has already begun (in the Kuroshio and Oyashio and to some extent the East Australia Current and the Agulhas). Work is in progress as part of WOCE to tie the Kuroshio transport to altimetric measurements to allow much better temporal resolution of transport changes. This work appears to be successful, and emulation for the other boundary currents should be considered. *In situ* measurements would still be required for heat transport estimates.

### 8.3.2 Proxy records of decadal and centennial variability

Upper ocean and atmospheric records are inadequate for unambiguously defining decadal to centennial time scales in the Indian and Pacific Oceans except in a very few places where coastal and meteorological records are of sufficient length. Climate proxies can provide records of several hundred up to 1000 years at a number of sites and longer records in ice cores. Thus they can be used to define the time scales and to some extent the spatial modes of the decadal variability, and can suggest centennial variability.

Paleoclimate data from corals, varved sediments, tree rings, and ice cores have the potential to provide detailed reconstructions of tropical sea surface temperature, salinity, and rainfall, as well as teleconnected responses on land and in mid-latitudes. In the tropics, corals are most useful for recovering long time-series of SST and rainfall, although ambiguities exist because coral growth depends on both physical and nutrient conditions. In mid-latitudes, tree rings are capable of providing similar long time-series although the interpretation is again complicated by ambiguities in the sensitivity of tree ring growth to both temperature and rainfall.

It is emphasised that spatial fields of paleoclimate data are far more valuable than individual sites. With these fields, climate indices, such as ENSO and the Australasian monsoon, can be reconstructed. Spatial fields of SSTs and teleconnected patterns can be constructed to compare with model output. Variability in primary ocean circulation features, such as upwelling systems and major currents, can be estimated. Thus it is a requirement of the programme that fields of paleoclimate data be produced to the extent possible. The CLIVAR-PAGES ARTS programme (Fig. 8.8), will go a long way towards providing cross-validated long records for which aspects of tropical decadal variability can be reconstructed.



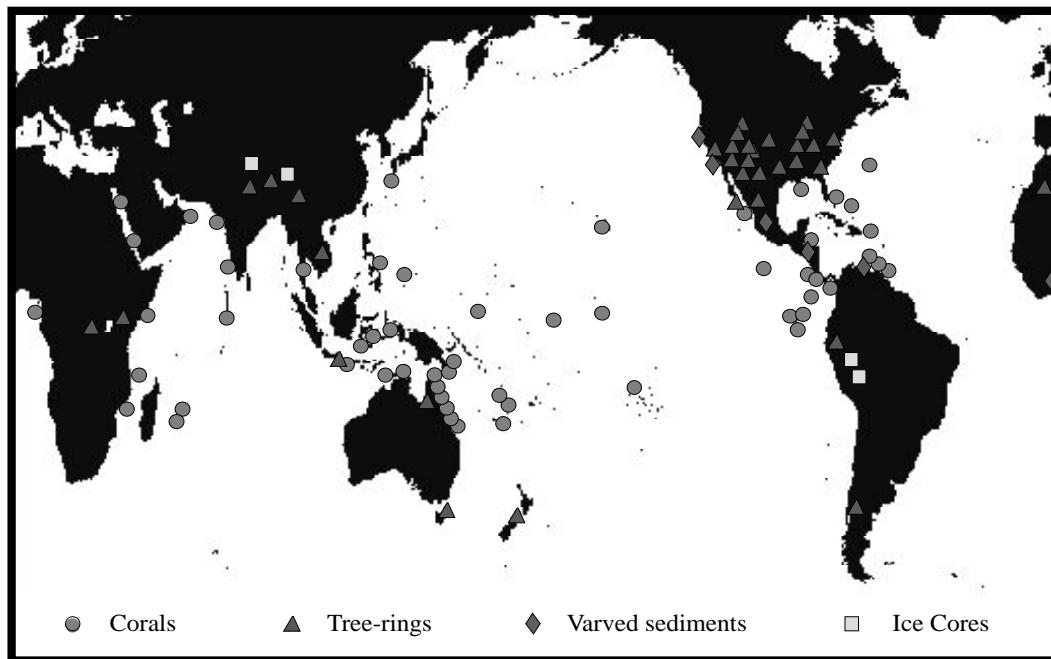


Fig. 8.8: Sites where paleoclimatic research on tropical climate systems and their teleconnections is underway, using archives with proven or potential annual resolution. This map includes sites where work is just beginning. In certain regions, individual sites are too numerous to identify and symbols represent regional efforts (e.g. tree-rings in North America; corals on the Great Barrier Reef) (PAGES, 1996).

## 8.4 FOCUSED RESEARCH PROJECTS

### 8.4.1 Introduction

The interdecadal Pacific climate mode described in Section 8.1.1 extends over the whole of the Pacific Ocean in a fairly simple spatial pattern. It modulates ENSO at decadal time-scales. The current hypotheses for its maintenance include subtropical gyre feedbacks on the atmosphere, tropical/ subtropical interactions through both the atmosphere and ocean, and a null hypothesis of excitation of a basic mode of the atmosphere which is imprinted on the ocean. Because description of this mode is so recent and because modelling and thinking about it are also so new, it is expected and hoped that significant evaluation of these hypotheses, including generation of even newer ideas, will be the major focus of Pacific climate research in CLIVAR.

CLIVAR sponsors a programme of global, sustained observations that is managed by its Upper Ocean Panel (UOP). The scientific questions suggest observations beyond what will be obtained in the UOP programme at the start of CLIVAR. Evaluation and generation of new hypotheses requires focused process experiments and a commitment to the global survey and monitoring in the Pacific. The proposed processes involve the upper ocean through the thermocline, feedbacks with the atmosphere, mixed layer formation and maintenance, connection from the mixed layer to the interior (subduction), and subsurface advection. Connections between the tropical, subtropical and subpolar gyres in the upper ocean may be important for carrying anomalies to other latitude regimes. Western boundary currents are likely to be important in these connections, as well as in rapid meridional advection of anomalies.

In addition to the global survey and paleoclimate requirements outlined above and the Kuroshio and Oyashio monitoring described below, several process experiments, some of large spatial extent, are proposed. All focus on the upper ocean. Each upper ocean study will require a carefully developed design of the optimum mix of observations to answer its scientific questions. It is recommended that design studies

begin immediately on an international level for the process-oriented observations required to be made in the Upper Pacific Ocean Studies.

As CLIVAR matures, some process-oriented observing networks might well be implemented on a global basis after proving their utility. At the start of CLIVAR it is not possible to predict all the observations required, in either the globally sustained or process oriented modes. However, it is possible to predict that by the end of CLIVAR, most of the observations taken will be assimilated into numerical models of the general circulation of the oceans.

The process experiments are necessarily accompanied by major work in coupled ocean-atmosphere modelling, with the intent of testing various feedback hypotheses. While these models might not necessarily match each of the process experiments, observational results will be used to refine the choice of model experiments.

#### 8.4.1.1 A Pacific basin-wide extended climate study

A significant new modelling and observation effort is required to raise the acuity of hypothesis and model testing using observations. What is required is a focused modelling and observation programme that spans a significant portion of the Pacific Ocean and is extended over many years. For reasons described below this new type of undertaking might be called a Basin-wide Extended Climate Study (BECS).

Traditionally climate models have been tested against observations through comparison of the gross structure of anomalies fields. It is clear from the recent progress in predicting ENSO that much more can be learned when data and models are combined in a more purposeful way to test the dynamics of change within the models. This requires effective procedures for assimilating data into models and requires observations that are coherent on the time and space scales of the climate phenomena, are sustained for many years, and are designed to test model representations of important processes.

Experience with operational data assimilating models used to study interannual variability indicates that over the ocean a density of observation significantly higher than is now available from sustained observations over most of the Pacific will be required to provide a significant test of model dynamics. The difficulty of coherently observing the ocean and air-sea fluxes limits the feasible area of coherent observations to a fraction of the Pacific. To study the processes important on either decadal or interannual variability the observations have to be extended over many years. Rather than a collection of traditional process experiments, a single large-scale low-frequency process experiment is needed. The focus of such a BECS would be a few data-assimilating model studies with data supplied by a network of observations concentrating on (a) air-sea fluxes, (b) temperature, velocity and salinity changes in the upper 500-1000 m of the ocean and (c) *in situ* observations that would be useful in improving analysis of the interior atmosphere over the ocean. Many of these observations would be of the same sort as the sustained global observations addressed by the Upper Ocean Panel but the observational density would be higher and the sampling array would be designed and managed in real-time to maintain its efficacy.

While there are important climate processes in many parts of the Pacific, the efficiency of using any Pacific BECS to study ENSO, its decadal modulation and decadal variability itself dictates that the area include the tropics and the neighbouring subtropical regions that are best connected to the tropics. The resultant model analyses would be of substantial assistance to conventional process experiments embedded within it and would contribute significantly to improvements in quasi-operational ENSO forecasting as well.

The resources for a BECS would initially need to be drawn from academic research. Since the highly co-operative and routine nature of the field work is foreign to academia a long period of planning and evaluation by academics will be needed. Consequently it is recommended that planning efforts for a Pacific BECS begin immediately and be encouraged to work toward site selection and pilot observations as quickly as is feasible.

#### 8.4.1.2 Mixing in the mixed layer and upper thermocline

Information on the exchanges of heat and freshwater are required and recommended for:

- The hydrodynamics of upper layer mixing and entrainment should be examined theoretically and with state-of-the-art direct hydrodynamic simulations with the goal of determining the primary mechanisms and suggesting ways to parameterise them.
- The processes of the surface layer should be examined with a comprehensive suite of modern observations under several characteristic forcing fields. Even when observations are aimed at different processes they often strengthen each other so it is important to examine 1-D and 3-D processes and interactions of the surface layer with the thermocline in the same experiment in which surface forcing is accurately measured.
- Effort should be placed in developing parameterised models that are realistic enough to be compared with observations, accurate enough to well describe oceanic response to forcing and simple enough to be included in coupled climate models.

One-dimensional processes. Two key aspects in mixed layers must be addressed before a good, physically-based, one-dimensional model of the surface layer can be developed or selected: (1) the effect of surface waves on mixing, and (2) mixing in the transition zone between the mixed layer and the stratified ocean interior. Turbulence in the oceanic mixed layer may be driven not only by wind stress and buoyancy flux but also by surface waves. There is a need to understand and parameterise surface waves in models better than is done now. The transition zone between the mixed layer and the stratified ocean beneath is crucial for climate. Modern observations show rapid diabatic changes taking place in this layer. It is a region of near total dynamical ignorance: How strong is mixing in it? Is mixing driven by large-scale shear of near-inertial internal waves or by small eddies or waves radiating from the base of the mixed layer? Do mixed layers unmix during spring and summer through turbulence or as a result of lateral radiative warming and/or lateral advection and quasi-adiabatic subduction processes?

Shortcomings in the ability to study in detail the physical processes within the oceanic boundary has been a major contributing factor to the uncertainties. However, the ability to measure and to numerically simulate ocean processes in this boundary layer has improved greatly in the past decade. It seems likely that significant improvement in upper ocean models can be made if these technological advances are exploited in aggressive process experiments during CLIVAR.

Three-dimensional processes. The surface layer of course has lateral variations. Large-scale variations can be due to the large-scale influences of advection and spatially-varying forcing. Large-scale variations can also be due to features such as surface fronts and jets or mesoscale eddies, phenomena which are too small to be resolved by the usual climate models.

Surface-layer density is determined primarily by temperature, with salinity generally having a compensating effect of about half the size. Rainfall is horizontally variable. How salinity anomalies evolve to establish the large-scale temperature/salinity relation of the surface layer has been the subject of theory but not of adequate observations. Bulk mixed layer models, routinely used in general circulation models, wistfully suppose that the velocity in the mixed layer is unsheared and that temperature and salinity are perfectly mixed in the vertical. However, Stommel's work has led to theories which emphasise how vertically sheared velocity fields can restratify the mixed layer by differentially advecting horizontal property gradients. Processes which involve mesoscale heterogeneity are not incorporated in the present generation of numerical models of the surface layer and, as a consequence, model surface layers cannot restratify by these processes.

Observational studies should improve parameterisations of horizontal mixing and restratification. There are three key objectives in this:

- To resolve the three-dimensional structures in the upper ocean and to relate them to mixing.
- To quantify the horizontal scale of air-sea fluxes of heat and fresh water.
- To observe the evolution of temperature and salinity as water moves downward out of the surface layer into the stratified ocean.

Three-dimensional structures must be resolved at different scales to quantify mixing. For example, mixing in the upper ocean is largely determined by the vertical shear of horizontal velocity. This shear may be geostrophic, or due to inertial motions which are usually unresolved in models of climate. Because geostrophic mesoscale eddies and fronts can have substantial relative vorticities, inertial motions can be focused and their shear increased. Baroclinic instabilities at fronts result in both vertical and horizontal fluxes.

### 8.4.1.3 Interaction of the upper thermocline with the surface layer: subduction

Detrainment from the mixed layer into the thermocline occurs when the mixed layer shoals, either due to decreasing wind stress, to increased buoyancy flux, or both. Detrainment leaves former mixed layer waters behind, where they may become isolated from subsequent surface forcing by increases of mixed layer buoyancy. Subduction fundamentally involves horizontal variations of mixed layer density and convergent circulation that force mixed-layer waters from the denser side of a front to flow beneath the lighter waters. Subduction may involve Ekman pumping, although the horizontal convergence may be due to processes other than wind-driving, such as ageostrophic flows resulting from baroclinic instability.

Pycnocline ventilation occurs by mixed-layer waters that are detrained or subducted and then flow along their isopycnal surface away from the location where that surface intersects the mixed layer. Thus, this water may be sequestered from surface processes for a significant duration, such as the time between passage of winter storms, a complete annual cycle, or longer. The longer periods of isolation are usually associated with significant horizontal advection.

Ventilation anomalies associated with climate variability may influence remote regions in a way which feeds back on the atmosphere. The dominant upper thermocline pathways are associated with the circulation of the wind-driven gyres. In order to close the mass budget of the upper ocean, significant cross-gyre transport in the thermocline must take place to balance the poleward transport that occurs in the tropics and subtropics. That pathways exist for this equatorward transport has been suggested through tracer studies and models, but not through direct velocity observations.

Subsequent entrainment of these waters into the mixed layer depends on their along-isopycnal advection into a region of stronger winds and/or more negative buoyancy forcing, or the shoaling of the pycnocline (spatially or in time). This entrainment may introduce heat anomalies to the surface mixed layer where they may interact with the atmosphere.

The process of detrainment from the mixed layer and flow of particles along isopycnals after detrainment was studied extensively in WOCE. The remaining issue for CLIVAR is the fate of the subducted subtropical waters, especially those carrying temperature anomalies.

- How long do water parcels retain any anomalies in temperature, salinity and density acquired from the mixed layer? e.g. what is the effect of mixing in the upper thermocline on anomalies?
- What is the effect of anomalous density set at the sea surface on advection of the anomalies?
- Does subducted water cross the North Equatorial Current into the tropics? If so, how? Can anomalous properties be retained into the tropics?

These questions can be studied through a direct velocity programme to determine the statistical path-

ways and through broadscale temperature and salinity profiling to map density and property anomalies. Transient tracers can be used to determine subduction rates and mixing and exchange time scales between the subtropics and tropics. Tracer maps in anomalous temperature structures can be a valuable tool.

#### 8.4.1.4 Direct observations of circulation

On time scales of ENSO and longer, advection of ocean properties over significant portions of the gyres is as important as the local exchange rates of these properties between the ocean and atmosphere. Therefore, observations of spatially well determined fields of ocean properties, together with the velocity field must be done. In the upper ocean, the ageostrophic velocity is as strong as the geostrophic velocity, so direct measurements are required. A variety of new techniques were developed in the first ten years of WCRP for direct velocity measurements over large spatial scales: surface drifters, subsurface floats and ship-mounted ADCPs. These can be used effectively for developing a data set for understanding the upper ocean processes which lead to climate change in the Pacific.

For instance, in the development of the SST anomalies in the western mid-latitude Pacific which dominate the PNA pattern, it is important to differentiate between advection and propagation of large-scale waves. The anomalies can also be created *in situ* through changes in storm-forced mixing and Ekman transport, or through meridional shift of the strong fronts. The upper ocean circulation patterns in this area can be mapped with drifters and floats. The flux of mass and vorticity into the mid-latitude Pacific from both the Kuroshio across the Izu Ridge and the Oyashio past Hokkaido can be monitored with VOS-mounted ADCPs. Such a programme of direct velocity measurements over the life of CLIVAR is comparable in scope to the direct velocity measurements in the tropical Pacific in TOGA which led to the establishment of several components of the sustained global observations.

A second example has already been mentioned in 8.4.1.3: using float measurements to observe the shallow overturning circulation in the subduction region of the eastern and southern subtropical gyre, to see to what extent it is completed by upwelling in the tropics.

#### 8.4.1.5 Enhanced surface meteorology

It is now possible to accurately measure the heat and momentum fluxes in a research mode as a result of techniques developed in TOGA COARE (e.g. Weller and Anderson, 1996). The capability to measure rainfall (especially from satellite measurements combined with other data) is rapidly developing (e.g. Xie and Arkin, 1996). The four components of the heat flux - shortwave radiation, longwave radiation, latent heat flux, and sensible heat flux - can be observed *in situ* under most conditions with an accuracy of better than  $10 \text{ W/m}^2$  assuming use of research quality observations as opposed to routine measurements. More sensitive but rugged anemometers have become standard, reducing wind speed uncertainty to close to 5%, so that wind stress errors become 10%. Rainfall measurements over the ocean are more difficult, but comparisons among various sensors indicate that they agree to about a factor of two. The accurate measurement of surface fluxes allows new insight into the processes of air-sea interaction.

Combining the flux measurements with observations of upper ocean salinity, temperature, and velocity reveals previously unidentified processes. The new rain measurements are a case in point. Rain falls into the ocean at a temperature close to the wet bulb temperature, producing fresh, slightly cool lenses. Depending on the rate and depth of freshwater mixing, the newly formed shallow fresh layer can reduce the penetration of heat and momentum, or, when the layer is very shallow, allow much of the penetrating short-wave radiation to pass through and heat the region below. Thus, rain, as well as the heat gain on diurnal and longer scales can control the depth of penetration of the momentum flux and the temperature structure of the mixed layer. In particular, it can dramatically change the relation between air-sea heat flux and changes of SST. These processes have recently been studied in the tropics, but in the mid-latitude North Pacific (PNA region) they are largely unknown.

The problem of obtaining the fresh water balance in the PNA region has not been tackled, but it is important for the maintenance of the permanent pycnocline. The operational atmospheric models use horizontal and vertical grids that do not fully resolve the variability of clouds. When there is variability in the clouds on scales close to, or smaller than, those of the grids, the modelled meteorological and flux fields do not replicate the observed horizontal variability well, particularly the rain and radiative fluxes. Climatologies suffer from the lack of accuracy in the original data, the formulae used to estimate the fluxes and from problems in data coverage. For example, recent buoy observations in the Arabian Sea show significant heat gain by the ocean during the southwest monsoon rather than the loss indicated by some climatologies. Surface fluxes are the expression of air-sea interaction, and direct observation is our best means of quantifying them and then improve the operational models with the new quantifications.

#### **8.4.1.6 Enhanced salinity measurements**

Recently oceanographers have developed a new suite of tools by which salinity variability that is expected to be associated with the climate changes in the upper layers of the Pacific can be observed on a routine basis without the use of expensive research vessels. XCTDs and thermosalinographs can be deployed from VOS and conductivity sensors can be attached to moorings, drifters and floats. There are good reasons to believe that tropical rainfall rate can be monitored from satellite borne sensors, making fresh water budgets feasible over limited areas of the upper layers of the Pacific. In regions where these fluxes determine the vertical distribution of stability, and the response of the SST to air-sea interaction, the upper ocean salinity variations can lead to significant changes in the mechanisms which force ocean currents and how SST anomalies develop.

Under the tropical Pacific rain belt that extends from the western Pacific warm pool along the ITCZ to the eastern warm pool of the Costa Rica Dome, surface fresh water layers can affect the development of the SST anomalies. Limited monitoring of the surface salinity is now done along several ship lanes in the western Pacific, but much broader coverage is required. Recent comparisons of observed numerical model fields with observed surface currents and sea-level suggests that salinity observations must be assimilated into ocean circulation models to effect accurate zonal geostrophic circulations, and subsequent SST anomaly development in the tropical Pacific.

#### **8.4.1.7 Subpolar North Pacific study**

The historical record of water mass distributions in the northwest Pacific reveals that the Okhotsk Sea is the region of the densest water mass formation at the surface of the North Pacific. This relatively dense source contributes significant buoyancy to the maintenance of the main thermocline. It affects the depth to which SST anomalies penetrate in the western Pacific. Are there changes of this water mass supply in time? In the Atlantic, changes in the supply of water which can lead to deep convection are thought to influence the SST anomalies in the entire subpolar gyre. Is a similar process in operation in the western Pacific? Changes in the patterns of the confluence of the Oyashio and the Kuroshio have been shown above to be associated with the changes of the SST patterns of the long-term behaviour of PNA. How much are the changes of the Okhotsk Sea processes contributing to the changes in the western Pacific subpolar front? Repeated surveys through the CLIVAR observing period can answer these questions.

#### 8.4.2 Southern Hemisphere subduction

Subantarctic Mode Waters, in excess of 600 m thick, are found on the northern flank of the Antarctic Circumpolar Current and are subducted into the lower thermoclines of the subtropical gyres of the Indian and Pacific Oceans. They are likely to dominate changes in the properties of the upper ocean overturning circulation in the Southern Hemisphere's subtropical gyres and hence could impact decadal climate change. Because of their remote location in the Southern Hemisphere, the global thin network is unlikely to yield sufficient coverage to explore formation, subduction and variability.

Because of their volumetric importance, it is recommended that regional studies of the Southern Hemisphere mode waters, which are outside the Basin-Extended Climate Study region of the tropical/North Pacific, be carried out.

#### 8.4.3 Monsoon variability

The seasonal Indian and Asian monsoons affect the entire tropical Indian Ocean and western Pacific regions. Monsoonal decadal variability could be of importance and interest, but the major thrust in monsoonal research at this time is at the interannual time scale. Strong decadal variability has been observed in coral records from the central Indian Ocean (Hunter, Charles, Cayan, personal communication); the decadal pattern of variability appears linked to that in the Pacific. This variability might modulate the monsoons and so is of potentially great interest. Further study of available data to reveal decadal to centennial modulation of the monsoons is recommended, including paleo records in the tropical Indian Ocean to reveal the longer time scales and their spatial patterns. The global observations network might not be adequate at this time for long-term monitoring, and so a design study and implementation of a more complete network might be necessary in co-operation with the CLIVAR project G2.

#### 8.4.4 Effects of western boundary currents on regional climate

*Kuroshio:* The path of the Kuroshio along the south coast of Japan is bi-modal; it takes either a meandering or a straight path, in a decadal pattern. It appears to change to a meandering path when its transport increases, which occurs when the Aleutian Low deepens. When the Kuroshio follows the large meander path, a cold cyclonic eddy appears; the SST changes are well correlated with coastal air temperature. During large meander periods, the large wintertime surface heat flux along the Kuroshio Extension increases markedly, possibly due to increasing SST along the Kuroshio path due to advection of anomalous warm water from the southwestern North Pacific. TRITON shall contribute to study the Kurishio Extension changes. The impact of such subtropical heat flux changes on the atmosphere and ocean has not been fully resolved. In particular, the effect of oceanic anomalous heating on the variability in cold-air outbreaks from the continent has yet to be clarified. As for the subtropical upper ocean processes, it is important to evaluate eddy heat transport from the Kuroshio Extension in order to elucidate the SST variability associated with the formation and subduction of the subtropical mode water.

*Oyashio:* The Oyashio flows southward off the east coast of northern Japan (Hokkaido) with intrusions of its waters extending southward along Honshu; the southernmost extent changes on seasonal to interdecadal time scales. Since the Oyashio is cold, low-salinity and nutrient-rich, its intensification results in cold-air events, high biological productivity and changes in the distributions of various fish species. Coastal temperatures and the Oyashio extension are possibly related to the strength of the Aleutian Low and hence can be an index for large-scale interdecadal signals. The offshore Oyashio Front varies meridionally on interdecadal time scales with an amplitude of about 1 degree latitude and is related to locations of the Pacific saury fishing grounds.

*East Australia Current:* Variations in mass and heat transports of the East Australian Current (EAC) have a significant impact on the climate of the Australian east coast. Changes in upper ocean heat content

in the Tasman and Coral Seas on decadal scales are related in part to variations in EAC transport. Associated variations in evaporation and consequently in atmospheric water vapour content over the Tasman and Coral Seas may be responsible for variations in rainfall on land. In the Coral Sea, changes in summer SST can lead to changes in cyclone behaviour and result in cyclone tracks not experienced in the past. Variations of EAC transport can be the result of several factors. Local wind forcing, spin up and spin down of the south Pacific subtropical gyre, and teleconnections with the “Pacific/North American” (PNA) mode have been identified.

*Agulhas:* The interbasin exchange between the Indian and south Atlantic is accomplished in the Antarctic Circumpolar Current and in the variable large rings which are shed at varying rates by the Agulhas where it retroflects south of Africa. In the global thermohaline circulation, this is a region of importance. Variability in the Agulhas region also has proven connection to rainfall over southern Africa, hence local climate.

*Mozambique and East Madagascar Currents:* Conditions in the Mozambique and East Madagascar Current regions also appear to be linked to southern African rainfall and to the advection of Indonesian throughflow waters towards the south Atlantic, but these currents are so underexplored that the first order of business must be to provide a basic description.

#### 8.4.5 Indonesian throughflow

The Indonesian throughflow provides the warm water connection between the tropical Pacific and Indian Oceans. The throughflow plume is clearly evident all across the Indian Ocean. Models suggest that variations in the throughflow can strongly affect Indian Ocean surface properties and Agulhas strength, and can also affect the western south and equatorial Pacific. The southern subtropical Indian Ocean has warmed; remote forcing via throughflow modulation is the most likely explanation. The possible links between these decadal changes in SST with the steady 40 year decrease in rainfall in southwestern Australia is under investigation. Sensitivity of Australian rainfall to Indian Ocean SSTs has already been demonstrated for interannual time scales (Nicholls, 1989). The sensitivity of the modelled throughflow to changes in Pacific Trade winds highlights its likely role as an ocean teleconnection for decadal climate variability. For example, given the observed wind changes associated with the Pacific Decadal Mode (or PNA), a remote Indian Ocean response is likely. The throughflow strength and variations should be monitored in CLIVAR, both in the Indonesian passages and across the Indian Ocean.

Though a robust result in OGCM's, the link between changes in throughflow magnitude and Indian Ocean SST on decadal time scales has yet to be demonstrated in the observations. Work is underway to reconstruct a throughflow transport time-series back through the instrumental record based on XBT archives and correlate it with SST patterns and regional climate changes. Calibration of these transports against the existing full-depth hydrographic sections and current meter observations is also needed. However, to determine the importance of the through-flow as an oceanic climate teleconnection, a long-term transport-resolving monitoring programme is required.

Present monitoring observations include the Voluntary Observing Ship (VOS) XBT line ‘IX1’ between western Australia and Sunda Strait put in place as part of TOGA-COARE and a pressure gauge array in the Indonesian passages. For future monitoring, at a minimum, the VOS sampling should be continued in both frequent, low spatial density and infrequent, eddy-resolving modes. Salinity and velocity sampling could be added. Altimetric data, in combination with *in situ* data, should be explored for recent and future monitoring. Arlindo (promoted by LEDO) and a surface buoy (scheduled by JAMSTEC) serve to observe the Indonesian Throughflow in co-operation with BPPT (Indonesia). A high resolution OGCM should be considered to help design monitoring experiments.

Special projects might include, for instance, description of the South Java Current and its role in the Indonesian throughflow, a mooring array off Sunda Strait, top-to-bottom surveys at peak monsoons and also in 2000/2001 to monitor water mass changes, and deep profiling floats.



## **8.5 DATA SET DEVELOPMENT, DIAGNOSTICS AND MODEL-ASSIMILATED DATA**

### **8.5.1 Data set development and studies based on existing data**

Much work can be done in analysis of the existing global data sets. In the Pacific Ocean, where there has been relatively good sampling, study of the variations in properties in the upper ocean, propagation of anomalies, relation to atmospheric forcing and teleconnections, and mixed layer properties/upper ocean heat content, are in progress. These are rich data sets and should provide much information to those with particular hypotheses to test. These data sets do not substitute for good distributed process experiments, especially those involving direct velocity and enhanced salinity measurements, but should provide useful hypotheses to test in the Basin-Extended Climate Study.

Relations between the decadal modes in the Pacific and Indian and climate variables such as air temperature and rainfall, especially over adjoining continents, could continue to be explored with existing data. The relation between the Pacific modes and those in the Atlantic and Southern Ocean could be considered, based on existing data sets.

In the tropical Indian Ocean and western Pacific, existing data sets can be mined for information on decadal variability in the monsoon and ENSO. These data sets include the large set of coastal time-series and proxy records. The various WCRP data sets and earlier data collected in the Indonesian throughflow region are being used to construct a transport time-series there.

In the mid-latitude southern hemisphere, good time-series, especially with distributed spatial coverage, are especially lacking. Continued analysis of what data do exist to uncover variations will be useful, but will be lacking in context.

### **8.5.2 Diagnostics**

The diagnosis of model mechanisms is as complex an undertaking as the diagnosis of observed atmospheric and oceanic data and has not yet been accomplished in all the model simulations. It offers the best hope of understanding this variability in the models and of the extent to which the models agree with observations.

Much of the climatic influences of the tropics on midlatitudes and the dominant modes of this interaction (Hadley cells, PNA patterns, etc.) have been found by the diagnosis and analysis of existing data. Ongoing support of (relatively inexpensive) diagnostics of atmospheric, oceanic, and atmosphere-ocean data is a requirement of the programme.

### **8.5.3 Model-assimilated data**

Good models provide a useful way of dynamically interpolating (in both space and time) observational data taken sparsely. It is a requirement of both process studies and routinely collected data that they be assimilated in models and the fields of model assimilated data be prepared.

## 8.6 LINKAGES WITH OTHER ELEMENTS AND PROGRAMMES

Because much of the deep and intermediate water in the southern Pacific and Indian Oceans arise from the region around the Antarctic, there will be strong connections to the D5 (Southern Ocean Climate Variability) element of CLIVAR.

Since the ENSO mode is decadal varying, there is an immediate connection to G1 (ENSO-Improving the Predictions) and the G2 (Interannual Variability of the Asian/Australian Monsoon).

To the extent that SST variations in the Pacific influence American Climate there is a connection to G3 (Variability of the American Monsoon System) and similarly, to the extent that Indian Ocean SST variations influence African Climate there will be a connection to G4 (African Climate Variability).

There will be strong connections to both components of ACC. Decadal variability both contributes to global temperature changes, especially over land through the COWL pattern, and masks the effect of more monotonic changes so requires that detection of Anthropogenic Climate Change fully understand the variability. Further, changes in variability under the anthropogenic addition of radiatively active constituents to the atmosphere will affect the predictions of ACC in the future.

There will be strong interaction with the results of the WOCE experiments, especially the subduction experiment, tracer release experiment, large-scale survey with XBT's, drifters, floats, and with some repeat hydrography.

The CLIVAR NEG's and Panels will play a major role in co-ordinating and in modelling the Indo-Pacific decadal variability. To the extent that TAO stays in the water for long periods of time, it will make major contributions to documenting and understanding decadal ENSO variability.

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### *III. The CLIVAR Principal Research Areas*

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## **9. SOUTHERN OCEAN CLIMATE VARIABILITY (D5)**

### **9.1 SCIENTIFIC RATIONALE**

#### **9.1.1 Antarctic Circumpolar Current**

The Southern Ocean provides the only deep ocean link between the major ocean basins. Within the circumpolar belt flows the Antarctic Circumpolar Current (ACC), transporting water from west to east at a rate of well over 100 Sv (average 134 Sv through the Drake Passage) along a 21,000 km path, forming the principle route for inter-ocean transport, muting the differences between the ocean basins stemming from ocean-atmosphere coupling. The ACC link makes possible a global thermohaline circulation which is responsible for much of the meridional heat transport in the Atlantic and in shaping the distribution of intermediate and deep water masses. The ACC allows for inter-ocean transport of heat and freshwater anomalies, permitting ocean route telecommunication of climate anomalies to regions remote from the Southern Ocean on a variety of time scales (e.g. Mikolajewicz and Maier-Reimer, 1990; White and Peterson, 1996). Additionally, changes in the strength of the ACC may be related to changes in the magnitude of the thermohaline circulation, and hence impact on global climate.

While the ACC is the major inter-ocean link, our understanding of the variability of the ACC and the impact of such variability on the climate system is rudimentary. The ISOS (International Southern Ocean Studies) experiment of the 1970s provided an estimate of the mean transport and variability of the ACC at Drake Passage. More recently, hydrographic sections occupied prior to and during WOCE have filled in details of the kinematics of the ACC (e.g. the location and structure of the major fronts). Satellite altimeters have provided an unprecedented view of the eddy variability of the Southern Ocean. High resolution numerical models such as FRAM have illuminated the dynamics of the current. Nevertheless, major gaps remain in our understanding of the ACC and its role with respect to climate variability.

#### **9.1.2 Meridional fluxes and intermediate water ventilation**

In the meridional plane, the ACC acts to isolate thermocline water from the polar ocean, forcing a perpetual glacial state of Antarctica. Density surfaces ‘geostrophically’ shoal across the ACC from abyssal depths north of the ACC to near surface levels south of the ACC. This allows isopycnal access of the abyssal ocean to the cold polar atmosphere, and complex interactions with sea ice and glacial ice. Meridional fluxes across the ACC, which connect the polar region of the Southern Ocean to the global ocean, are accomplished within deep boundary currents, by eddy and isopycnal mixing processes and within the Ekman layer at shallower levels.

The Ekman layer forces subduction of low salinity surface water from both north and south of the main core of the ACC, forming Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW). These waters ventilate the subtropical thermocline of the Southern Hemisphere oceans on decadal time scales and play a major role in the uptake of atmospheric CO<sub>2</sub>. Their freshwater content helps close the hydrological cycle of the subtropical evaporative regions. AAIW marks the base of the thermocline with a salinity minimum, limiting further downward penetration of thermocline heat and salt. Understanding SAMW and AAIW formation rates, mechanisms and circulation paths, and their susceptibility to change, is relevant to CLIVAR for several reasons: the sites of SAMW and AAIW formation represent regions of significant ocean to atmosphere heat flux; changes in SAMW and AAIW formation rate or properties may alter the shape of the thermocline and hence the heat storage capacity of the subtropical gyre; SAMW and AAIW provide a useful integral measure of climate change in the ocean in response to changes in forcing on the decadal time scale; SAMW and AAIW mix with the overlying waters and in this way influence SST at sites remote from their formation region; and SAMW and AAIW play an important part in recycling North Atlantic Deep Water (NADW) and helping close the thermohaline circulation.

### 9.1.3 Deep and bottom ventilation

The cold, dense water flooding the deepest part of the global ocean, the Antarctic Bottom Water (AABW), forms at many sites along the continental margins of Antarctica. Sinking of AABW (and AAIW) balances upwelling of Circumpolar Deep Water (CDW), fed by injection of NADW, between the ACC and Antarctica. Exposure to the cold polar atmosphere, sea ice, and glacial ice, converts the upwelled CDW to either lighter surface water that eventually spreads north to feed into AAIW, or into AABW that sinks in plumes over the continental slope to the sea floor, or into the deep ocean in what may be called Antarctic Deep Water. Within the Weddell Sea there are also signs of sporadic deep reaching open ocean convection, similar to that observed in the Labrador, Greenland and Mediterranean Seas.

The Antarctic Zone (the region south of the ACC) is the site of extensive seasonal sea ice cover, which is intricately involved with the water mass modification process. Ocean/glacial ice interaction also plays a role, as glacial melt water is a significant ingredient in AABW. The circulation and vertical fluxes within the Antarctic Zone not only influence the overall characteristics of the deep ocean and thus the global climate, but also affect sea ice traits, provide the physical setting for the unique ecological system of the region, and perhaps influence the stability of the glacial cap of Antarctica. All of these attributes influence the global heat/fresh water and CO<sub>2</sub> budgets as well as sea level changes.

The thermohaline stratification within the Antarctic Zone over the open deep ocean consists of cold surface water “floating”, by virtue of its reduced salinity, over a much thicker stratum of warmer and saltier deep water. Winter hydrographic data indicate significant inclusion of the deep warmer/saltier water into the winter mixed layer. It is likely that the extensive winter sea ice cover of the Southern Ocean is in fact limited in its thickness by the introduction of warm and salty deep water into the winter mixed layer. The static stability between the mixed layer and deep water is quite weak; small factors influencing the salinity budget can upset it, causing vigorous convection. It is likely that a network of negative feedbacks (depending for the most part on the freshwater balance including sea ice formation and melting rates) maintains the thin veneer of sea ice in a more-or-less stable configuration.

The Weddell polynya of the mid-1970's (Fig. 9.1) is a dramatic example of an abrupt and significant change in deep ocean properties and air-sea heat flux. The climate impact of such an anomaly is uncertain. The possibility exists of changes in the frequency of open ocean polynyas associated with changes in the ocean and atmosphere coupling. During the Weddell Polynya, ocean stratification was destroyed by vigorous deep reaching convection which cooled the ocean to nearly 3000 m depth, marking it as a major climate event. There is evidence that the cold signal imposed on the deep ocean in the Weddell Sea by the polynya has propagated into the deep South Atlantic. We do not understand what controls the stability of each mode, and what might trigger a transition. Could there be a sudden change in the dominance of one mode over the other, perhaps as a response to the expected “greenhouse” induced warming trend? Reliable answers to these questions will be possible only after a better understanding of the air/sea/ice processes which control the stratification of the upper ocean in the Weddell Gyre is achieved.

### 9.1.4 Sensitivity of climate models to Southern Ocean sea ice

Rind et al. (1995) show that 38% of global annual mean surface warming for 2xCO<sub>2</sub> studies using the GISS AGCM is due to change in the sea ice fields - 70% of this is attributed to change in Antarctic sea ice. Addition of improved ocean-ice coupling alters the global mean response by about 30%. Washington et al. (1995) and Manabe et al. (1995) report significant influence of sea ice on their global climate simulations, but show opposite responses in sea ice fields to changes in surface forcing. Meehl and Washington (1990) and Rind et al. (1997) show that changes in sea ice albedo and ease of melting have significant impact on global climate.

Global models with varying sea ice treatments thus show the pivotal role of sea ice in global climate. Surface temperature fields support this sensitivity in the high northern latitudes, while there is insufficient data to test this in the Southern Hemisphere. Therefore, models and sparse data suggest that sea ice fields require considerable attention to improve their representation in models; to monitor them because of their sensitivity; and to establish how this global link is manifested in reality.

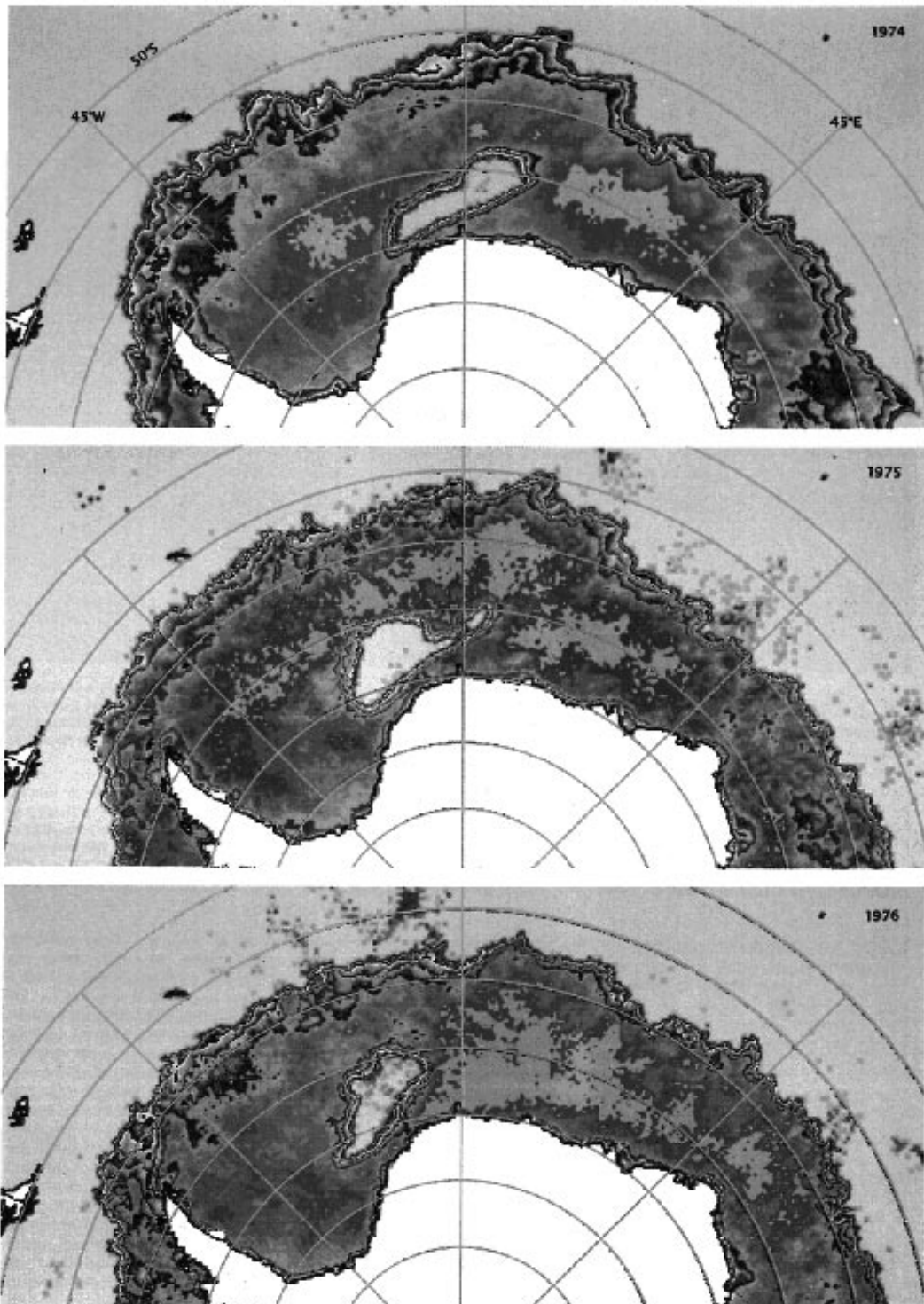


Fig. 9.1: Weddell Polynya: An enormous ice-free region amid the ice cover near the Weddell Sea formed during three consecutive Southern Hemisphere winters. In these satellite images, which were made in September of 1974 (top), 1975 (middle) and 1976 (bottom), the white region represents the Antarctic landmass and grey shaded regions represent ocean areas covered by various concentrations of sea ice. Dark grey regions are almost completely covered by ice and light grey regions are ice-free. In summer the polynya disappeared with the melting of the ice cover. At its largest the polynya measured about 350 by 1000 kilometres. It had measurable effects on the temperature of the underlying ocean at depths as great as 2500 meters (from Gordon and Comiso, 1988).



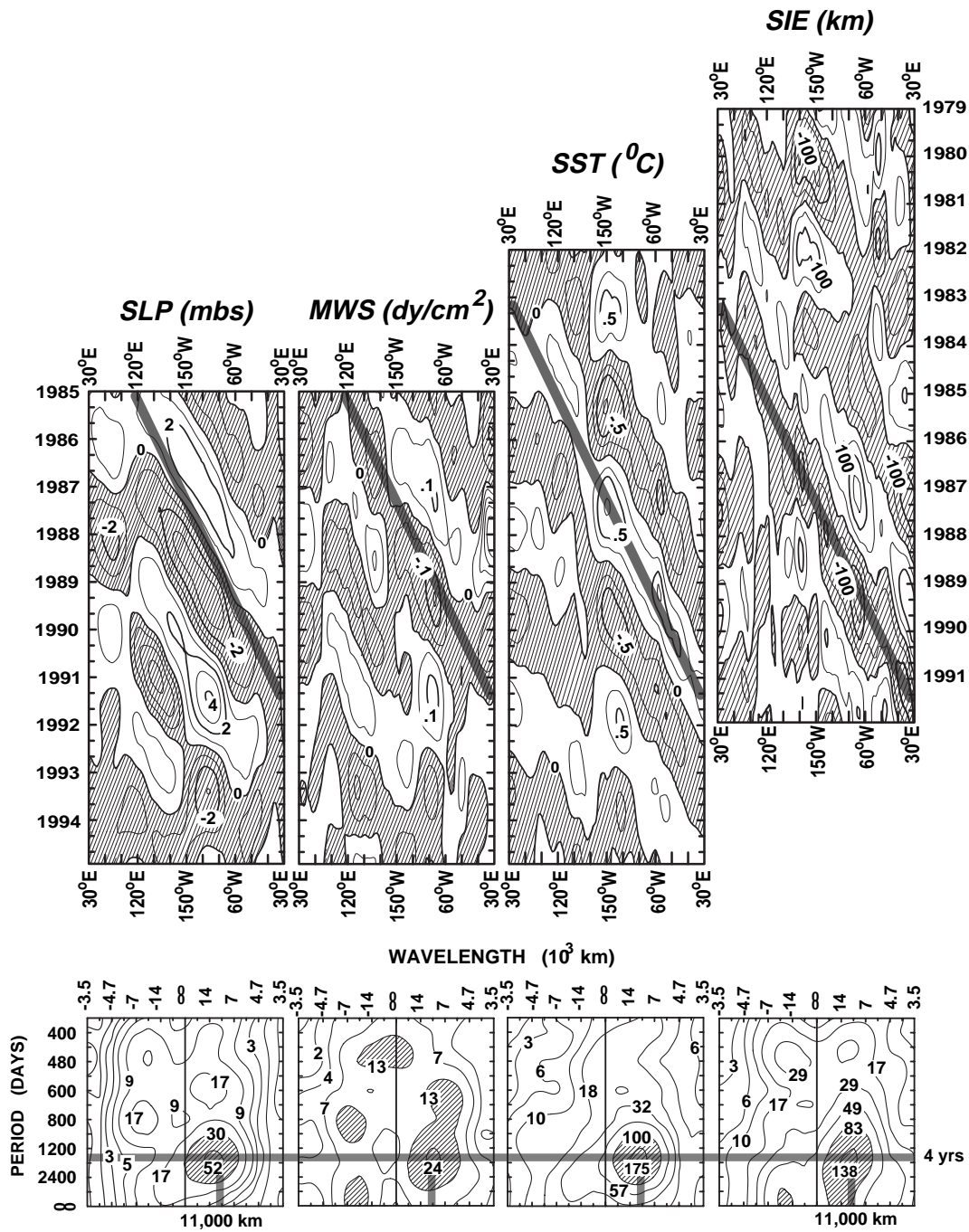


Fig. 9.2:

Top panels: time-longitude diagrams of interannual anomalies along 56°S in sea-level pressure (SLP), meridional wind stress (MWS), sea surface temperature (SST) and, along 5° longitude increments, in meridional sea ice extent (SIE). Negative and southward anomalies are shaded. The grey bars in all panels are synchronous in time and space. Contour intervals are 1.0 hPa for SLP, 0.05 dyn cm<sup>-2</sup> for MWS, 0.25°C for SST and 50 km for SIE.

Bottom panels: two-dimensional auto-spectra of the above quantities, computed from unsmoothed monthly anomalies. Positive wave-lengths denote eastward propagation. Contoured values are in power units of the above quantities (units-squared times frequency), and are selected such that each contour is statistically independent from its neighbours (from White and Peterson, 1996).

### 9.1.5 Sensitivity of climate models to heat storage and overturning in Southern Ocean

Early simulations of the response of the climate system to increasing atmospheric CO<sub>2</sub> showed a dramatic contrast between the rate of warming in the Northern and Southern Hemispheres. Deep mixing in the model Southern Ocean absorbed large amounts of heat, slowing the rate of surface temperature increase in the Southern Ocean (Manabe and Stouffer, 1988). These models may have overestimated the extent of deep mixing in the Southern Ocean. In any case, these simulations underscore the fact that heat storage in the Southern Ocean may impact climate on at least hemispheric scales. Climate models must accurately represent the structure of the upper layers of the Southern Ocean if they are to produce reliable estimates of future climate change. The extent to which heat storage anomalies in the Southern Ocean affect climate variability on shorter time scales is unknown.

### 9.1.6 Coherent climate patterns and variability in the Southern Hemisphere

Much of our knowledge regarding the nature of large-scale coherent climate patterns such as the NAO, PNA, etc. and their relationship to regional climate states has come from analysis of the extensive data sets available for the Northern Hemisphere. The scarcity of such data in the Southern Ocean has greatly hindered our ability to evaluate the global nature and extent of such patterns, and their global means of communication and sensitivity.

Analysis of those data that are available suggest that there are at least two large-scale coherent patterns in the Southern Hemisphere. One, the Antarctic Circumpolar Wave (White and Peterson, 1996), is a recent discovery that displays an eastward propagating coherent response between the ice edge position, SST, SLP and surface winds (Fig. 9.2). The other shows that a meridional teleconnection pattern exists across the South Pacific and South America (sometimes called the Pacific-South American (PSA) pattern, analogous to the PNA pattern in the Northern Hemisphere) during the warm phase of ENSO in the southern winter, though it appears to be weaker and more variable than the Northern Hemisphere teleconnection (van Loon and Shea, 1985; 1987; Karoly, 1989). The weaker and more variable response in southern winter is consistent with the relatively weaker tropical forcing, as well as the weaker zonal gradients in the mean flow providing less of a geographical focus for the mid-latitude (Southern Ocean) teleconnections.

In addition to the presence of the coherent patterns, a change in the Southern Hemisphere atmospheric circulation is evident in the late 1970s with SLP in the circumpolar trough generally lower in the 1980s than in the 1970s and with the changes most pronounced in the second half of the year, so that the tropospheric polar vortex remained strong into November and was associated with a delayed breakdown in the stratospheric polar vortex and the beginning of the ozone deficit in the Antarctic spring (Hurrell and van Loon, 1994). It is not believed that the ozone depletion was responsible for the change but it does highlight a dynamical component to the ozone hole problem. Instead it seems likely that the changes are associated with the increase in tropical SSTs and associated changes noted for the North Pacific. Finally, interannual variations are found in the zonal mean flow and there appears to be a profound influence of the low-frequency circulation on the Southern Ocean storm tracks (Trenberth et al., 1998), with possible implications on the transient eddy poleward heat flux (Karoly, 1990).

Increased understanding of these patterns and large-scale coherent variations are necessary in order to better define coherent climate structure in the Southern Hemisphere and establish the nature and mechanisms of their large-scale communication and regional impacts. This is best studied through more regular and widespread observations (as outlined in Section 9.4) and through modelling studies.

### 9.1.7 Unique Southern Ocean paleoclimate information

The fact that the ACC serves to mix and redistribute water masses from all of the ocean basins offers a unique opportunity for estimating the nature and relative contributions of the water masses from the various basins during paleoclimate states through use of the deep sea sediment record. A number of proxy indicators exist that may allow the deciphering of the primary mixture and its sources. Consequently, such records may provide an indication of the range of ocean circulation modes that may occur given changes in the climate state. The comparison of the climatic evolution of the high latitudes of the North Atlantic Ocean with that of the Southern Ocean during the geological past and the reconstructed global deep water circulation should provide new insights on the control of the thermohaline circulation by the salinity/density contrast between the high latitudes of both hemispheres.

Ice core records from the central Antarctic ice sheet provide a past record of Antarctic climate, as well as the Southern Hemisphere atmospheric chemistry. Ice cores along the high snow deposition coastal regions and in the western Antarctic ice sheet can provide past records of local or regional climate change with annual resolution. Such records may provide an indication of past changes in the ice sheet itself including its stability. As the ice sheet contains the overwhelming majority of the world's glacial ice, the mass balance of this ice sheet plays a major role in global sea level. By studying its past variability, such as the stability of the West Antarctic ice sheet, we are afforded a better idea of the rates and magnitude of balance changes (and thus sea level changes) that have occurred in the past. Cores from the coastal sites may also help extend the polar ocean climate back through time, enhancing our ability to tie the regional climate changes to ENSO and other global climate phenomena.

### 9.1.8 Scientific rationale summary

The Southern Ocean helps shape the global ocean stratification; it plays a unique role in coupling the ocean to the atmosphere and cryosphere; and it plays a central role in global sea level. Variations in these aspects of the global climate system may be expected to be linked to and perhaps drive global climate variability and hence is relevant to CLIVAR's global charge. Specific Southern Ocean climate foci that warrant further study include:

1. The Antarctic Circumpolar Current that connects the major ocean basins permitting a global-scale thermohaline circulation and providing an inter-ocean communication route for heat and freshwater (climate) anomalies.
2. The Southern Ocean coupling of the ocean and atmosphere within the subantarctic belt and its polar-extrapolar communication of heat, freshwater and CO<sub>2</sub> through the production of Antarctic Intermediate Water and Subantarctic Mode Water, which spread northward injecting cool low salinity water into and along the base of the main thermocline helping close the hydrological cycle.
3. Upwelling of Circumpolar Deep Water poleward of the Antarctic Circumpolar Current provides the site for major venting of deep oceanic heat into the atmosphere and associated cryosphere (sea ice and its polynyas and glacial shelf ice), it may also influence sea level as a result.
4. The production of the very cold dense Antarctic Bottom Water which dominates the lower two kilometres of the global ocean, chilling the global ocean to an average temperature well below the coolest temperatures possible from the North Atlantic Deep Water.
5. The Antarctic sea ice fields that represent a highly mobile and mutable surface property whose distribution and characteristics may play a major role in the global radiative budget and thus global climate.
6. The large-scale coherent variability of the atmospheric circulation over the Southern Ocean and the mechanisms of these variations and their geographic communication, are directly involved in the

propagation of anomalies across the various climate zones.

Interpreting the causes of temperature and salinity variability observed in the ocean interior requires an understanding of the formation of Southern Ocean water masses and the circulation paths they follow. Changes in heat supplied by the deep ocean may influence the atmosphere directly or through changes in sea ice, which in turn may affect albedo, air-sea heat and gas exchange.

The state of observations and modelling of the Southern Ocean is not as developed as it is in other regions of the ocean and atmosphere. While major strides have been made in the last ten years, presently we have only a “glimpse” of the mean state and variability of the Southern Ocean, its coupling with the atmosphere and cryosphere, and of the zonal and meridional fluxes. Our observations are incomplete in space and time, while our models do not properly simulate ventilation processes, and thus provide an incomplete picture of the Southern Ocean impact on climate. While we can formulate specific plans for some phenomena, the Southern Ocean component of CLIVAR requires more emphasis on exploratory investigations than do CLIVAR activities in better-sampled ocean basins.

## 9.2 SCIENTIFIC FOCI OF SOUTHERN OCEAN CLIVAR

For practical considerations not all of the Southern Ocean climate related issues can be covered by CLIVAR research. A subset is selected that is considered as important and for which significant progress can be expected. The scientific rationale summarised above can best be addressed by focusing on four phenomena:

### 9.2.1 Variability in the Antarctic Circumpolar Current

The best documented surface pattern displaying variability over a variety of time scales is that of the Antarctic Circumpolar Wave (ACW) which manifests itself as an eastward propagating anomaly in sea ice extent, SST, SLP and meridional wind stress (White and Peterson, 1996) (Fig. 9.3). The wave shows strong correlation to ENSO and the Indian Monsoons ( $r = 0.7, 0.75$  over all bands - not filtered, Yuan et al., 1996). The PSA and variability in the mean zonal wind are also climate structures that appear to be fairly well documented.

These recently discovered patterns require concentrated study in order to:

1. establish if they represent formal modes (i.e. a spatially organised climatic component showing spatially preserved coherence during systematic temporal variation);
2. establish their spatial extent and connectivity in the ocean, atmosphere and sea ice;
3. determine their dominant/controlling physical mechanisms; and
4. determine if their surface signal penetrates in the ocean to intermediate or deep layers.

Advancement of our understanding of these phenomena requires:

1. further data analysis (including special care to proper statistical assessments);
2. model “verification” (i.e. do models capture the spatial/temporal coherent patterns and if so, what other patterns do they imply for data-poor regions in the Southern Hemisphere?); and
3. process studies to determine how air-sea-ice coupling and internal oceanic processes contribute to the phenomena.

Sustained observations of the following are needed:

1. sea ice extent;
2. ice thickness to evaluate freshwater impact of anomalies;
3. surface and sub-surface temperature and salinity in data-sparse areas of the southern oceans to determine the internal ocean structure of the patterns and to examine the coupling between the polar and subtropical modes, and to test mechanisms involving coupled instabilities.

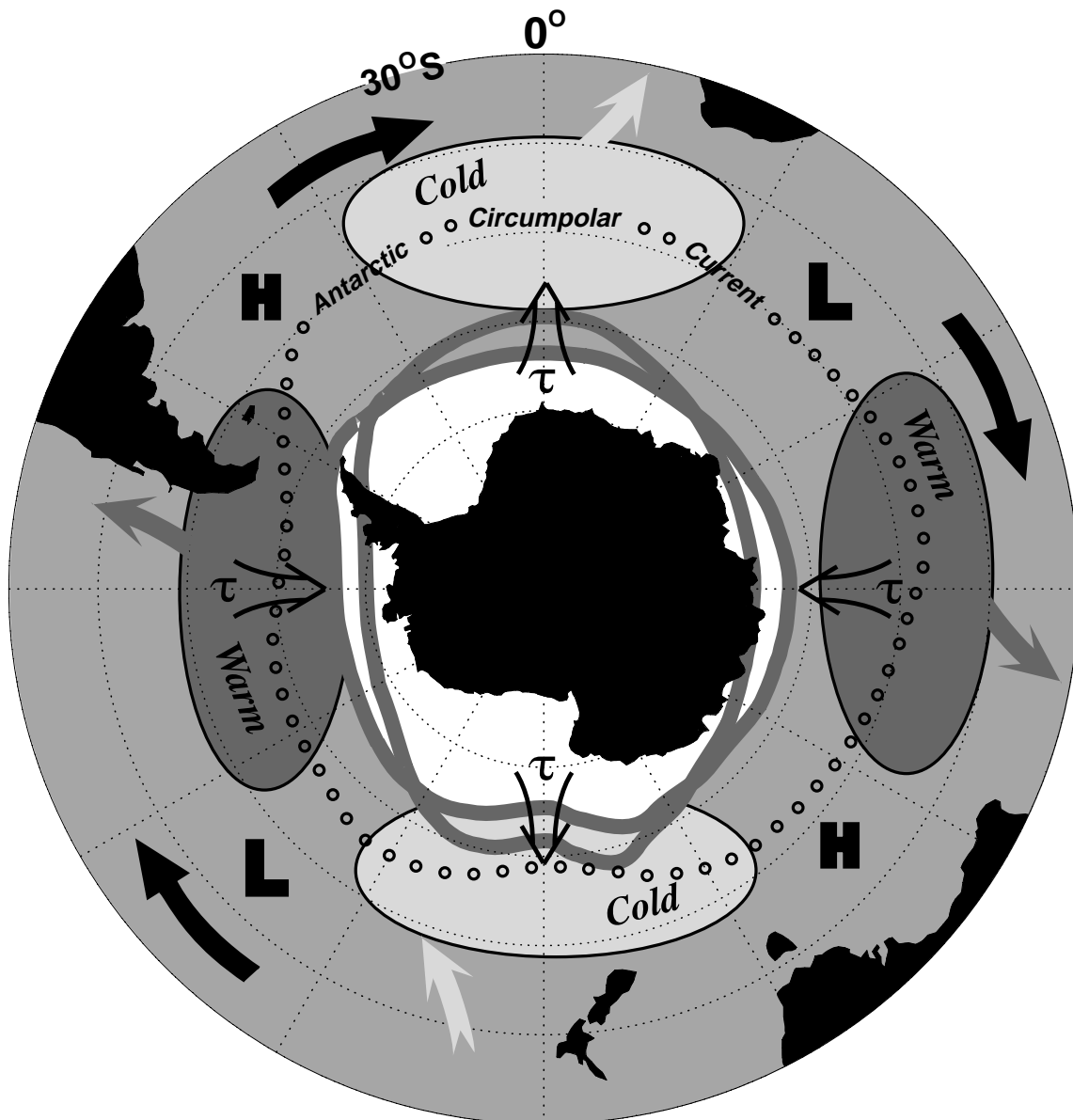


Fig. 9.3: Simplified schematic summary of interannual variations in sea surface temperature (dark shading, warm, light shading, cold), atmospheric sea-level pressure (bold H and L), meridional wind stress (denoted by  $\tau$ ), and sea-ice extent (grey lines), together with the mean course of the Antarctic Circumpolar Current (dotted line). Sea ice extent is based on an overall 13-year average. Heavy black arrows depict the general eastward motion of anomalies, and other arrows indicate communications between the Antarctic Circumpolar Current and the more northerly subtropical gyres (after White and Peterson (1996)).

### 9.2.2 Variability of subantarctic mode water and Antarctic intermediate water

Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) ventilate the subtropical thermocline of the Southern Hemisphere oceans on gyre circulation time scales. Understanding the formation rates, evolution, and penetration of SAMW and AAIW is relevant to CLIVAR for several reasons. The range of densities of SAMW/AAIW spans the main thermocline, and changes in its formation rate or characteristics could change the shape and heat content of the southern subtropical gyres. The SAMW renews itself, at least partially each winter, and provides a useful way to measure climate change over longer time periods. Some of the warmer subtropical water lying above mode water was cooled and converted into mode water as part of the convective formation process, and therefore might be considered the descending branch of an upper ocean thermohaline cell. Similarly, some of the NADW reaching the Southern Ocean is recycled as AAIW and returned to the lower latitude oceans. Variability in these cells could involve surface as well as subsurface properties, with mechanisms distinct from those of the wind-driven gyres.

Quantitative estimates of SAMW formation rates and their distribution around the continent are lacking. The process of formation has been clear for a long time, and involves the generation of deep winter mixed layers as buoyancy is lost to the atmosphere north of the Circumpolar Current. These layers become a source of low potential vorticity (PV) and high oxygen, marking the penetration of mode waters to lower latitudes. The origin of the water replacing that lost to lower latitudes may be to the south of the ACC polar front as well as from the subtropics, but the relative contribution of each is unknown. Nor can we identify the mechanisms which control the spreading to lower latitudes. Though it is established that mode waters do vary over time, the roles of wind and buoyancy forcing are not unravelled. Similar uncertainties exist for AAIW.

Mode water is famous for its insensitivity to change, yet it has been found to vary somewhat over time. The 18°C mode water of the North Atlantic shows changes in PV and other properties (Talley and Raymer, 1982; Joyce and Robbins, 1996) on time scales of years to decades. Changes in SAMW properties have been found too (Bindoff and McDougall, 1994), with amplitudes of several tenths of a degree and roughly one tenth ppt. These changes are consistent with cooling and freshening on isopycnals and are coherent over large spatial scales between the late 1960's and early 1990's. The changes are also consistent with warming and freshening at high southern latitudes sometime within the two decade period separating measurements, though the time scale of the changes themselves is not resolved.

The circulation of mode and intermediate water in subtropical gyres implies a link between air-sea interaction in the Southern Ocean and thermocline variability at lower latitude. A focused effort will be undertaken as part of CLIVAR to investigate this link and determine the mechanisms of mode water propagation and evolution. A combination of observations and model studies are required, as described below.

### 9.2.3 Coupled variability of deep water formation, sea ice and the atmosphere

The variability in deep water upwelling and bottom water formation (overturning cell) and the coupled response in the distribution, extent and thickness of sea ice, glacial ice and the atmosphere (including the possibility of abrupt change) require further research.

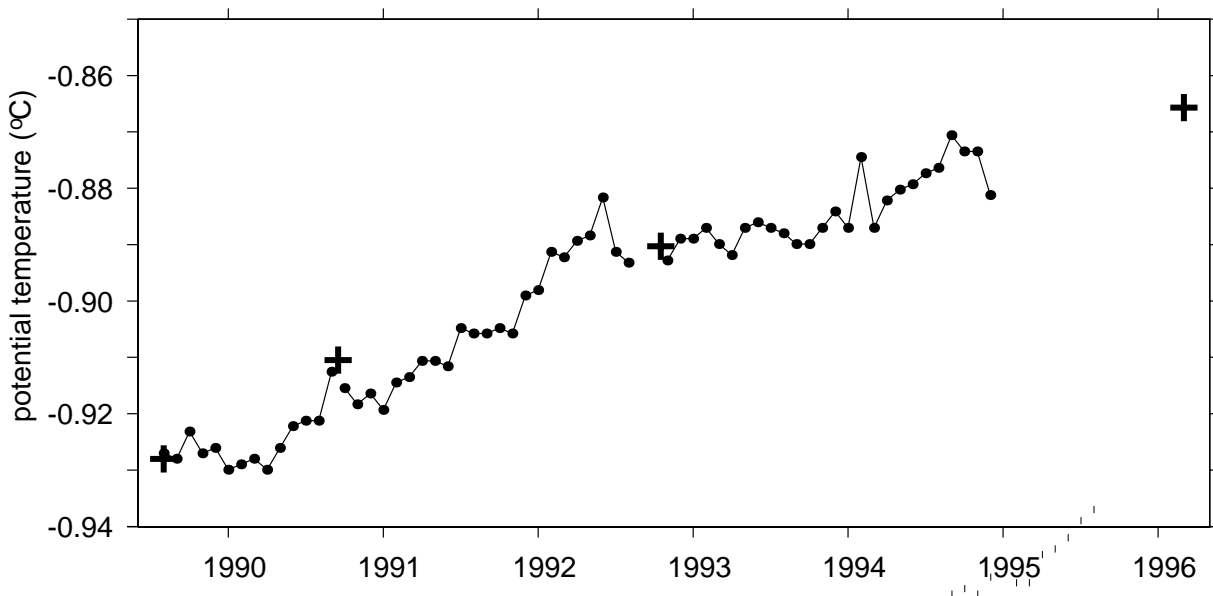
Upwelling of deep water in the Antarctic zone provides heat and salt into the surface layer. Modification of the upwelled water leads to the downward flux of AABW. The exact spatial and temporal patterns of Southern Ocean overturning and its vulnerability to change is only vaguely known. Observations and modelling of this process must be improved.

The deep water heat is lost to the atmosphere, and on the annual mean the deep water salt mixes with freshwater induced by excess precipitation and by glacial melt to renew the surface water layer. Upwelling rates suggest that the Antarctic Surface Water has a residence time of only 1.5 years, as about 24 Sv of warm deep water upwells into the surface layer (Gordon and Huber, 1990). The upwelling balances the divergence of surface water, half of which is lost to the north by Ekman transport, and half of which sinks into the deep

ocean as AABW and Antarctic Deep Water. The path followed by a parcel of upwelled deep water depends on the spatial and temporal variability in the pycnocline separating the cold surface layer from the relatively warm deep water, which in turn depends very much on the freshwater fluxes. A dominant component of the freshwater flux is the formation, transport and melting of sea ice.

Ice extent and volume are potentially an indicator of climate change. Changes in ice extent/volume can feed back on the atmosphere and ocean via altered ocean-atmosphere heat exchange and vertical salt flux. To date there is no evidence of a trend in the hemispheric extent of sea ice. Propagating anomalies of ice extent, however, have been identified as part of the Antarctic Circumpolar Wave. Few observations of ice thickness exist, so it is not possible to say whether there is any trend or identifiable anomaly pattern in ice thickness or volume.

The main mode of deep ocean ventilation in the Southern Ocean is through formation of dense water on the continental shelf, and subsequent sinking within slope plumes as AABW. Equation of state thermobaric and cabbling effects likely play a central role in the sinking process. In certain shelf areas salt accumulation from sea ice formation can lead to the formation of high salinity shelf water. Some of this relatively saline cold water slips off the shelf to the deep sea, and some flows below the ice shelves, diluted slightly by glacial melt and cooled even further by the depressed freezing point induced by the elevated pressure at the ocean - glacial ice contact. This process produces Ice Shelf Water, which provides for a significant contribution to the shelf water sinking within the plumes, at least within the Weddell Sea. The total amount of AABW formed in the continental margins is not as precisely known as are the components of NADW. A best guess at this time is between 10 to 15 Sv of water colder than  $-1^{\circ}\text{C}$ . The outflow of bottom water in the western Weddell Sea is subject to significant seasonal and interannual variation (Fahrbach et al., 1995). A gradual warming was recently detected (Fig. 9.4) over the time scale of 5 years which affected large parts of the Weddell Sea Bottom Water (Fahrbach et al., 1997).



Recent studies of the upwelling of relatively warm deep water (Gordon and Huber, 1990; Martinson, 1990, 1991; McPhee et al., 1996; Gordon et al., 1993) reveal the very delicate nature of static stability within the Antarctic Zone. Upwelling and sinking occur at small spatial and temporal scales, making observation and modelling exceedingly difficult. Slight changes to the pycnocline stability would alter the access of the deep water heat and salt to the surface layer, and hence to the atmosphere and sea ice. The immense heat supply of the deep water could remove the winter ice cover, should the winter pycnocline weaken sufficiently. This happened for three years running in the Weddell Sea in the mid 70's during the Weddell Polynya phenomena (Gordon, 1982). Repeat surveys of the warm layer on the Greenwich Meridian indicate a warming trend since the early 1980s (Fig. 9.5). Might the Polynya mode of convection become more or less common in the future? If a Weddell Polynya becomes the rule rather than the anomaly, there would be a complete change of the way the Southern Ocean ventilates the deep ocean, perhaps on a par with the turning on and off the North Atlantic Deep Water (NADW) associated with the glacial cycles and other abrupt changes in the global climate.

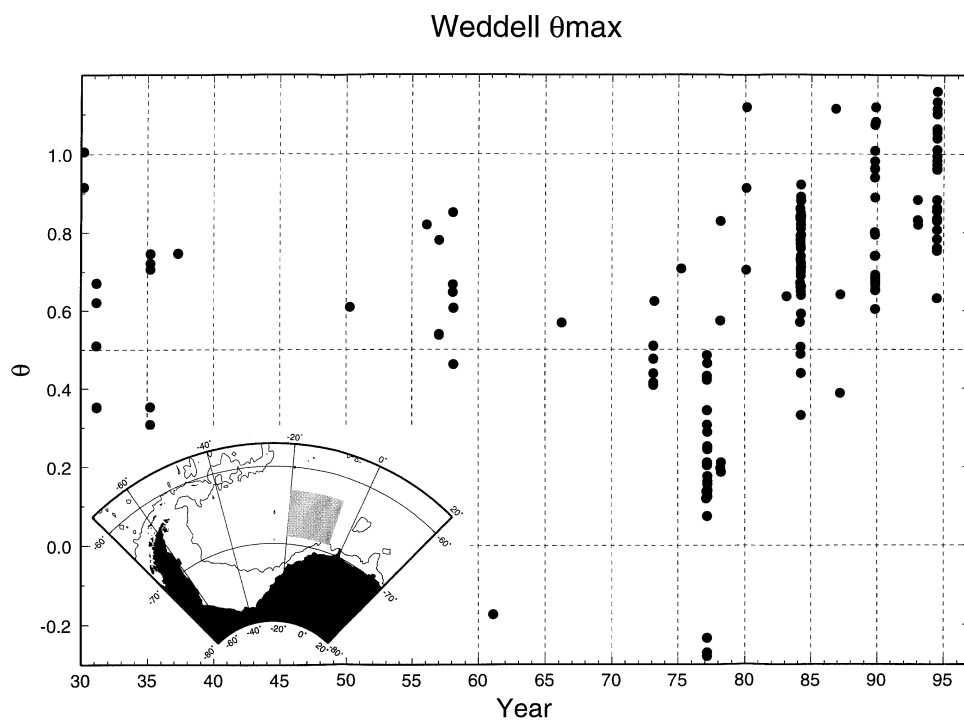


Fig. 9.5: Potential temperatures obtained from repeat surveys of the warm layer on the Greenwich Meridian indicate a warming trend since the early 1980s (from Gordon, pers. communication).

This focus is best approached by sustained observations of: atmospheric conditions over the Antarctic zone; sea ice distribution and thickness; the drainage of cold deep and bottom water from sites of AABW formation; and ocean circulation and stratification within the Antarctic zone. These observations are needed to improve the simulation of sea ice in regional and global models. Additionally, a process oriented experiment to investigate the formation mechanisms for AABW is needed before that important process can be properly captured in ocean models. Should the Weddell Polynya re-appear it is recommended that an observational programme be launched to measure the active overturning processes associated with the polynya.



#### 9.2.4 Formation mechanism of Antarctic bottom water

The three foci listed above can be addressed with the large-scale observational and modelling activities (see Sections 9.3 and 9.4). However, a special process-oriented experiment is needed to better resolve the spatial and temporal scales associated with formation of AABW along the continental margin. AABW formation is not represented in large-scale climate models and the processes responsible for the formation of this globally pervasive water mass is poorly understood. How robust is AABW formation? Might it be vulnerable to change?

It is indeed remarkable that formation of such a globally influential water mass as AABW stems from small-scale processes associated with the shelf-slope front. As the parent waters for AABW are found in abundance along the margins of Antarctica, it is suspected that the “bottle-neck” which effectively governs AABW production occurs at the shelf-slope front, where various equations of state subtleties, such as the thermobaric effect and cabbeling come into play. Faced with the small spatial scales associated with AABW production one can ask: can global-scale models properly simulate the thermohaline processes leading to globally important AABW? As a first step the observational understanding of AABW formation must be strengthened. This will then allow for better evaluation of the model performance, and further development of AABW representation in the models.

The exact design of a AABW field experiment is not delineated in the following sections, it is recommended that a cost efficient programme be designed to address the basic issue:

1. What controls the rate and water properties of deep reaching convection within the continental margins of Antarctica?
2. How are these coupled to atmospheric and associated sea ice forcing?

### 9.3 MODELLING AND PREDICTION

As for other areas of CLIVAR, a hierarchy of models is required in order to address properly the range of issues spanning a variety of space and time scales, and differing degrees of complexity.

#### 9.3.1 Global circulation model studies

The lack of observations in the Southern Ocean means that documenting patterns of variability is difficult. In this context, AGCMs driven with imposed SST or ice anomalies at their lower boundary have a role in elucidating the sensitivity of the climate system to Southern Ocean anomalies. Similar experiments with OGCMs would assist in developing hypotheses as to the nature and impact of oceanic teleconnections between high and low latitudes.

The response of coupled climate models to increasing atmospheric CO<sub>2</sub> concentrations has been shown to be sensitive to the representation of Southern Ocean sea ice, mixing and circulation. However, it is difficult to draw clear conclusions from such simulations as to the role of the Southern Ocean in the real climate system because the models fail to capture major features of the Southern Ocean circulation. The models are improving rapidly, however, so this situation is likely to change during CLIVAR.

The ability to simulate the Antarctic Circumpolar Wave and the Pacific - South American teleconnection needs to be explored in models as well as in ocean observations. Since these climate patterns display coherent patterns of hemispheric climate phenomena, their large-scale teleconnections, as well as regional and local climate influences, provide a strong diagnostic for GCMs. Once these patterns are properly simulated in models, an attempt should be made to: evaluate their underlying mechanisms and sensitivities; identify any predictive capabilities that may result from their broader linkages; isolate new patterns not cur-

rently identified in the sparse observational base, which may help locate future monitoring sites; and clarify the characteristics of the patterns, including the full extent of their geographic influences and covariability between various properties and the different components of the climate system.

One of the significant discrepancies between present “state of the art” ocean models and observations is the failure of the models to simulate the salinity minimum of the Antarctic Intermediate Water. A model which fails to form and export mode and intermediate water is unlikely to correctly simulate the ocean's ability to store heat and other properties. Seasonality is likely to be important in the formation of SAMW and AAIW, so models which are driven with seasonal forcing and respond by reproducing the observed seasonal cycle are needed.

One of the major difficulties facing modellers of the Southern Ocean is the poor knowledge of the surface forcing (SST or heat flux, SSS or freshwater flux, and wind stress). Some of the observations proposed below (e.g. surface drifters, PALACE floats measuring salinity, satellite measurements) are crucial to improving estimates of surface forcing over the Southern Ocean. Such estimates are not only needed to drive ocean-only models, but to validate coupled models.

### 9.3.2 Regional model studies

In addition to the GCM studies designed to examine the global influence and feedbacks of the Southern Ocean characteristics, regional models are required to better determine which processes are critical to the regional evolution, and therefore must be properly parameterised in the GCMs. Such models are essential to the study of specific processes and sensitivities involved in: deep and intermediate water formation and their flow rates and paths; regional preconditioning of the polar gyres and their sensitivity to convective overturn; glacial ice-ocean interaction, particularly its influence on the stability of the ice sheet and sea level; gyre scale ocean-ice interaction and its influence on the ice distribution in space and time; communication of properties between polar and sub-tropical regions and its sensitivity; and other such processes thought to be critical in the Southern Ocean's influence on climate.

### 9.3.3 Local process models

Finally, local process models are required to explicitly target individual processes or phenomena in an effort to determine the relative control by competing processes, appropriate sub-grid scale parameterisation schemes, critical sampling intervals and scales, and sensitivities to changes in the forcing and initial conditions. These sensitivities are important, since in larger scale models the initial conditions and often the forcing at local scales will be determined prognostically, so these sensitivities define acceptable levels of fidelity required of the regional and global models in order to represent the important local processes properly.

Local process models are still required to address: all characteristics of the sea ice and its interaction with the ocean and ice, in order to better define the ice-albedo feedback, ice-cloud feedback, surface energy balance, generation of lead area, and ice-ocean interaction; glacial ice-ocean interaction including formation of dense deep water and in the mass balance of the ice, critical to sea level change; the formation of deep and bottom waters along continental shelves and its sensitivity; and the local atmospheric response (heat and moisture) to changes in surface characteristics. The latter is quite important for global change studies in which dramatic changes in the sea ice cover may be offset by changes in the overlying cloud cover and temperature profile.

### 9.3.4 Modelling strategy

Current limitations in the modelling and prediction of the vast Southern Ocean and some of its geographically unique processes, involve a broad range of scales and issues. Consequently, modelling support for this component must be multi-faceted. In particular, some issues must be resolved by concentrated efforts while others can be addressed by fostering co-operation between existing programs. The latter will be particularly helpful when serving to integrate the hierarchy of models, and/or combining modelling and observational efforts.

In general, global circulation modelling studies must focus on improved ocean-atmosphere-ice process representation (in co-operation with regional and process-oriented modelling studies), improved fidelity of large-scale critical circulation features (e.g. intermediate waters, ACW, etc.) in co-operation with observationalists, and sensitivity studies aimed at identifying critical components (processes and circulation characteristics) in the Southern Ocean's role in global climate. Regional modelling studies are required to address the sensitivity issue, focusing on the role of local (sub-grid-scale) processes on the regional and global-scale system, and in testing specific parameterisations. Local models must further elaborate process-sensitivities while primarily improving the representation of sub-grid-scale processes in the larger scale models.

## 9.4 OBSERVATIONAL STRATEGY

The observations required to address the first three foci (Section 9.2) of the Southern Ocean component of CLIVAR DecCen should contain the following specific elements. These elements are described in a unified fashion rather than within each of the individual scientific foci, as each measurement generally contributes to more than one of the scientific questions to be addressed. As mentioned above the fourth focus, the process study of AABW formation will require a more focused workshop to develop. For example, it will be considered within the SCOR affiliated Working Group "iAnZone".

### 9.4.1 Chokepoints: Fluxes monitoring associated with the ACC between the three ocean basins

Checkpoint monitoring is best done using a combination of observational tools. Profiling CTDs or dynamic height moorings at either side of each of the chokepoints between Antarctica and the other Southern Hemisphere continents will measure changes in the net baroclinic transport. Deep pressure gauges at either side of the chokepoints provide a low-cost means of monitoring changes in the absolute transport. The location of the checkpoint lines should repeat sections taken during WOCE in order to extend time-series measurements. These are section SR1 across Drake Passage, SR2 south of Africa and SR3 south of Tasmania (WCRP, 1988). Sections should meet the established WOCE standards.

To measure changes in the heat flux, measurements at the end points are not sufficient. Repeat XBT sections across the checkpoint sections will provide measurements of changes in upper ocean heat content and SST on seasonal and interannual time scales. In addition, by exploiting the relationship between upper ocean temperature and dynamic height, XBTs can be used to infer velocities even in the Southern Ocean where salinity changes are important (Rintoul et al., 1997). In this way XBT sections can be used to measure changes in the heat carried by the Antarctic Circumpolar Current. Freshwater fluxes require use of XCTD's to measure salinity as well as temperature. Taking into account the zonal variations of the XBT tracks and the uncompleted time coverage a restricted number of moorings with profiling CTDs should be maintained on the checkpoint lines to avoid aliasing of the seasonal signal.

While repeat XBT sections across the Southern Ocean chokepoints provide a cost-effective way to monitor changes in upper ocean heat content and the transport of volume and heat, they are not able to measure changes in deep ocean properties or the transport of deep layers. For this purpose, full-depth CTD sec-

tions are required. Such sections will include tracer measurements that will help resolve the time scale of the inter-ocean communication. The sections will be repeated at a minimum every 3-5 years across each chokepoint; to avoid aliasing such signals as the ACW annual sampling is required on at least at one of the chokepoints, with Drake Passage probably the best choice.

To provide additional information regarding the atmospheric transports and forcing for models, standard atmospheric observations should be made during each transect across the chokepoints. Most important are measurements of the heat and moisture, wind velocity, sea level pressure, cloudiness, and radiosondes when possible.

Altimetry plays a particularly important role in the Southern Ocean because other aspects of the observing network are so sparse. In the context of chokepoint monitoring, altimetry provides year-round sampling (over ice-free areas), while XBT and CTD sections are likely to be limited to the summer season. Altimetry provides the only measurement which samples the entire Southern Ocean, allowing propagation of signals to be determined. The altimeter also of course measures a different quantity than the XBT/CTD sections - it includes the barotropic as well as the baroclinic signals.

#### 9.4.2 Mid-latitude zonal sections

Meridional fluxes of mass, heat and salt will be measured to determine the connection of the circumpolar water belt to the three ocean basins. Zonal sections will be occupied across the southern parts of the three ocean basins. The location should correspond to WOCE sections to provide earlier repeats: A10 or A11 in the Atlantic, I5 in the Indian Ocean, and P6 in the Pacific (or the SCORPIO section at 43°S). To determine variability on decadal scales, repeats every 3-5 years are necessary. The sections should be carried out according to WOCE standards. Absolute currents should be measured using ADCP's. Currents at the boundaries and over the ridges should be monitored using moored instruments; at a minimum 4 profiling CTDs/CMs are needed (one on each boundary and one on each side of the mid-ocean ridge). Altimeter data will provide near-continuous measurements of sea surface height. Float deployments (PALACE or RAFOS) should be used to determine the current field. XBT (XCTD) sections repeated seasonally will complement the more comprehensive, but less frequent, hydrographic sections. The basic suite of atmospheric measurements, as listed in Section 9.4.1, should be made during each transect. The combined data set will allow the variability on shorter time scales to be measured and thus avoid aliasing.

In addition to their primary use for measuring changes in interior temperature, salinity and tracer distributions and changes in fluxes, the zonal sections near 30-40°S help define (along with the chokepoint studies) a set of closed volumes which can be used for budget or inverse method studies. Because the major water masses of the Southern Ocean are formed over broad areas by a variety of poorly-understood processes, it is not feasible to design a process study which can determine formation rates. The only way to do this is to determine the net convergence/divergence in isopycnal layers over large regions. The WOCE sections provide us with a single occupation of a set of not-quite-synoptic hydrographic lines with which to carry out such a calculation. The repeat zonal and meridional deep hydrographic sections and complementary measurements discussed above will permit the formation and export rates of SAMW, AAIW and AABW to be estimated.

#### 9.4.3 Periodic (~ 5 year) repeats of selected additional deep hydrographic lines

For the purpose of observing changes in the ocean interior, a few additional deep hydrographic lines will be repeated. These sections would also help to define a set of smaller boxes which could be used in budget studies, to refine estimates of water mass formation based on isopycnal layer divergence. These lines should repeat high-quality sections occupied as part of WOCE or earlier experiments. Candidates include: 170°W in the South Pacific (WOCE P15), 55°E and 100°E in the South Indian Ocean, and 50°W in the South Atlantic (A23).

The WOCE S4 and SR4 lines should also be repeated on this time-frame to monitor changes in the formation and export of AABW and to estimate the air-sea heat flux south of the sections required to balance the oceanic heat transport.

#### 9.4.4 Additional VOS sampling where practical

The only practical VOS platforms in the Southern Ocean are vessels used to supply the Antarctic bases. As many of these lines as possible will be used to obtain repeat XBT and XCTD sections. Thermosalinographs should also be installed, in particular to measure sea surface salinity which is poorly known in the Southern Ocean (see below). (Most of these vessels are operated by organisations with no particular interest in oceanography or climate research; while they may be willing to assist with the deployments, they are unlikely to supply the XBT or XCTD probes themselves. The success of an expanded Southern Ocean VOS programme will require a source of probes funded through another source.) Fundamental atmospheric measurements should also be made whenever possible.

High priority lines to instrument, since the capabilities either exist or can be easily fitted to the involved vessels, include: South African and German vessels supplying bases south of Africa; French lines between Reunion, Crozet, Kerguelen and Amsterdam Islands; numerous ships crossing Drake Passage; vessels supplying McMurdo and Terra Nova Bay bases in the Ross Sea; and Australian, French and Japanese vessels operating in the Indian Ocean. Some of these lines are already occupied occasionally, usually at low density. The value of these lines is increased when the same ship track is repeated each voyage, and of course when the line is occupied several times during the year.

#### 9.4.5 Salinity sampling; PALACE floats to monitor $T(z)$ , $S(z)$ and the circulation

In the remote regions of the Southern Ocean, monitoring changes in upper ocean temperature and salinity is only possible using drifting platforms due to the lack of merchant shipping. Profiling ALACE floats with temperature and salinity sensors (SPALACE floats) provide a cost-effective means of monitoring such regions. In addition, the floats of course provide a measure of the absolute velocity field. ALACE floats are not appropriate for measuring the strong jets of the ACC itself. Rather, an array of PALACE floats sampling salinity is most appropriate for monitoring changes in the Subantarctic Mode Water and Antarctic Intermediate Water north of the ACC, where the flow is weaker. Such an array will serve two purposes: measure changes in the SAMW and AAIW near the formation region and indicate the path and rate at which these water masses leave the Southern Ocean to enter the subtropical thermocline. The optimal deployment strategy for such a float array requires additional study.

#### 9.4.6 Surface drifters (including drifters in the sea ice zone)

Although the requirements for surface drifters is the same as that of the CLIVAR sustained observations, their importance in the Southern Ocean is emphasised here.

*SST*: Satellite sensors will provide the primary means of measuring SST. However, *in situ* observations are needed to remove biases in the satellite measurements. The most practical way to measure *in situ* SST over large areas of the Southern Ocean is by surface drifters.

*SLP*: Measurements of surface pressure from drifters is crucial to improve analyses produced by operational atmospheric models. Such models are likely to provide the best estimates of wind stress, and perhaps the air-sea flux of heat and freshwater we can get over the Southern Ocean. These fluxes are needed to drive

ocean models and to validate coupled climate models. For this reason, maintaining an array of surface drifters in the Southern Ocean is important to attaining the goals of CLIVAR.

*SSS*: Sea surface salinity is very poorly known over most of the Southern Ocean, yet it is the primary controller of surface density south of 60°S. Of particular concern is the near absence of late winter SSS over much of the Southern Ocean, as this determines the water mass character and the location of deep/bottom water formation as well as establishing the surface characteristics and its ability to support a sea ice cover. Correct specification of Southern Ocean SSS is essential for realistic spin-up of global ocean models, and this specification is presently not possible. We also know very little about the variability of SSS and its role in modulating convection, water mass formation rates and sea ice distribution. Furthermore, climate models indicate that the dominant global warming signal south of 60°S is not SST increase, but SSS decrease, and that this freshening is critical in reducing convection and maintaining cool surface conditions and sea ice cover in these models.

There are several possible ways to increase the coverage of SSS measurements. Monitor (at least annually) the upper ocean  $S(z)$  along several meridional lines using CTDs or XCTDs. Thermosalinographs should be installed on Antarctic research and supply vessels. At high latitude, the late winter SSS may be estimated from the salinity of the temperature minimum layer, which is formed by the remnant winter mixed layer. Such sections would provide some indication of the variability and trend in SSS. Profiling floats with conductivity sensors should be used to obtain salinity profiles in data-sparse regions when this technology becomes proven. Similarly, drifters equipped with salinity sensors would be of great use when this becomes practical. These measurements would help fill gaps in the SSS climatology used for model spin-up.

*Surface velocity*: Surface drifters provide direct measurements of the velocity of the surface layer. These measurements can be used to derive quantities such as heat flux divergence in the surface layer.

#### 9.4.7 Deep boundary current measurements

The formation of AABW involves a complicated interplay between the atmosphere, ocean and both sea ice and land ice. The important processes often occur over small spatial scales, in logistically difficult regions of the ocean. Monitoring the important processes in the formation region is difficult. An alternative is to monitor the outflow of AABW at some distance from the source region. Changes in the transport and properties of the AABW provide an integral measure of changes in the formation region.

It is recommended that a small number of current meter arrays be deployed to monitor variability of AABW export. Because the Weddell Sea is believed to be the primary source of AABW, an array in the northwest corner of the Weddell Sea is the highest priority. Expendable current meters deployed from Antarctic research/supply ships would provide a cost-effective means of monitoring these outflows.

As part of this monitoring a time-series of thermohaline and tracer stratification from the southern limits of the ACC, across the Weddell-Scotia Confluence and into the northwestern segment of Weddell Gyre will be occupied. This repeat section (once per 2 years) will monitor changes in the inventories of heat, freshwater and select tracers in these three ocean zones. It will continue the time-series which has revealed a slow warming of the Weddell Deep Water since the last Weddell Polynya, as well as changes in the deeper stratification.

#### 9.4.8 Satellite monitoring of SST, sea level, winds and sea ice

D5 is dependent on satellite measurements of SST, sea level, wind stress and sea ice extent in the sparsely sampled Southern Ocean and these must be continued through CLIVAR. To effectively measure sea ice concentration and extent from satellite data, improved algorithms need to be developed by validation against *in situ* data.

#### **9.4.9 Ice and snow thickness**

The SCAR ASPECT programme will define basic climatology and seasonal development but is unlikely to be accurate enough to give variability. There is no prospect of a space-borne system for even thin ice for 5+ years. In the meantime: (1) quasi-permanent moored upward looking sonar (ULS) arrays (with profiling CTDs?) should be maintained at key sites (e.g. 0°E (Weddell), 80°E (Prydz Bay), and 150°W (Ross Sea)), supplemented when possible by ice drifters that include ice/snow thickness; (2) short-period ice divergence (and hence new ice production rates) should be estimated from synoptic monitoring of ice velocities measured by active radar satellite systems (space segments are in place or planned); (3) the variability (seasonal and interannual) in the size of coastal polynyas, which may act as ice factories should be monitored by satellite; and (4) a proxy ice age/thickness distribution should be derived by Lagrangian flow tracking with radar satellites.

#### **9.4.10 Monitoring of fast ice thickness at key sites**

Heat supplied by ocean currents is a key factor regulating the thickness of fast ice around the Antarctic margin. Models have successfully inferred the ocean-ice heat flux based on observations of fast ice thickness and meteorological variables (Heil et al., 1996). Measurements of the thickness of the fast ice are relatively easy to make near Antarctic bases. Such measurements will provide a record of seasonal and interannual variability in the supply of deep ocean heat to the Antarctic continental margin.

#### **9.4.11 Combination of moored measurements and “rapid response” cruises**

The changes in deep water properties resulting from the Weddell polynya (Fig. 9.1) are among the most dramatic observed in the deep ocean. The climate impact of the presence or absence of a Weddell polynya has not been sufficiently explored. However, because the changes can be large and abrupt, the possibility of a link to lower latitude climate needs to be considered during CLIVAR. Deep water temperatures in the Weddell Sea have warmed since the polynya disappeared in the mid-1970's. If satellite measurements indicate a recurrence of the Weddell polynya, a special process study should be considered to monitor the development and impact of a Weddell polynya.

### **9.5 LINKAGES WITH OTHER CLIVAR COMPONENTS AND PROGRAMMES**

#### **9.5.1 Other elements of CLIVAR**

Atlantic Thermohaline Circulation (D3) and North Atlantic Oscillation (D1): The Southern Ocean component of CLIVAR is closely linked to the thermohaline circulation component within DecCen: global models suggest that anomalies carried by the ACC may influence the variability of overturning in the North Atlantic, and the overturning cells within the Southern Ocean recycle NADW to close the thermohaline circulation. Variability in the formation or circulation of the water masses ventilating the Southern Hemisphere thermocline (SAMW and AAIW) is likely to influence SST, heat and freshwater storage at lower latitudes, and thus is related to the elements of DecCen which focus on decadal variability at mid- and low-latitudes, as Tropical Atlantic Variability and Pacific and Indian Decadal Variability.

Heat and freshwater anomalies carried between basins by the ACC appear to be linked to climate variability on shorter time scales, via the Antarctic Circumpolar Wave (ACW). It has been suggested by Peterson and White (1998) that the ACW anomalies migrate to low latitudes to form an ocean telecommunication with interannual climate fluctuations, including ENSO. The ACW research thus has bearing on improving and expanding the predictions of ENSO.

Detection of the penetration of an anthropogenic tracer signal in the Southern Ocean is clearly related to the foci of the Anthropogenic Climate Change component of CLIVAR.

### 9.5.2 Other WCRP programmes

Southern Ocean CLIVAR will build on the base established by the World Ocean Circulation Experiment (WOCE).

The goals of the Arctic Climate System Study (ACSYS) are similar to a number of the goals of Southern Ocean CLIVAR. The sea ice in the Arctic and Antarctic have many similarities and many significant differences. CLIVAR will be best served by establishing a coherent atmosphere-ocean-sea ice-glacial ice programme for the Southern Ocean within CLIVAR, rather than by attempting to graft an Antarctic programme onto ACSYS. Good lines of communication between polar oceanographers and sea ice scientists working in the Arctic and Antarctic must be maintained.

Surface fluxes provided by the Global Energy and Water Cycle Experiment (GEWEX) will be particularly important for the Southern Ocean, where existing estimates are poor. The fluxes are needed to drive ocean-only models and to validate the fluxes in coupled ocean-atmosphere models. Southern Ocean observations made in CLIVAR will in turn support GEWEX goals.

The Southern Ocean CLIVAR has important links with the WCRP sea ice thickness and drift programmes.

### 9.5.3 Programmes outside of WCRP

Both SCAR and SCOR have established Southern Ocean programmes: the SCAR programme is called Antarctic Sea-Ice Processes, Ecosystems and Climate (ASPeCt); International Antarctic Zone (iAn-Zone) is a SCOR affiliated programme. Both of these programmes are directly concerned with the coupling of the Southern Ocean and atmosphere in the regions covered by year-round and by seasonal sea ice.

The CLIVAR-PAGES link offers an invaluable and unique opportunity for expanding the paleoclimate data base, and thus extending the Southern Ocean records of climate back through time over a broad geographic range. The paleoclimate records from the Antarctic ice sheet, and from the circumpolar belt are of particular interest to the Southern Ocean component of CLIVAR and thus highly encouraged.

In the remote regions of the Southern Ocean, monitoring changes in upper ocean temperature and salinity is only possible using drifting platforms due to the lack of merchant shipping. Profiling ALACE floats with temperature and salinity sensors provide a cost-effective means of monitoring such regions. In addition, the floats of course provide a measure of the absolute velocity field. ALACE floats are not appropriate for measuring the strong jets of the ACC itself. Rather, an array of salinity sampling PALACE floats is most appropriate for monitoring changes in the Subantarctic Mode Water and Antarctic Intermediate Water north of the ACC, where the flow is weaker. Such an array will serve two purposes: measure changes in the SAMW and AAIW near the formation region and indicate the path and rate at which these water masses leave the Southern Ocean to enter the subtropical thermocline. The optimal deployment strategy for such a float array requires additional study.

Some observations required for Southern Ocean CLIVAR (e.g. repeat XBT/XCTD sections) will likely form part of the Global Ocean Observing System (GOOS).



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### *III. The CLIVAR Principal Research Areas*

### III. THE CLIVAR PRINCIPAL RESEARCH AREAS

#### (iii) CLIVAR ACC

There is widespread concern that humans are affecting global climate. The Second Assessment Report (SAR) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 1996) concluded that:

- climate has changed over the past century
- the balance of evidence suggests a discernible human influence on global climate
- climate is expected to continue to change in the future
- there are still many uncertainties.

CLIVAR-ACC will assist in the reduction of these uncertainties in a number of ways. It will seek to develop understanding, modelling, and predictive capabilities of the response of the climate system to the anthropogenic increases in radiatively active gases and changes in aerosols and to identify the patterns of anthropogenic modification to the mean state and to the variability of the climate system. It will also use the understanding of natural climate variability derived from GOALS and DecCen as a baseline for detecting the trends and signatures associated with increases in greenhouse gases and the effects of other anthropogenic changes.

The scientific objectives of CLIVAR-ACC are:

- To better understand and quantify the relative contributions of natural variability and anthropogenic factors to observed climate change;
- To identify and apply statistical techniques and strategies that are appropriate for the early detection of anthropogenic climate change;
- To predict, up to the year 2100, climate change from increasing concentrations of greenhouse gases and other anthropogenic influences;
- To provide predictions of regional climate change to the extent possible;
- To provide guidance for the establishment of observing systems to monitor climate change.

CLIVAR successes in meeting its objectives under this component would do much to reduce the “many uncertainties” noted by the IPCC SAR. The SAR identified the most urgent scientific problems requiring attention to reduce these uncertainties:

Concerning the rate and magnitude of climate change and sea level rise, the SAR focused attention on the factors controlling the distribution of clouds and their radiative characteristics; the hydrological cycle, including precipitation, evaporation and run off; the distribution and time evolution of ozone and its radiative effects; the direct radiative effects of aerosols and their effects on the characteristics of clouds; the response of terrestrial and marine systems to climate change and their positive and negative feedbacks; the response of ice sheets and glaciers to climate; the influence of human activities on emissions; the coupling between the atmosphere and ocean, and ocean circulation; and the factors controlling the atmospheric concentrations of carbon dioxide and other greenhouse gases.

Concerning the detection and attribution of climate change, the SAR saw the need for systematic observations of key variables and the development of model diagnostics relating to climate change; and the relevant proxy data to construct and test paleoclimatic time-series to describe natural variability and forcings of the climate system.

### III. The CLIVAR Principal Research Areas

Regarding regional patterns of climate change, the SAR identified the need for research on land-surface processes and their links to atmospheric processes, and the coupling of scales between global climate models and regional and smaller scale models, as well as the need for simulations with higher resolution climate models.

The SAR concluded that: *“The research activities for each objective are strongly interconnected. Such research is and needs to be conducted by individual investigators in a variety of institutions, as well as by co-ordinated international efforts which pool national resources and talents to more efficiently engage in large-scale integrated field and modelling programmes to advance our understanding.”*

CLIVAR-ACC will provide the international co-ordination to advance our understanding of anthropogenic climate change, by focusing on many of the areas of uncertainty identified in the IPCC SAR.

In order to accomplish this, CLIVAR-ACC will have two Principal Research Areas:

- Climate Change Prediction (A1):  
Improving prediction through the use of coupled climate models of the likely climate change in response to scenarios of effects of future human activities.
- Climate Change Detection and Attribution (A2):  
Detecting and attributing anthropogenic climate change in the presence of the natural variability of the climate system.

These components are clearly closely related. Attribution of the causes of climate change, for instance, requires the prediction of how specific forcing mechanisms might affect climate. Improved coupled ocean-atmosphere models are required for this task and the development of and experimentation with such models will be the core activity of CLIVAR-ACC. Model development and experimentation will be co-ordinated through the Working Group on Coupled Modelling. The modelling work required will include sensitivity studies, the calibration of simple models, the development of standardised forcing scenarios, and coupled model intercomparisons.

CLIVAR-ACC, as predominantly a modelling activity, will not organise field experiments or process studies. It will, therefore, rely on other activities in WCRP and IGBP to improve our understanding of how a variety of physical processes could be better represented and included in coupled models. CLIVAR-ACC will also not be directly involved in the gathering and management of global data sets for climate change detection purposes. This activity will be conducted under other programmes such as GEWEX, GCOS, and the World Climate Data and Monitoring Programme (WCDMP). Nevertheless, CLIVAR-ACC will play a role in advising on the observations and information needed for climate change detection and attribution.

#### **Reference:**

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## **10. CLIMATE CHANGE PREDICTION (A1)**

### **10.1 SCIENTIFIC RATIONALE**

In order to address the requirement for reducing uncertainties in the prediction of human influence on climate, the following objectives have been accepted for A1:

1. To better understand and quantify the contribution of anthropogenic factors to climate.
2. To predict, up to the end of the 21st century, climate change from scenarios of concentrations of greenhouse gases and anthropogenic influences.
3. To provide corresponding estimates of regional climate change to the extent possible.

As a basis for meeting these objectives, A1 requires:

- Historical records of anthropogenic emissions of greenhouse gases and aerosols, and changes in land use.
- Physically based models to convert emissions to concentrations to radiative forcing.
- Physically based climate models which incorporate the processes necessary to simulate the response to the forcing accurately.
- Evaluation of models against observations.
- Model integrations using the historical forcing record and idealised forcings.

In addition, projections of the human influence on climate in the future require

- Scenarios of future anthropogenic emissions.
- Extension of historical integrations into the future under these scenarios.

#### **10.1.1 What is known now**

The 1995 IPCC assessment noted (Gates et al., 1996) that coupled climate models simulate many aspects of the observed climate with a useful level of skill at hemispheric and continental scales. Many current models use flux adjustments to avoid serious local errors or long-term drift in simulating present climate. The comprehensive diagnosis and evaluation of models, an essential part of model development, are limited by the lack of observations and data sets. Models can reproduce some of the gross features of recent climate change (for example, Fig. 10.1), though this agreement could arise from a cancellation of errors in estimates of past radiative forcing and model sensitivity (Kattenberg et al., 1996). There is broad agreement in the qualitative simulated response to a gradual increase in greenhouse gases between models, though the magnitude of the global mean temperature change varies by a factor of more than 2 (Fig. 10.2). The changes are physically plausible. Regional changes and changes in variability (for example storm tracks) are generally inconsistent from model to model. Simulations with a simple representation of aerosols indicate that forcings other than that due to greenhouse gases need to be taken into account in both hindcasts (for example Hegerl et al., 1997) and projections of the future (Fig. 10.3).

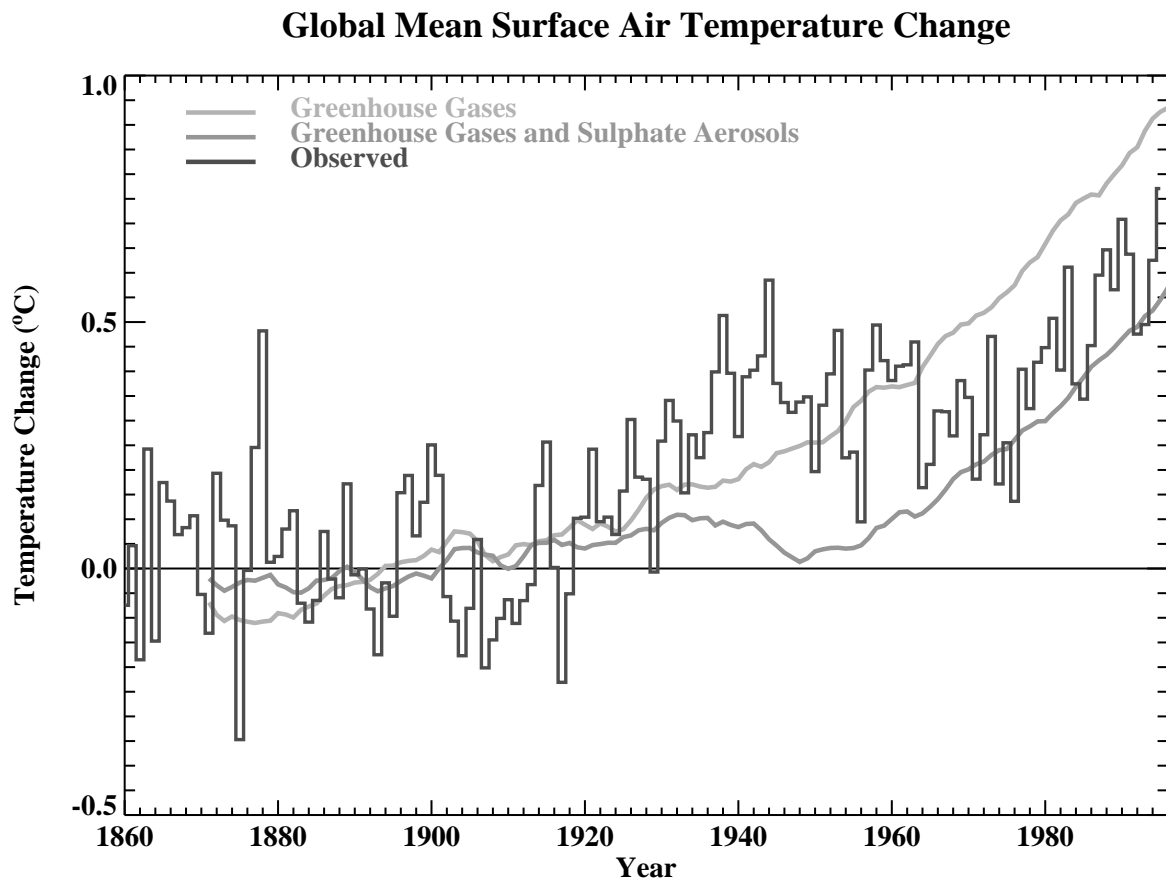


Fig. 10.1: Simulated global annual mean warming from 1860 to 1990, allowing for increases in equivalent  $\text{CO}_2$  only (light gray) and allowing for increases in equivalent  $\text{CO}_2$  and the direct effects of sulphates (darker gray) (Mitchell et al., 1995). The observed changes are from Parker et al. (1994). The anomalies are calculated relative to the 1880 - 1920.

### 10.1.2 What is being done now

Improvements are being made to the representation of forcing due to greenhouse gases and sulphate aerosols, and the effect of other factors is being included. Development of climate models which include the carbon and sulphur cycles are well under way. There is a general trend to use higher resolution which combined with other improvements is producing simulations without flux adjustments which are more realistic. Modelling programmes such as AMIP and CMIP are fostering improvement in the extent and standards of model evaluation. A major limiting factor is the improvement in the way subgrid-scale processes are represented, particularly clouds, and the lack of satisfactory means for evaluating the correctness of such parameterisations (Dickinson et al., 1996).

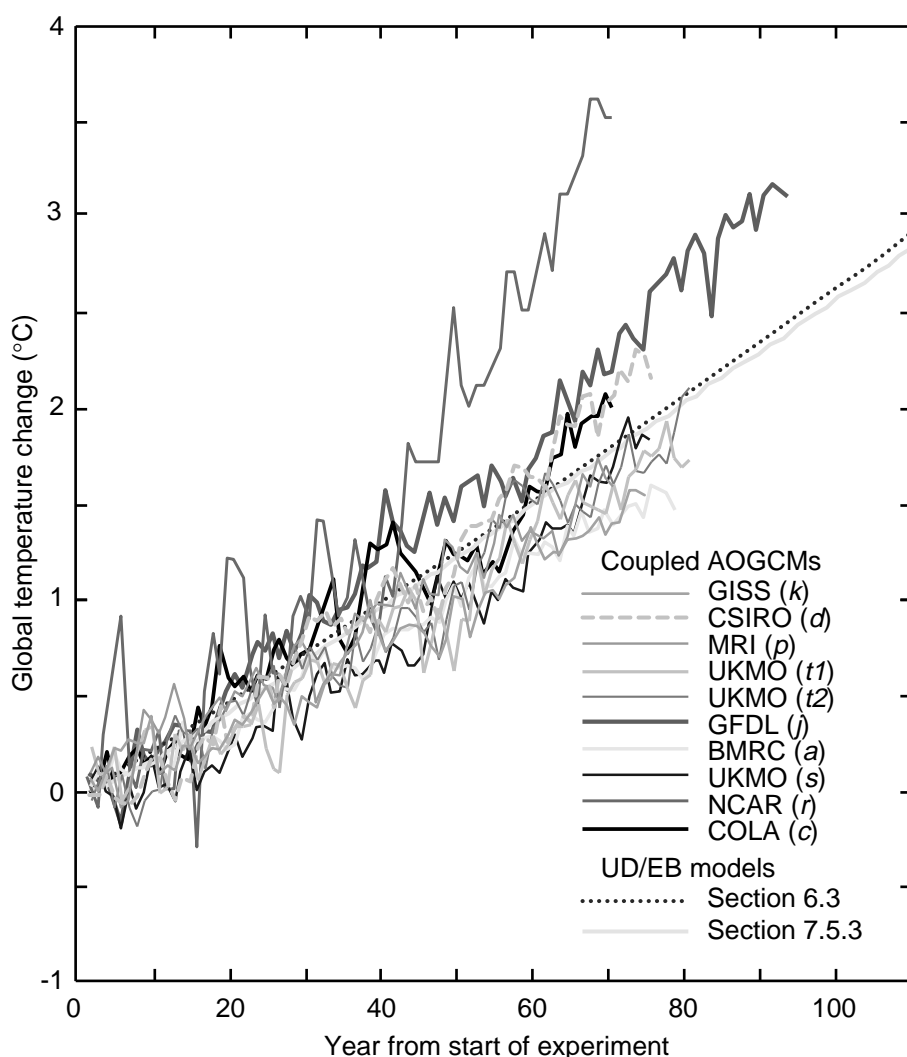


Fig. 10.2: Comparison between several AOGCM simulations (climate sensitivities between 2.1 and 4.6°C), the UD/EB model (see IPCC, 1996, Sect. 6.3) (climate sensitivity 2.5°C) and the simple climate model of IPCC 1995, Sect. 7.5.3 (climate sensitivity 2.2°C). All models were forced with 1%/yr (compound) increase of atmospheric CO<sub>2</sub> concentration from equilibrium or near-equilibrium in 1990 (from IPCC, 1996).

### 10.1.3 Among the questions remaining are

*How can we reduce uncertainty in estimating the magnitude and effect of factors which have influenced climate in the past? How sensitive is climate to increases in greenhouse gases? How much does the ocean thermohaline circulation slow down the response to changes in forcing? Is climate susceptible to rapid changes in equilibrium (“surprises”)? Does climate change alter climate variability?*

The main sources of uncertainty in simulating recent and future climate are the specification of anthropogenic radiative forcing and the sensitivity of climate to change. A more complete list, based on McBean et al. (1996) is given below.



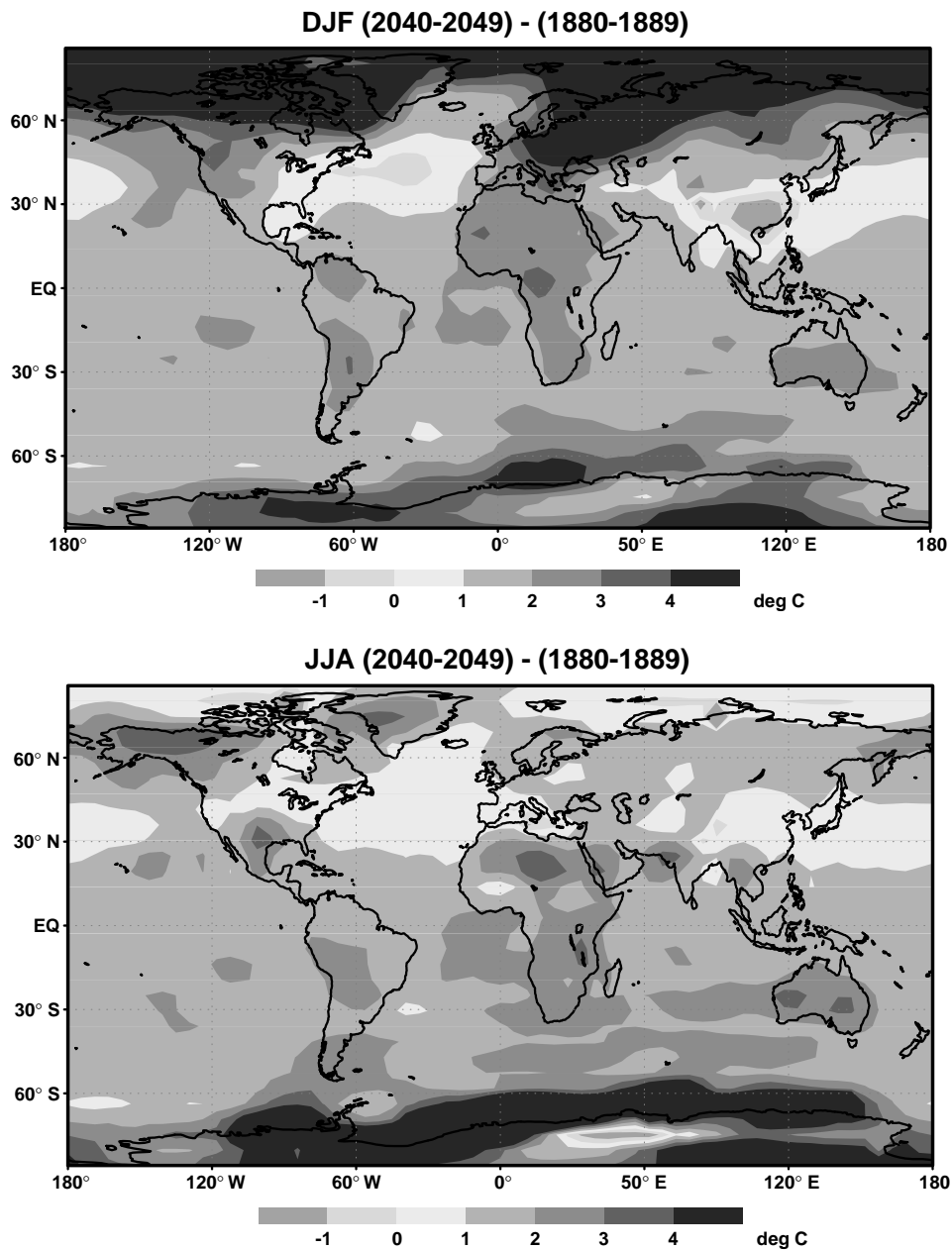


Fig. 10.3: Seasonal change in surface temperature from 1880 - 1889 to 2040 - 2049 in simulations with aerosol effects included. Contours every 1°C. Upper panel: December to February; lower panel: June to August (after IPCC, 1996; Hasselmann et al., 1995).

Uncertainties governing the rate and magnitude of climate change and sea level rise:

- the factors controlling the distribution of clouds and their radiative characteristics;
- the hydrological cycle including precipitation, evaporation and runoff;
- the distribution and time evolution of ozone and aerosols and their radiative characteristics;
- the response of the terrestrial and marine systems to climate change and their positive and negative feedbacks;

- the response of ice sheets and glaciers to climate;
- the influence of human activities on emissions;
- the coupling between the atmosphere and oceans, and ocean circulation;
- the factors controlling the atmospheric concentrations of carbon dioxide and other greenhouse gases.

Additional uncertainties relating to regional patterns of climate change

- land surface and atmospheric processes and their linkages;
- coupling between global, regional, and smaller scales.

#### 10.1.4 Where CLIVAR can help

The problems of climate change are too large to be undertaken by any one institution or nation. While there are certain principles on which modellers are in general agreement, there is a large number of ways of implementing these principles, and it is by no means obvious which approaches are both correct and practical. For example, there is no agreed or fail-safe method for initialising climate models: the existence of several major modelling centres around the world allows a diversity of approach which is more likely to bring progress than relying on one or two centralised institutions. Thus, one of the roles of CLIVAR is to co-ordinate the diverse approaches taken around the world so that progress is maximised. This includes facilitating the sharing of results, joint planning of future activities avoiding unnecessary duplication, and ensuring a comprehensive approach to the problem in a way that does not stifle individual creativity. CLIVAR is also responsible for providing guidance on the assignment of priorities for funding agencies so that critical areas receive adequate resources in a timely manner.

CLIVAR through A1 can improve the prediction of climate change by:

- Ensuring the research necessary to reduce the uncertainty in climate change is carried out, and in particular, ensuring active co-operation between the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and those sections of GEWEX concerned with water vapour and cloud feedbacks.
- Ensuring the research necessary to reduce the uncertainties in radiative forcing is carried out, particularly by organising collaboration between JSC/CLIVAR WGCM and IGAC, GAIM, and SPARC.
- Making clear to funding agencies the need for long-term development and evaluation of climate models. This can be done through strong recommendations made by the JSC/CLIVAR WGCM.
- Ensuring a deeper analysis of climate experiments to understand the mechanisms of the simulated response and to identify reasons for differences in model responses. A careful analysis of experiments is necessary if we are to advance our understanding of climate change and reduce uncertainties in predictions of the future. The need for a fuller analysis of climate simulations should be communicated to funding agencies to make sure the financial support for such work is available.
- Ensuring the evaluation of climate models against well documented past climates, in conjunction with CLIVAR/PAGES.

- Define standard forcing scenarios, including improved scenarios of future emissions in conjunction with IPCC and make them generally available to the modelling community.

A1 is largely a modelling programme and differs from other principal research areas of CLIVAR in that it depends on inputs from observational and modelling programmes outside CLIVAR for success (for example GEWEX, IGAC). The most important task for CLIVAR is make sure that effective collaboration occurs between A1 and these outside programmes at working level.

## 10.2 INPUT REQUIRED

In order to validate models now and in the future, we need to know the factors which influence climate. The forcing factors have to be determined now, because there is no way to measure them retrospectively. Measurements should include both anthropogenic and natural forcing factors to allow hindcasts of recent climate change for validation of models, and for the detection and attribution of climate change.

Forcing factors (which need to be monitored continuously and accurately) are:

- Greenhouse gases
- Tropospheric aerosols (sulphate, biogenic, mineral, soot)
- CO<sub>2</sub> sinks etc.
- Surface albedo changes (land use, etc.)
- Solar output
- Volcanic aerosols

In the case of gases and aerosols, both emissions and concentrations are required for evaluating the models which convert emissions to concentrations. Solar and volcanic forcing are included for completeness - without knowing these it is impossible to separate anthropogenic and natural climate change (see A2). The current status of the different forcing factors is summarised in Fig. 10.4 (adapted from IPCC, 1996).

### 10.2.1 Improvements in the representation of physical, chemical and biological processes in models

The main sources of uncertainty in models used to predict and detect anthropogenic climate change are the estimates of radiative forcing (greenhouse gases, aerosols, changes in land use, etc.) (Fig. 10.4) and the modification of the climate response through certain feedbacks, e.g. clouds, water vapour, snow and ice, vegetation etc. Of the feedbacks, the main uncertainties arise in cloud feedbacks (uncertain to a factor of 2 or 3) and the feedback due to aerosol effects on clouds (estimated by IPCC to cool current climate between 0 and 1.5 Wm<sup>-2</sup>, compared to a warming of 2.4 Wm<sup>-2</sup> by the main greenhouse gases). Improving the estimates of the indirect forcing and the magnitude of cloud feedbacks should be given the highest priority.

Understanding of the physical, chemical and biological processes involved in forcing and feedbacks and their representation in models are urgently required. These will only be provided with a lot of help from programmes outside CLIVAR, including GEWEX, IGAC, GAIM, ACSYS and SPARC as well as parts of CLIVAR DecCen. Seeing that there is efficient and effective collaboration between the relevant parts of these programmes is the most important task for CLIVAR in assuring the success of A1 and A2. Given the importance of these linkages, they are discussed in detail in Section 10.6.

Another major uncertainty in modelling climate change is the rate at which heat is mixed from the surface into the deep ocean. This a governing factor in determining the rate and patterns of climate change and will require continued and extended measurements of ocean parameters (See also Section II.4.2.1 and II.4.2.2).

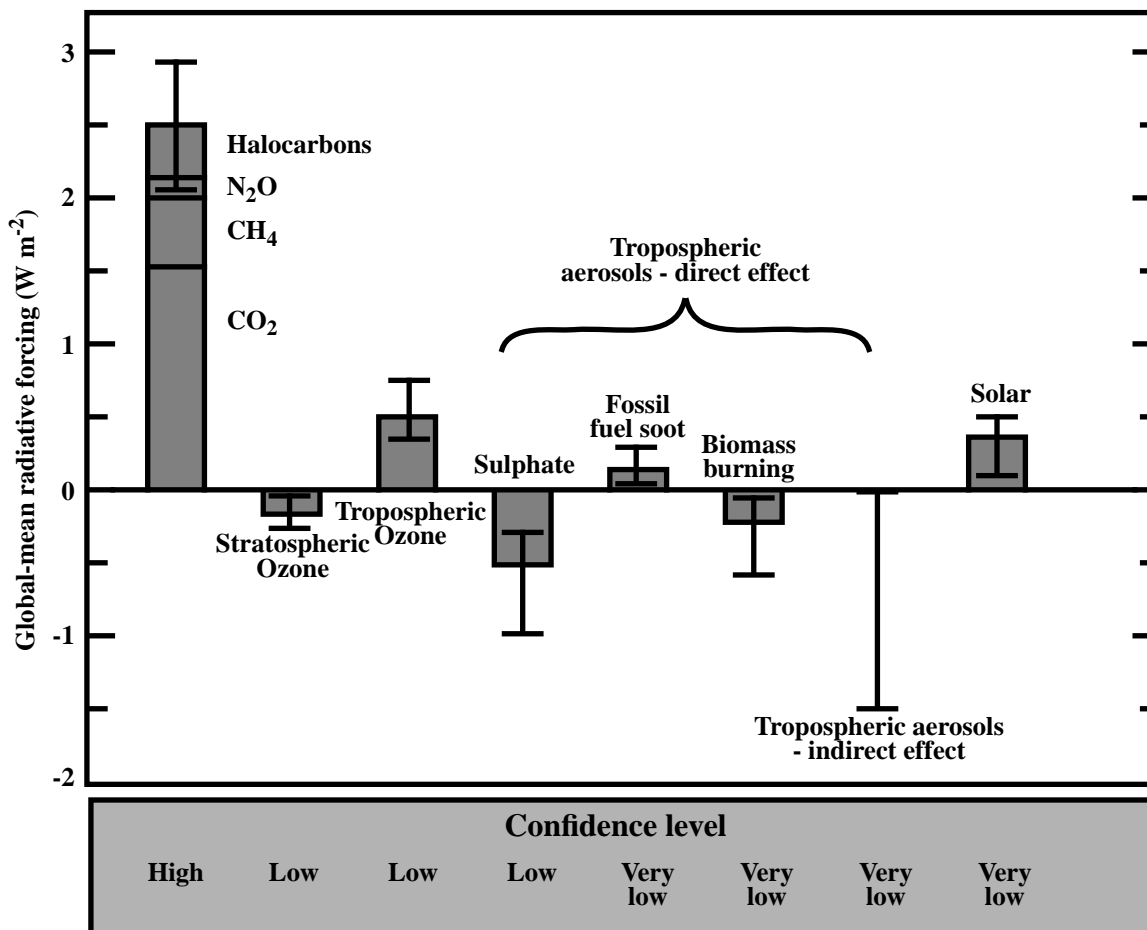


Fig. 10.4: Estimates of the globally and annually averaged anthropogenic radiative forcing (in  $\text{Wm}^{-2}$ ) due to changes in concentrations of greenhouse gases and aerosols from pre-industrial times to the present day and to natural changes in solar output from 1850 to the present day. The height of the rectangular bar indicates a mid-range estimate of the forcing whilst the error bars show an estimate of the uncertainty range, based largely on the spread of the published values; our subjective confidence that the actual forcing lies within this error bar is indicated by the "confidence level". (From IPCC, 1996).

### 10.3 MODELLING AND PREDICTION

Numerical modelling is the core activity of CLIVAR ACC. In addition to simulating future climate change, activities will include model improvement, intercomparison and evaluation, sensitivity and predictability studies, calibration of simple models for scenario development and activities to provide guidance on observing systems. Numerical experimentation under CLIVAR for A1 and A2 (and DecCen) is being co-ordinated and monitored by JSC/CLIVAR WGCM. It is recognised that setting priorities for modelling experiments under A1 should be co-ordinated with the IPCC process.

### 10.3.1 Model improvement

Progress in understanding the response and predicting the response of climate to anthropogenic forcing depends on improving coupled ocean atmosphere climate models. This includes the improvement of current parameterisations and the inclusion of new processes (notably biological and chemical feedbacks). Progress in model development will be continually reviewed to assess model improvements made through numerical experimentation, and to identify areas which require further process studies. For the latter case, requirements to the appropriate WCRP or IGBP projects will be specified (see Section 10.6) and co-operation will be fostered with these projects.

### 10.3.2 Model evaluation

The evaluation and validation of models is essential both in assessing the impact of model development and the credibility of simulations of climate feedbacks and climate change. The programme proposed for model intercomparisons by CLIVAR is outlined in Section 10.5.4. A standard approach to model validation is one of the requirements for IPCC assessment. Several groups have completed long control simulations with coupled ocean atmosphere GCMs both to enable analysis of mechanisms of simulated decadal to centennial variability and to provide estimates of internal climate variability for climate detection. The same models have been used to simulate the instrumental temperature record using estimates of the historical forcing due to increases in greenhouse gases and simplified representation of the direct forcing by sulphate aerosols for climate detection studies, and these simulations have been extended into the future using a limited number of emission/forcing scenarios.

Simulations of paleoclimate: whereas numerical weather prediction models can be tested daily by verifying against observations, the opportunities for testing climate models on actual changes in climate is limited. Although there are large uncertainties in estimates of past forcing and climatic reconstructions, past climates provide the only opportunity of testing models with a substantial change in climate. The most promising periods are the mid Holocene (6000 years BP) and the last glacial maximum (21000 years BP) which have been selected by PMIP (Paleoclimate Modelling Intercomparison Project) an ongoing joint CLIVAR/PAGES activity.

### 10.3.3 Idealised studies

Models will need to be run with idealised forcing scenarios to allow the comparison of mechanisms of change in different models. At present, there is no accepted way of initialising coupled models for prediction experiments, or for bringing them to full equilibrium with a given set of boundary conditions. Each group uses its own method to initialise their model, and it is not clear that a method which has proved successful with one model will work for another model. Hence, in the initial round of comparisons, some latitude in the method of spin up and the initial conditions will be allowed. As techniques for bringing coupled models to equilibrium are developed, the comparisons will be more tightly controlled. Simulations of the last hundred years or so will be run to aid the detection and attribution of climate change (see below) using, where appropriate, standard forcing data sets.

### 10.3.4 Predictions

A limited number of simulations based on standard future forcing scenarios will be encouraged as contributions to IPCC. Note that the scenarios are likely to be idealised in some respects. Simpler models may have to be used to interpolate the results to specific IPCC scenarios.

### 10.3.5 Multi-century simulations

The predictability of climate, and the scales on which climate is predictable remain open questions. Currently, simulated internal variability is sufficient to warrant ensemble simulations for both detection and prediction. Multi century simulations are also needed to investigate whether or not climate change alters shorter term climate variability such as ENSO and North Atlantic Oscillation. The stability of climate is to be investigated using numerical experimentation (e.g. Manabe and Stouffer, 1994). Model studies can also provide guidance on the spatial and temporal coverage necessary for monitoring climate to the accuracy necessary for climate change detection. Such studies are analogous to the observing system studies carried out for weather prediction purposes.

### 10.3.6 Regional modelling

The assessment of impacts of climate change require details of climate change on at least a regional (country) scale. At present, their usefulness is limited by the quality of the driving - as noted in IPCC95, (IPCC, 1996) confidence in simulated GCM changes at regional scales is low. However, these techniques need to be and are being developed and evaluated so that they are ready to take advantage of future improvements in global models. Thus the development of techniques to predict small-scale changes in climate are an essential part of A1.

At present, the approaches are rather diverse in terms of technique and region. CLIVAR can help by promoting two kinds of studies

1. Evaluation of regional models driven by reanalysis data to determine the accuracy of the regional response when driven by perfect boundary conditions. Comparison with runs driven by GCM data will indicate the extent to which poor boundary conditions degrade the model.
2. Comparison of the accuracy of statistical downscaling techniques with regional modelling. There is a requirement for a more systematic evaluation and intercomparison of the various techniques for estimating regional climate change. (Numerical aspects of regional models are currently the remit of WGNE).

## 10.4 COMPUTING REQUIREMENTS

Climate modelling is limited by available computing resources and hence requires state of the art supercomputers. Current models running with 30 levels on a 4 degree latitude/longitude grid require about one and a half hours computing time on a single processor of a CRAY C90. Even at this resolution, the long simulations required to investigate climate change can only be carried out at a handful of centres. The increase in computing time with resolution is given below

Resolution (degrees)	4x4	2x2	1x1	0.5x0.5
CPU Time	1	10	100	1000
Data	1	5	25	125

Thus increasing the resolution from 4 to 0.5 degrees (which are necessary to resolve e.g. important aspects of the thermohaline circulation in the ocean) would require a factor of 1000 increase in computing and over 100 in data storage) to maintain the current length of experiments (centuries to millennia). At present, there are demonstrated benefits in increasing atmospheric resolution to at least 1 degree and ocean resolution to a small fraction of a degree, with appropriate increases in vertical resolution. Even now, computing resources limit the running of hierarchies of experiments which are needed to elucidate feedbacks

and explore sensitivities so that the model response is well understood and the model uncertainties are quantified, and ensembles of experiments to enable a better definition of the anthropogenic “fingerprint” for detection studies. There is also a continuing need to maintain experienced staff to improve models, to diagnose results, and to design and carry out the appropriate field studies to guide model development.

## 10.5. SPECIAL FOCUSED RESEARCH PROJECTS

### 10.5.1 Idealised sensitivity studies

*Purpose:* To identify mechanisms of climate change and understand the reasons for differences in model response.

*Background:* The IPCC95 (IPCC, 1996) assessment produced a range of a factor of two in models driven by a 1% per year increase in CO<sub>2</sub> (Kattenberg et al., 1996). Much of the discrepancy can be traced to differences in cloud feedback (Senior and Mitchell, 1993; Cess et al., 1996).

*Feasibility:* Experiments and intercomparisons need to be carefully designed in order to help increase our understanding and to identify the reasons for the differences between different models. This requires a commitment of resources from individual modelling centres to fully understand the response of their own model, and to run idealised experiments and store diagnostics which enable meaningful comparison of models.

1. Experiments with prescribed changes in SST (to identify cloud and other feedbacks).
2. Equilibrium 2 x CO<sub>2</sub> experiments with mixed layer oceans (to calibrate the climate sensitivity of the atmospheric component of coupled models).

Transient experiments with a 1% per year increase in atmospheric CO<sub>2</sub> (along with 2. above to determine the slowing effect of the oceans).

### 10.5.2 Calibration of simple models

*Purpose:* To estimate the climate response to a variety of forcing scenarios. At present, the only practical approach is to use simpler models. In order to support the results thus obtained, the simpler models need to be calibrated against full GCMs.

*Background:* Past IPCC reports have relied on energy balance models to investigate the response of the global mean temperature response and sea-level rise to a range of emission scenarios and model sensitivities. Only in the 1995 report were attempts made to show that energy balance models could be used to interpolate and extrapolate GCM results (Kattenberg et al., 1996).

*Feasibility:* Calibration of other models has continued at a low priority and in a rather ad hoc fashion. Careful calibration is time consuming and hence has not been readily undertaken.

### 10.5.3 Standardised forcing scenarios

*Purpose:* To enable an evaluation of the model dependence of results, and identification of the reasons for differences in model response.

*Background:* In IPCC95, assessment of results was hampered by the use of different forcing scenarios.

*Feasibility:* Attempts to standardise forcing scenarios have failed in the past as institutions have chosen different forcing scenarios, perhaps due to pressure to use the “latest” emission scenarios, or limitations on resources. In the past, certain scenarios have become established in time as standard, and this process can be facilitated by JSC/CLIVAR WGCM. Data sets of historical forcing, forcing for idealised experiments, and for future emission scenarios are required. Collaboration with IGAC and IPCC will be required. As climate models evolve to include chemical processes, scenarios will be defined by emission scenarios rather than by concentrations.

#### 10.5.4 Coupled Model Intercomparisons (CMIP)

*Purpose:* To allow independent evaluation of the performance of models used to make climate projections, to identify common model errors and identify priorities for model improvement, and observational studies to guide that improvement. A more complete description of CMIP is given in Section II 2.3.1.

*Background:* As part of IPCC95, an intercomparison of coupled models used later in the report had to be carried out (Gates et al., 1996). This was inevitably limited in scope by the time and resources available.

*Feasibility:* Setting up model intercomparisons is easy, but doing them well is difficult. For example, AMIP revealed a lot about differences in model performance and errors which are common across models, but improvement in models has been more difficult to achieve. The first stage of CMIP to look at model control simulations is under way, and a second stage, to look at differences in response to transient forcing, has been set up. The second stage will be repeated if and when a satisfactory method of producing uniform initial conditions can be found. Intercomparisons are particularly effective if based on idealised experiments designed to accentuate particular aspects of the models response (e.g. oceanic inertia).

## 10.6 LINKAGES

CLIVAR ACC is mainly a modelling activity and will not organise process studies. Hence it relies critically on other activities in WCRP and IGBP. The need for linkages is discussed throughout much of the text above. One of the most important roles of CLIVAR is to co-ordinate research, especially for A1 which is largely a modelling programme dependent on other programmes for observational input. Those processes already identified as being the most critical and the appropriate projects are listed below, with high priority items given first (see also Fig. 10.5). Clear communication of needs from CLIVAR ACC (usually through JSC/CLIVAR WGCM) to the relevant projects and frequent updating of progress in the key areas are required. This may be in the form of joint workshops, invited experts and reports.

- Clouds and related processes (GEWEX)

This is probably the main source of uncertainty for A1. Particular attention will be paid to those processes which govern climate sensitivity, especially to determine if they are realistic and faithfully represented in models.

- Aerosol forcing (IGAC)

Aerosol forcing is a major source of uncertainty both for detection and prediction of climate change. CLIVAR will rely on the work of IGAC for the conversion of emissions to concentrations and the specification of radiative properties. The appropriate links for making needs known to IGAC and keeping in touch with the relevant parts of IGAC will be established. Progress in aerosol modelling intercomparisons will be monitored.



- Land surface processes (GEWEX)

Most of the impacts of climate change are effected through change in near surface climate over land. Hence accurate prediction of land surface processes is a primary concern for CLIVAR ACC. CLIVAR ACC will rely on GEWEX for model improvements in this area. Progress in the PILPS and other intercomparison projects will be monitored.

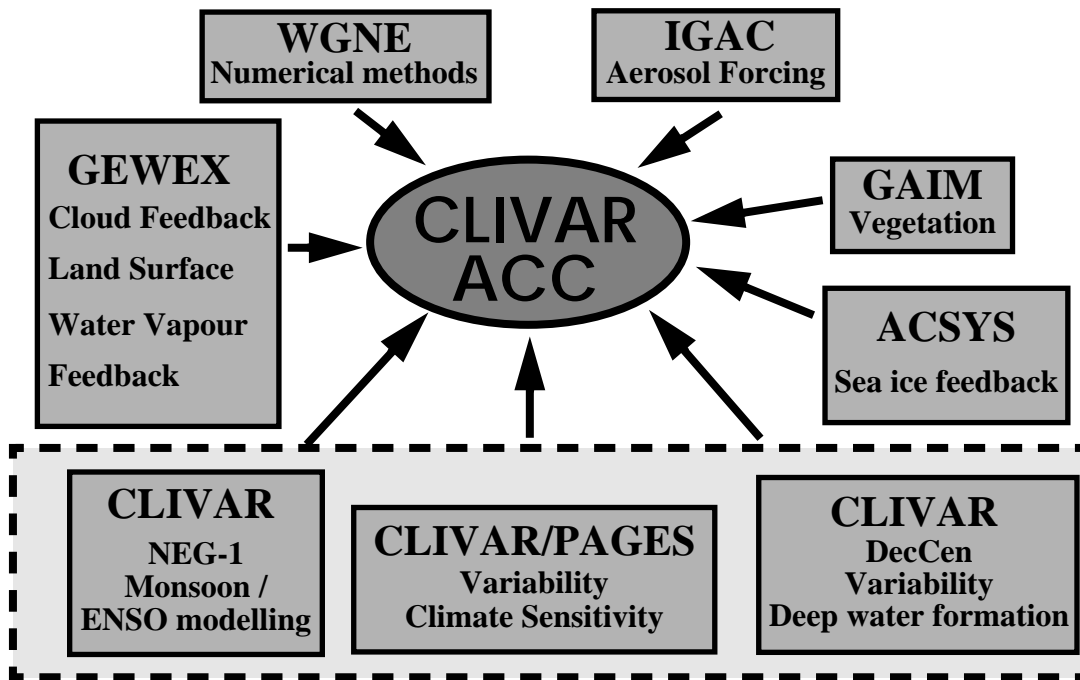


Fig. 10.5: Schematic diagram of the linkages between CLIVAR ACC and other programmes.

- Water vapour feedback (GEWEX - GVaP)

There remain considerable uncertainties in the processes governing upper tropospheric water vapour in the tropics, how well these processes are represented in models, and the magnitude of the water vapour feedback expected with global warming. Reducing these uncertainties is of high priority for maintaining the credibility of climate models, and there is potential to make considerable progress before IPCC 2000.

- Sea ice (ACSYS)

Sea ice has strong influence on the sensitivity of climate in high latitudes, as well as on the formation of deep water.

- Deep water formation (DecCen)

This is important in determining poleward heat transports. The stability of the deep ocean circulation is still unresolved.

- Stratospheric processes (SPARC)

Changes in ozone due to human activity, volcanic eruptions and changes in solar output need to be taken into account in both A1 for prediction and understanding of past climate and in A2 to enable separation of natural and human effects.

- Biological processes (GAIM)

The correct prediction of future carbon dioxide levels will need to couple atmosphere-ocean models with biogeochemical models, including biological models of the oceans and vegetation. Coupling with dynamical vegetation models will also be needed to correctly represent the changes in land surface processes.

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*III. The CLIVAR Principal Research Areas*

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## 11. CLIMATE CHANGE DETECTION AND ATTRIBUTION (A2)

### 11.1 SCIENTIFIC RATIONALE

Detection of climate change is the process of demonstrating that an observed variation in climate is highly unusual in a statistical sense. Detection of climate change requires demonstrating that the observed change is larger than would be expected to occur by natural internal fluctuations alone. Attribution of change to human activity requires showing that the observed change cannot be explained by natural causes, forced or unforced. It is the process of establishing cause and effect relations, including the testing of competing hypotheses. CLIVAR ACC will facilitate progress in both these areas.

#### **Detection of climate change requires:**

- Systematic observations of key variables, especially (but not exclusively) the three-dimensional temperature structure of the atmosphere.
- Historical records of these variables, and relevant proxy data to construct and test paleoclimatic time-series, to describe natural climate variability.
- Long model integrations with constant forcings, and with varying natural forcings, to estimate natural climate variability.
- The development and refinement of statistical techniques for detection.

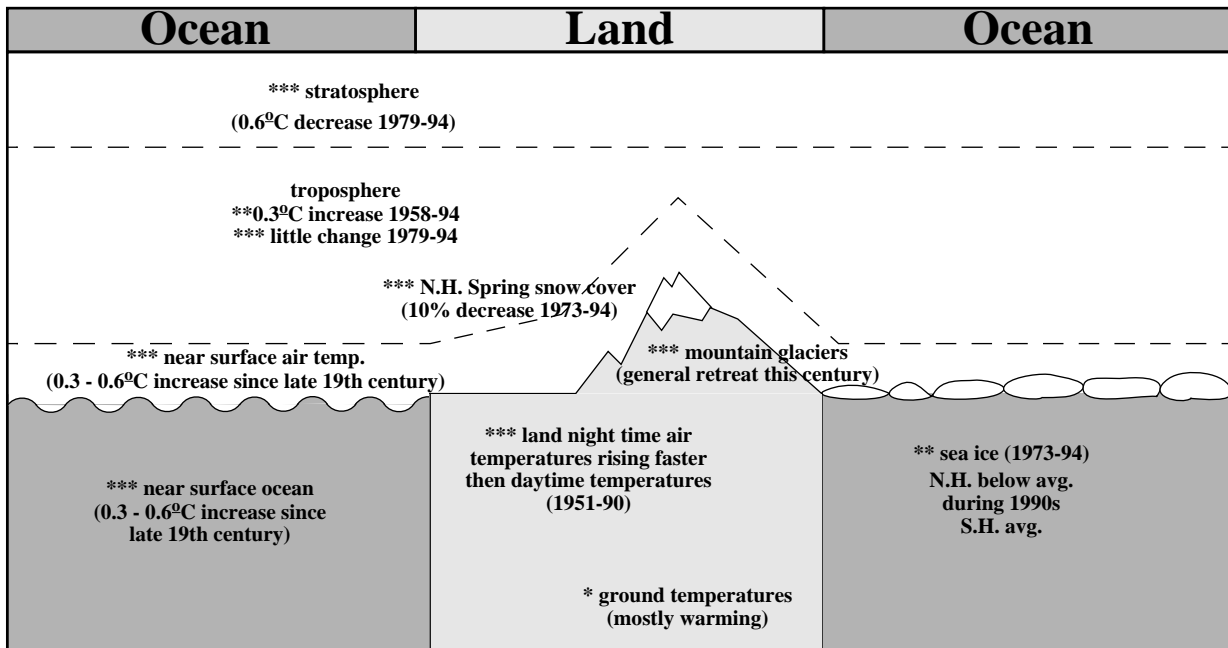
#### **Attribution of climate change to human activity requires, in addition:**

- Observations of the relevant human inputs to the atmosphere (i.e. greenhouse gases, sulphate aerosols).
- Methods to parameterise the effects of these human inputs on climate.
- Climate model integrations with various specified human inputs, for comparison with the observed behaviour of the atmosphere.

The IPCC Second Assessment Report (Santer et al., 1996a) on climate change noted that although few would argue that completely unambiguous detection and attribution of climate change had already occurred, the ‘balance of evidence suggests a discernible human influence on global climate’. This evidence included:

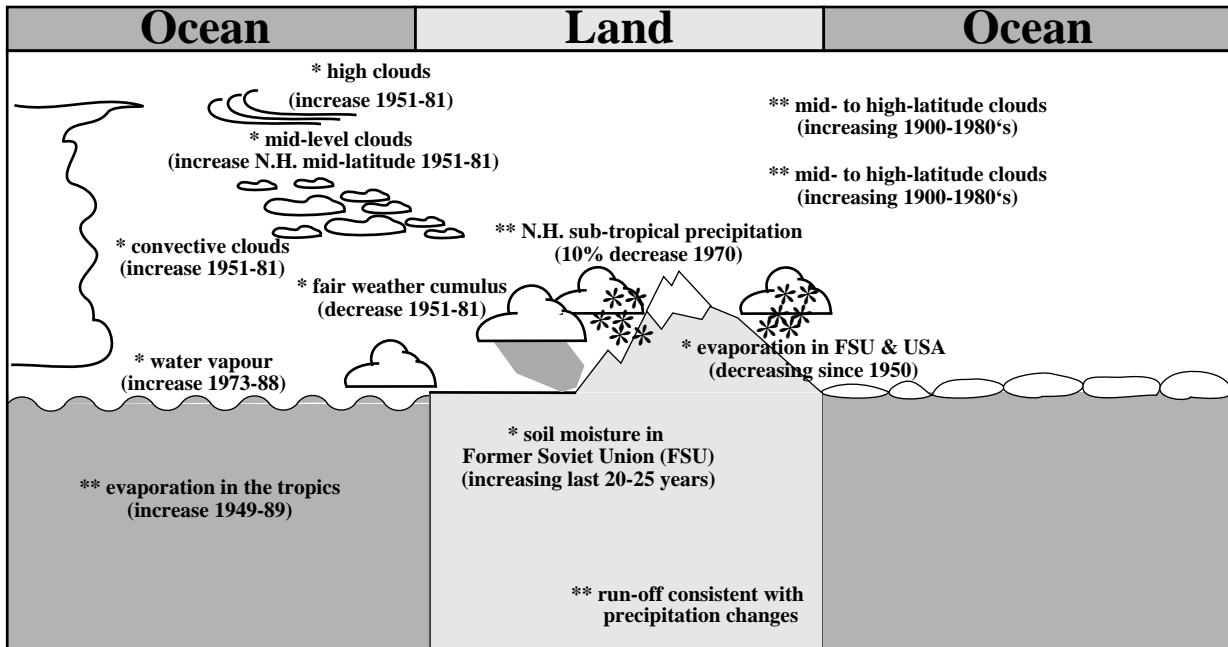
- Some evidence indicating that 20th century global mean temperature was at least as warm as any other century since at least 1400 AD. Data prior to 1400 are too sparse, at the moment, to allow the reliable estimation of global mean temperature.
- Assessments of the statistical significance of the observed global mean temperature trend over the last century have detected a significant change and shown that the warming is unlikely to be entirely natural in origin.
- Pattern-based studies, in which the modelled climate response to combined forcing by greenhouse gases and anthropogenic sulphate aerosols is compared with the observed geographical, seasonal and vertical patterns of atmospheric temperature change have found that pattern correspondences have been increasing, as would be expected with an anthropogenic signal increasing in strength. The probability that these correspondences could arise by chance is very low.
- Considerable qualitative correspondences have been found between models forced with greenhouse gases and anthropogenic aerosols, with observed changes such as a reduction in the diurnal temperature range (Fig. 11.1).

**(a) Temperature indicators**



Asterisk indicates confidence level (i.e. assessment): \*\*\* high, \*\* medium, \* low

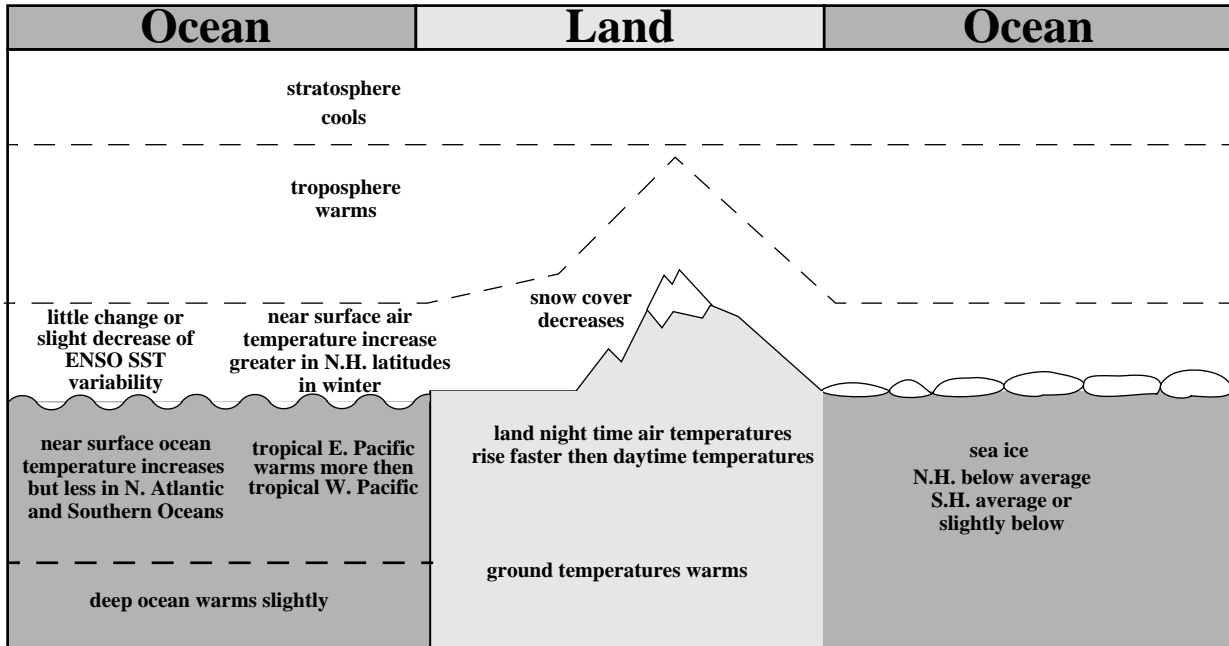
**(b) Hydrological indicators**



Asterisk indicates confidence level (i.e. assessment): \*\*\* high, \*\* medium, \* low

Fig. 11.1 a), b): Summary of observed climatic trends during the instrumental period of record (from IPCC, 1996).

**(c) Temperature indicators**



**(d) Hydrological indicators**

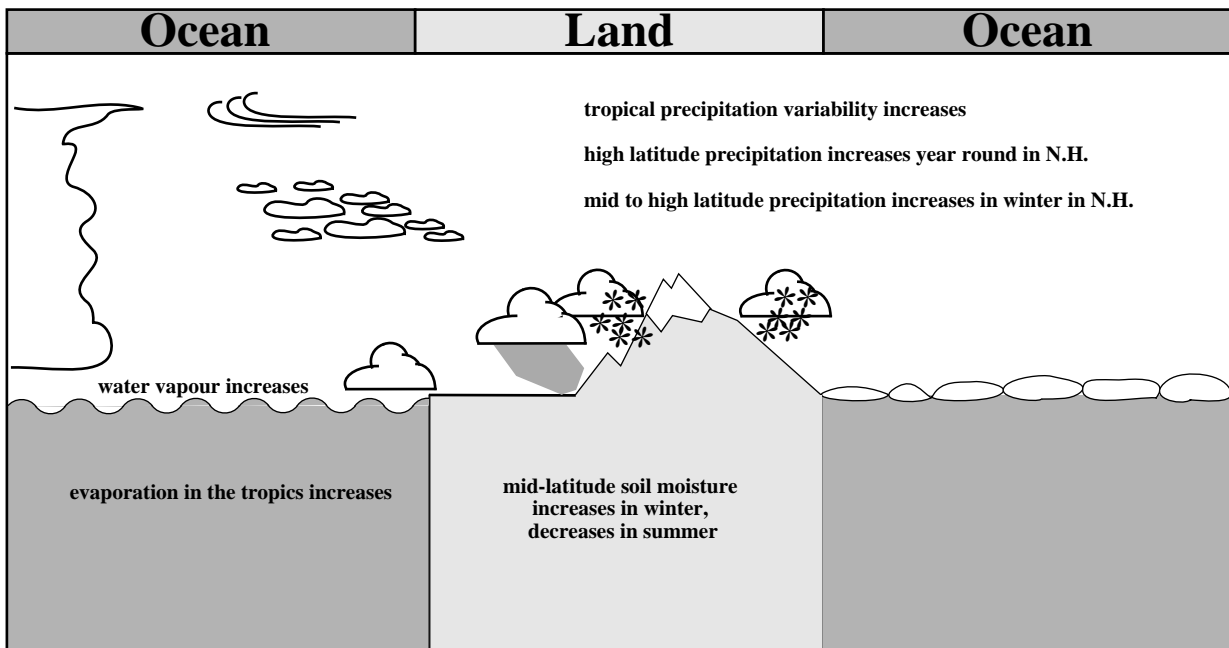


Fig. 11.1 (continued): A qualitative description of modelled anthropogenic climate change for some temperature (c), and hydrological indicators (d) (from IPCC, 1996).

### III. The CLIVAR Principal Research Areas

Studies published since the IPCC Second Assessment Report (e.g. Santer et al., 1996b; Hegerl et al., 1996; Tett et al., 1996) have continued to present evidence of a significant change in global climate, and evidence that this change is due, at least in part, to human activities (Fig. 11.2, Fig. 11.3). These studies have used the “fingerprint” approach to climate change detection and attribution. The “fingerprint” of climate change simulated by a climate model forced by greenhouse gases and/or aerosols is compared with the observed pattern of changes in the vertical (or horizontal) temperature patterns. This approach is more powerful than simply examining the global annual average temperature time-series (Fig. 11.4). Considerable uncertainties still exist however, precluding a definitive conclusion that human activities are affecting climate change as yet.

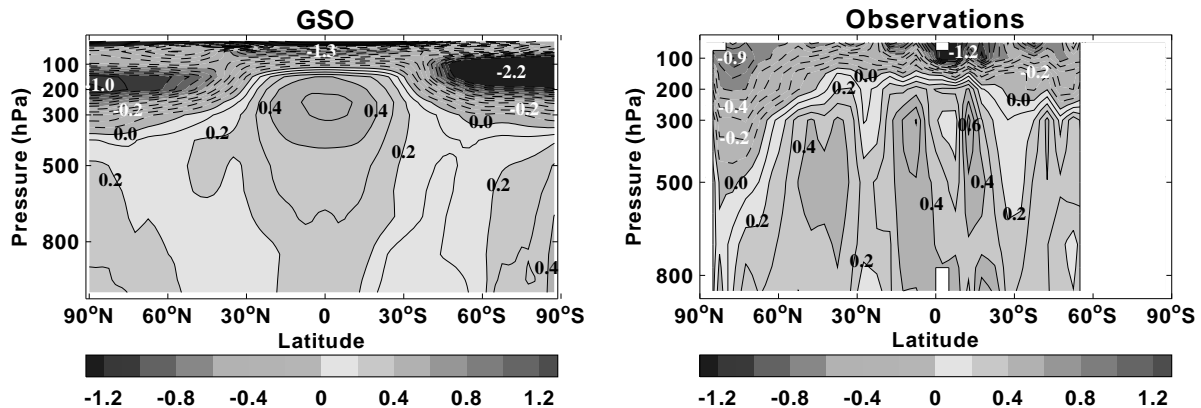


Fig. 11.2: Simulated and observed zonal mean temperature changes. Left panel: Model run HADCM2 (Hadley Centre) with greenhouse gas forcing + sulphate aerosols + stratospheric ozone; right panel: observations. All signals are defined to be the difference between the decadal mean from 1986 through 1995 and the 20-year from 1961 through 1980 (Tett et al., 1996).

One important aspect of climate change regards the possibility that, globally, the climate may become more extreme in the future. The IPCC Second Assessment found no compelling evidence that the climate was becoming more extreme - some climate extremes were becoming less frequent, while others became more frequent (Nicholls et al., 1996). A combination of modelling and empirical studies, on better global data bases, will be required to determine conclusively whether the climate is becoming more extreme as a result of human activity (Karl et al., 1997).

The El Niño - Southern Oscillation phenomenon is associated with climate extremes (droughts and floods) across much of the globe. Any changes to the El Niño - Southern Oscillation would have important effects on the interannual variability of climate. Trenberth and Hoar (1996) note that the behaviour of the El Niño - Southern Oscillation has been unusual since the mid-1970s, and they question whether this could be due to human effects on the global climate system. On the other hand, the recent behaviour could just be a chance occurrence due to natural variation (Cane et al., 1997). Because changes in ENSO and the NAO (Fig. 5.2, p 167) greatly affect surface temperature changes, determination of how ENSO and the NAO change with global climate change is extremely important.

The possibility that climate may change abruptly, rather than gradually, as human impacts on the atmosphere increase, needs to be addressed. The onset of the unusual El Niño - Southern Oscillation behaviour in the mid-1970s appears to have been quite sudden. Relationships between several climate variables in the Australian region appear to have changed abruptly in the early 1970s (Nicholls et al., 1996). The chances that such rapid changes could represent natural variability, rather than a climate change, need to be assessed. Paleoclimatic studies and modelling studies are the best way to address this question. The IPCC Second Assessment Report noted that climate had changed abruptly in the past (Nicholls et al., 1996) although such abrupt changes had been weaker during the Holocene. The studies in DecCen, of longer time scales of natural variability, will provide much needed information to assess the likelihood of abrupt climate changes due to human impacts on the atmosphere.

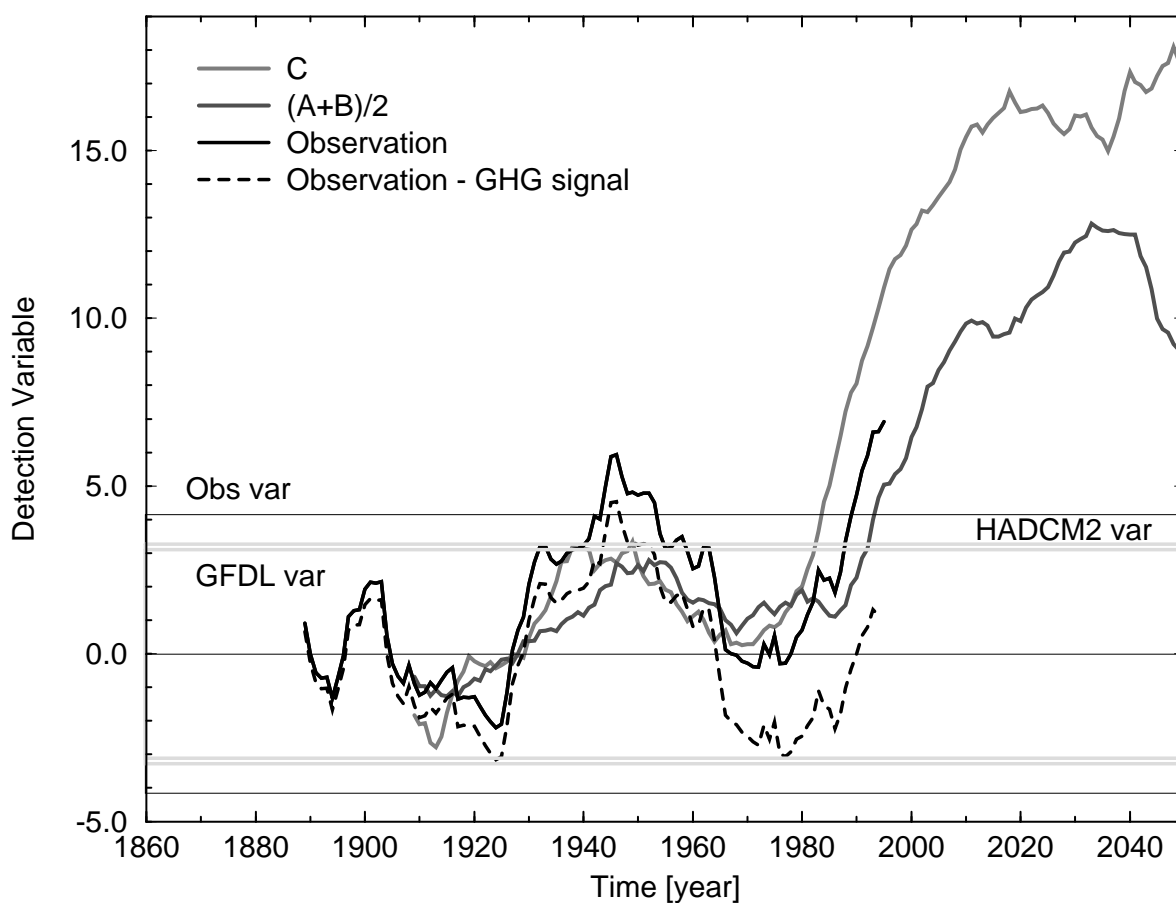


Fig. 11.3: Evolution of the detection variable (computed with the optimal fingerprint) for 30-year trend patterns for the observations with and without greenhouse gas signal (GHG), the average  $((A+B)/2)$  of the simulations A, B and simulation C. The time refers to the final year of the 30-year interval used to compute the trend pattern. 95% confidence intervals derived from three sets of variability data are also indicated. Experiments: C: with greenhouse gas forcing only; A, B two simulations including aerosol effect. All simulations ECHAM3+LSG, (Hegerl et al., 1997).

CLIVAR, through A2, can improve the current state of studies of climate change detection and attribution thereby reducing some of the current uncertainties, through:

- Ensuring the development of historical time-series of relevant climate data, with GCOS.
- Ensuring the development of proxy climate data, in association with PAGES.
- Ensuring the development of improved coupled models, through JSC/CLIVAR Working Group on Coupled Modelling.
- Ensuring the development of improved statistical techniques for climate change detection and attribution.
- Ensuring the development of historical time-series of natural and human forcings (including aerosols and ozone).
- Ensuring long coupled ocean-atmosphere model integrations, with standard forcings from natural and human sources.



CLIVAR can, through encouraging and facilitating these studies, provide solid progress in the area of climate change and detection, in preparation for the IPCC Third Assessment Report, expected to be completed in 2000.

For the moment, formal detection studies seem likely to continue to focus on the geographical pattern of change in near-surface temperature, and in the vertical patterns of temperature change. This is because the expected signal-noise ratio of anthropogenic climate change is likely to be highest in temperature, and because the global-scale fields of temperature are better than most other meteorological variables. However, informal detection studies of other variables can provide important information. For instance, trends in observed cloudiness, if they matched those predicted in models, could provide supporting evidence useful in the attribution of the cause of climate change. As well, trends in meteorological variables of greatest concern to local populations (e.g. extreme weather events) need to be monitored and examined for change, even if it at first proves difficult to determine the likely cause of these changes. Continued improvement in models, and improved historical climate data sets, will lead to ways of using even variables with high signal-noise ratios in climate change detection studies.

In determining the causes of observed climate change, many variables and their extremes and higher moments, and the physical links between them, including circulation, need to be considered.

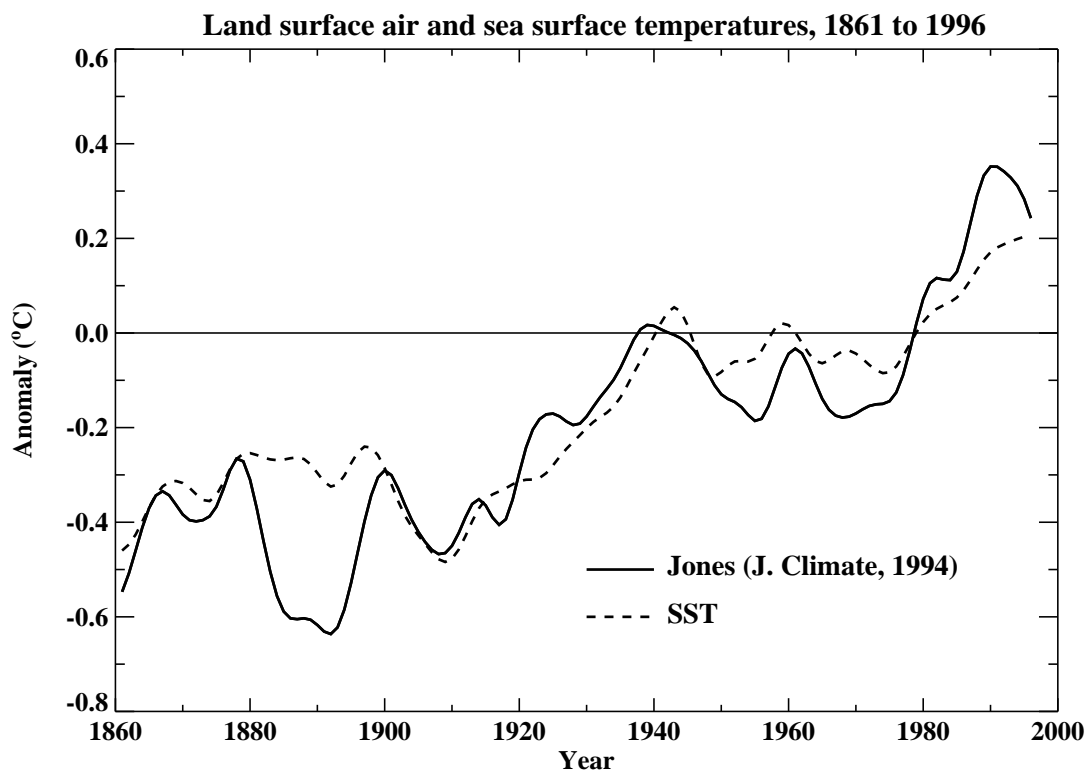


Fig. 11.4: Global land-surface air temperature anomalies (solid line) and Sea Surface Temperature anomalies (broken line) (°C) 1861 to 1994, relative to 1961 to 1990 (after IPCC, 1996).

## 11.2 MODELLING AND PREDICTION

Several groups have completed long control simulations with coupled ocean atmosphere climate models both to enable analysis of mechanisms of simulated decadal to centennial variability and to provide estimates of internal climate variability for climate detection. The same models have been used to simulate the instrumental temperature record using estimates of the historical forcing due to increases in greenhouse gases and simplified representation of the direct forcing by sulphate aerosols for climate detection studies. These simulations have been extended into the future using a limited number of emission/forcing scenarios.

Improved climate models are required in the future, for this task. The improvement of models for this task should arise from the various model intercomparison studies under way. Progress in understanding the response of climate to anthropogenic forcing depends on the improvement of parameterisations in coupled ocean-atmosphere models and the inclusion of extra processes (notably biological and chemical feedbacks). Progress in model development will be continually reviewed to assess model improvements made through numerical experimentation, and to identify areas that require further process studies. For the latter case, requirements to the appropriate WCRP or IGBP projects will be specified and co-operation fostered with the programmes. There is considerable overlap here with the requirements of A1, and of CLIVAR DecCen. Much of this model development will be monitored and encouraged through the activities of the JSC/CLIVAR Working Group on Coupled Modelling, which will service both DecCen and ACC, as well as other WCRP programmes.

As models improve, further integrations with constant forcings, as well as with changing natural forcings (e.g. volcanic activity and solar forcing variations) and with the inclusion of human forcings, are needed. Several groups have completed long simulations with coupled ocean atmosphere models, partly to provide estimates of internal (natural) climate variability for climate detection studies. The same models have been used to simulate the instrumental record using estimates of the historical forcings due to increases in greenhouse gases and simplified representations of the direct forcing by sulphate aerosols for climate change attribution studies. Further integrations, with more and improved models, and with better representation of the historical forcings will be undertaken. Ensembles of integrations will be needed, to isolate the signal due to the forcings from internally generated variability.

Specific modelling tasks relevant to A2 are:

- Coupled Model Intercomparison Project (CMIP). Improvement of coupled climate models is essential for progress in climate change detection and (especially) for attribution. CMIP will provide a focus for examining and improving these models. The first step of CMIP will be to prepare an updated intercomparison of selected features of the control climates of coupled models.
- Coupled model response to forcings. This is the second step of CMIP and will lead towards the use of standardised (specified) forcing scenarios, including atmospheric carbon dioxide and aerosol loading and distribution, as well as solar variation and vulcanism, to be used by coupled modelling groups in transient experiments.
- Natural variability experiments. Integration of models with standardised historical forcings, including solar activity and vulcanism. These long experiments will provide guidance on the natural and internal variability present in the climate system.
- Simulation of historical climate. Ensembles of extended climate model integrations forced by both natural and human forcings (i.e. including greenhouse gas and aerosol loading and distributions, as well as solar variability and vulcanism) will provide information on the causes of observed climate variations.

These modelling experiments will be co-ordinated through the CLIVAR/JSC Working Group on Coupled Modelling (WGCM) and are included in this document (see section on Global Modelling (II 2.3)).

### 11.3 OBSERVING NEEDS

The first step in the detection/attribution of climate change is the assembly of high-quality time-series of key variables, especially of the three-dimensional temperature structure of the atmosphere. We need to ensure that credible historical and paleoclimatic time-series are available, through the correction for time-varying biases caused by changes in observing practices, instrumentation, and location. As well, continuation of high-quality climate observations into the future is a prime requirement. GCOS and GOOS have a leading role in ensuring the continuation of such observations, as does WMO with its Reference Climate Station programme. CLIVAR will need to support GCOS/GOOS/WMO in these endeavours, and can provide the scientific support and justification for observing system enhancements as part of the CLIVAR sustained observations system.

The single climate element of most value in climate change detection is near-surface temperature (Fig. 11.4). Unfortunately, the present rate of decline of global data acquisition and exchange across the Global Telecommunications System threatens estimates of this element. Historical temperature data are plagued by inhomogeneities from changes in instrumentation, exposure, site-changes, and time-of-observation bias. Many of these problems can be overcome by thorough comparisons between stations and with the help of documentation regarding site and instrumentation changes. Few countries, however, provide adequate information for such activities. GOOS/GCOS is likely to lead to enhancements of the available information, and CLIVAR can again provide the scientific support for this activity.

The vertical distribution of temperature trends can provide information of considerable importance for the attribution of climate change (Fig. 11.2). However, the conventional upper air temperature observations are sparse and have even greater problems with historical consistency. There have been changes in radiosonde instrumentation in the past few decades, and careful study is required to adjust for artificial, instrumental biases or changes which could be interpreted as real climate changes or trends. Satellite observations provide a means for overcoming some of the problems with conventional, radiosonde measured, temperatures, but the relatively short record from satellites necessitates the careful blending of the conventional and satellite records, if the data are to be very useful in climate change detection. As well, changes in satellites and the possible resulting effects on the data need to be taken in account in the derivation of climate series. The satellite data, just as the conventional data, will suffer from changes in instrumentation.

Apart from temperatures, continued monitoring of many other variables and the production of high-quality historical data sets is necessary for some aspects of climate change detection. Although the formal detection studies seem likely to continue to focus primarily on large-scale temperature fields, informal studies will compare observed trends with modelled trends, using a variety of variables, including rainfall, cloudiness, extreme weather conditions (including hurricanes), lower-tropospheric water vapour in the tropics, etc. Time-series of such variables are often even more problematic than is the case for temperature. However, the development of climate change indices combining several individually less-powerful variables may provide a useful approach.

A variety of fields is also necessary for studies to improve the models used in climate change detection. For instance, upper tropospheric water vapour is poorly measured, and probably poorly modelled, at the current time. Improved observations are needed to identify improved methods for dealing with this important variable in the models. These will be dealt with primarily in collaboration with GEWEX (see Appendix 5).

The recent move to undertake historical re-analyses of meteorological data, using a consistent analysis method, should provide more consistent three-dimensional analyses of the atmosphere. These will be useful in understanding the variability of the atmosphere, and thus may be useful in climate change and detection studies. Care will still be needed, however, because instrument changes throughout the past few decades means that the observational base has changed, even if a consistent analysis method is adopted.

Sub-surface ocean temperature is seen as a key variable in climate change detection, because of its likely high signal to noise. New approaches such as acoustic tomography may prove useful in climate change detection and attribution. The three-dimensional spatial structure of changes in ocean temperature

and salinity may be particularly useful in differentiating between natural variability and anthropogenic change.

The recently formed CLIVAR/CCL Working Group on Climate Change Detection (WGCCD) will work towards the definition of requirements for enhanced observations and monitoring of appropriate elements of the climate system related to inter-decadal variability and climate change.

## **11.4 FOCUSED RESEARCH PROJECTS**

### **11.4.1 Developing indicators and indices for climate extremes**

*Purpose:*

To produce time-series of global and regional indicators and indices of climate extremes by exploiting daily weather data, and develop a mechanism to update these indicators and indices on a regular basis.

*Background:*

Lack of integrated data sets of high-resolution data has limited our ability to develop indicators and indices related to various aspects of climate extremes. The question of changes in climate and weather extremes is of fundamental interest to the economic well-being of all nations and is of major concern to understanding natural and anthropogenic climate variability. Over the years various international and national projects have now made more high-resolution data available electronically, but there has not been a concerted effort to integrate these data in a common data base for international use and assessment of climate extremes. This project will spearhead this much-needed focus. The World Data Center-A for Meteorology has the capability to assist with data set integration for this project. This project should be undertaken with the CLIVAR/CCL Working Group on Climate Change Detection (WGCCD), and the GCOS Data and Information Management Panel (GCOS-DIMP).

*Feasibility:*

The process of assembling various aspects of weather extremes into meaningful indices or indicators has been demonstrated in numerous applications. A CLIVAR/GCOS workshop in mid-1997 focused on developing new indices and indicators, appropriate for varying climates as well as employing those already developed. These indices and indicators can be tailored for specific interests, e.g. climate change detection, insurance impacts, etc. Continuation of this project, through the WGCCD and GCOS-DIMP, should lead to improved global data bases for detecting changes in climate extremes. A follow-up meeting is to be held in 1999.

### **11.4.2 Development of historical global temperature series from paleoclimatic data**

*Purpose:*

To combine high-quality paleoclimatic records of temperature, to provide an estimate of annual-decadal global or hemispheric annual or seasonal mean temperature for the past 1000 years, to assist in the detection of climate change.

*Background:*

IPCC Second Assessment Report used a proxy record of summer, Northern Hemisphere decadal temperatures, from 1400 AD, to provide an estimate of 'natural climate variability', with which to compare the 20th century warming. This proxy temperature record was assembled from 16 summer temperature records

### *III. The CLIVAR Principal Research Areas*

from North America, Europe, and East Asia. More high-quality proxy records, with wider spatial representation, need to be combined to provide improved estimates of global or hemispheric mean temperature for comparison with observed 20th century climate change. This project should be undertaken through the PAGES/CLIVAR Working Group.

#### *Feasibility:*

An increasing number of high-resolution, high-quality paleoclimatic estimates of temperature over the past 1000 years are becoming available. It should be feasible to assemble these data into a proxy record of hemispheric or even global temperature, from about 1000 AD, for comparison with recent observed temperature trends. This could be best accomplished through arranging, with PAGES, a workshop of developers of high-quality, high-resolution paleoclimatic data sets, and historical temperature data sets, with an interest in providing such a combined, proxy, temperature series. Such a workshop could be held in 1999. This would provide sufficient time for the development of the time-series before the start of the IPCC Third Scientific Assessment of Climate Change.

### **11.4.3 Development of standard sets of historical climate forcings (natural and human-induced)**

#### *Purpose:*

To develop a standard set of historical forcings, for use with climate models in estimating natural climate variability, and in comparing model output with observed climate variations, for the detection and attribution of climate change.

#### *Background:*

Estimation of internal climate variability is required to allow the detection and attribution of climate change. The use of models forced with natural climate forcings (e.g. sea surface temperatures, volcanism, and solar variability) provides a mechanism for estimating, from models, this natural variability. Running climate models with historical natural and human-induced forcings can allow the comparison of model output with observed climate variations. This is necessary for attributing climate change. This project should be undertaken through the CLIVAR/CCL WGCCD, in association with IPCC and the CLIVAR/JSC WGCM.

#### *Feasibility:*

Several groups have used climate models, with estimates of historical forcings from natural and human-induced sources, to simulate recent climatic behaviour. Different groups have used different historical forcings. Use of a standard set of historical forcings would provide a basis for ascertaining whether differences in model results were due to model differences. This would enhance confidence in the estimates of natural variability from models, and in their use in attribution of recent climate variations. The WGCM reviews and collates forcings used in model simulations with a view to recommending a standard set.

#### 11.4.4 Improved statistical methods for climate change detection and attribution

*Purpose:*

To provide a suite of statistical methods for improved detection and attribution of climate change.

*Background:*

The IPCC Second Assessment Report examined the various statistical techniques used for detection and attribution of climate change. The most useful techniques, to this point, compare observed climate variations with model-predicted spatial patterns of temperature change (Fig. 11.2 and 11.3). These predicted patterns come from models forced with a combination of human-induced forcings (e.g. greenhouse gases, ozone depletion, and aerosols). For the IPCC Third Assessment, improved detection techniques should be investigated. These may include statistical techniques using more than just the three-dimensional pattern of mean temperature change. For instance, changes in other variables, or in the frequency distributions of temperature and other variables, may provide a more powerful approach to climate change detection and attribution.

*Feasibility:*

The number of scientists involved in the development and application of advanced statistical techniques for climate change detection and attribution is quite small. They employ a variety of approaches, but further approaches could be developed, and applied to the improving historical climate data base, for instance, by using the indices of extremes to be developed under Focused Research Project, ‘*Developing Indicators and Indices for Climate Extremes*’ (11.4.1). Improved techniques and approaches will be encouraged by holding expert workshops as appropriate.

### 11.5 DATA SET DEVELOPMENT, DIAGNOSTICS AND EMPIRICAL STUDIES

The detection and attribution of anthropogenic climate change will require high-quality historical climate data sets, as well as continued monitoring of the climate in the future. IPCC (1996) noted that current data and observational systems are inadequate for the complete description of climate change. Virtually every monitoring system and data set requires better data quality and continuity. New monitoring systems, as well as improvements on current systems and studies to reduce quality problems in historical data, are required. Conventional meteorological data, both now and in the past, were collected for weather prediction and for the description of current climate. They require considerable work to ensure they are useful for monitoring climate and change.

The preparation of high-quality, historical climate data sets for climate change detection will be pursued through the CLIVAR/CCL Working Group on Climate Change Detection (WGCCD). This group has the expertise and access to data and station documentation necessary for the detection and removal of inhomogeneities in the historical data. The GCOS Data and Information Management Panel (GCOS-DIMP) too has a role in this area. Close co-ordination between the WGCCD and the GCOS-DIMP will ensure that duplication of effort is avoided, and that the best quality data sets are produced for climate change detection studies.

One specific activity that could be pursued through the WGCCD is the estimation of errors for the historical global mean annual temperature record (Fig. 11.4). The estimation of these errors is of considerable importance in the detection of climate change, but is also a difficult problem, because of the several sources of error in these annual means. Errors are caused by the incomplete global coverage, as well as by instrumental changes.

The WGCCD should develop a set of proposed climate indicators based on operational observations. Following the definition of the appropriate climate change and variability indices the group will develop a

plan for implementation of operational observations to support routine monitoring of these indices.

An essential part of the detection of climate change will be the estimation of trends in climate variables. These will necessarily include near-surface and vertical patterns of temperature, but should also include precipitation, cloud and, as highlighted above, a variety of indices of extreme weather. Trends in such variables will be helpful in the informal studies of climate change, as well as being necessary for studies of the possible impact of climate change. The GCOS-DIMP, together with the WGCCD, will foster such studies, which will usually require co-ordination of studies in many countries, to provide a useful near-global coverage.

One important requirement for climate change detection studies is long-term (typically 1000 years) hemispheric or global-scale temperature, with annual-decadal resolution. Such time-series are important to determine the amplitude of natural variability. Estimates of natural climate variability are needed for comparison with recent climate variations, to determine whether recent trends are within the compass of natural variability. CLIVAR DecCen is also interested in the estimation of temperatures on these time scales and resolution. The Joint CLIVAR-PAGES Working Group will co-ordinate studies aimed at providing estimates of natural climate variability from paleoclimatic data (see Focused Research Project '*Development of Historical Global Temperature Series from Paleoclimatic Data*') (11.4.2).

Historical records of natural and human forcings, necessary to force models to investigate natural climate variability and to compare the observed climate record with that predicted from the forcings, will be produced from Focused Research Project '*Development of standard sets of historical climate forcings (natural and human-induced)*' (11.4.3). These will need to be archived for easy access by modelling groups and others.

## 11.6 LINKAGES

CLIVAR ACC should provide scientific support for Working Group I of IPCC, i.e. that body concerned with the science of climate change. The IPCC Second Assessment identified many scientific questions and priorities. CLIVAR-ACC should monitor scientific progress on addressing these priorities, and encourage work in areas where progress could be enhanced.

One priority area identified by IPCC was that of observations of key variables. Here CLIVAR should remain well-connected with GCOS, to ensure that observing systems necessary for climate change detection and attribution are established. CLIVAR-ACC can provide the science necessary for GCOS to identify systems and variables needed for the detection and attribution of climate change.

CLIVAR will need to remain in close contact with the WMO Commission for Climatology (CCI), which represents the bodies archiving climate observations. The establishment of the joint CLIVAR/CCI Working Group on Climate Change Detection (WGCCD) should facilitate this collaboration.

CLIVAR also needs to collaborate closely with the paleoclimatic scientific community, largely represented by IGBP-PAGES, to ensure that paleoclimatic data appropriate for the estimation of natural climate variability is assembled. The PAGES/CLIVAR Working Group should facilitate this collaboration.

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### *III. The CLIVAR Principal Research Areas*

## 12. ASSESSMENT OF CURRENT STATUS OF PRINCIPAL RESEARCH AREAS

The Principal Research Areas represent research foci within the global remit of the CLIVAR project that have already been explored at meetings and discussions within the international CLIVAR framework. CLIVAR is studying climate variability and change on the global scale, and must be built on a strong foundation of global scale activities. These represent a continuation and strengthening of programmes initiated by the research community under TOGA, WOCE and the various modelling programmes of the WCRP as well as a wide variety of national agencies in support of a variety of oceanic and atmospheric services. Accordingly, as described in Section II, there needs to be a global framework for the Principal Research Areas that includes global modelling, empirical, analytical and diagnostic studies, global sustained observations, and dataset development and archival. For these foci there is already a relatively well-developed understanding of the scientific and implementation issues.

The following is an assessment of the status as of mid-1998 of the Principal Research Areas of CLIVAR. These are subject to change and evolution as nations make their interests known and commit to parts of CLIVAR, and the will and resources of scientists and the governments of the world are brought to bear on the scientific questions. Note also that these Principal Research Areas continue in the context of the global components of CLIVAR and that some level of activity is desirable in all areas, as described in Section I. Note that the order here is the same as that when the Principal Research Areas were introduced and does not imply priority.

- **ENSO: Extending and Improving Predictions (G1):**

This project builds directly on TOGA in dealing with the global aspects of ENSO. The CLIVAR (formerly TOGA) observing system is in place and is being continued by national agencies. The project is ready and feasible, and is growing as infrastructure develops in many nations to capitalise on the success of TOGA in demonstrating skill in forecasting ENSO. These activities have accelerated as the 1997/98 El Niño has caught attention around the world. The establishment of international organisations such as IRI and IAI as well as the continued interest of national and regional forecasting centres such as NCEP, ECMWF, and BMRC in improving forecast skills for ENSO imply a strong international commitment to G1. The oversight of the observing system is being transitioned to GCOS as ENSO forecasting develops as an operational climate service. CLIVAR, through G1, will coordinate modelling activities aimed at improving the quality of these forecasts as well as examining the effectiveness of and refining the observing system.

- **Variability of the Asian-Australian Monsoon System (G2):**

This research project focuses on the variability and predictability of the Asian - Australian Monsoon system. It has developed within the scientific community brought together by TOGA and TOGA COARE. An international panel has been established by CLIVAR following several international workshops and other meetings. Some pertinent activities are in progress (e.g., SCSMEX). The panel is developing scientific and implementation plans in coordination with the GEWEX activities under GAME, the NEAR-GOOS project of IOC, and various national programmes and activities directed to these issues and this region.

- **VAMOS: Variability of the American Monsoon Systems (G3):**

This project deals with the variability in the American monsoon. Recognizing that there is an interested scientific community and organisations to form the basis of a CLIVAR activity, CLIVAR has established an international panel to develop the activity. It is building on the planning and coordination activities of a number of other programmes and organisations operating in the Americas, many of which are considered to be national contributions to VAMOS and CLIVAR, such as LBA, PACS, GCIP, PIRATA, AARAM, IAI, IRI, etc. While strong interest and commitments exist in the component parts, planning activities to build a cohesive focused programme have just begun.

- **African Climate Variability (G4):**

While the need for better understanding of climate variability in Africa is very high, the infrastructure and scientific basis for making advances needs to be developed. A task group has been established by CLIVAR to begin this process. Also, there are a number of current initiatives directed toward improving the collection and distribution of climate information within Africa. The challenge to CLIVAR is to develop a research programme directed toward better understanding of those aspects of climate variability over Africa which are predictable while also assisting the development of basic meteorological and climate services to many parts of the continent, and helping to address the impacts of climate variability.

- **Atlantic Variability: The North Atlantic Oscillation (D1), Tropical Atlantic Variability (D2), Atlantic Thermohaline Circulation (D3):**

While these Principal Research Areas each focus on a different feature of Atlantic variability, they share a need for a continued description of the seasonal to decadal variability of the ocean and its overriding atmosphere over the entire Atlantic. For the purposes of implementation, these three Atlantic Principal Research Areas should be considered together because of their intersection with regard to the observations and modeling. The NAO and tropical Atlantic variability are important modes of variability affecting the climate of the surrounding land masses. Documenting and modelling changes in the Atlantic thermohaline circulation is important to Principal Research Areas A1 and A2, especially because of the possibility of abrupt climate change. The Atlantic has a large community of ocean and atmospheric scientists who have a rich history of collaborative activity over the last century, with central interests expressed by scientists in Europe and North America, in particular. The challenge for CLIVAR is to find an organisational structure that can encompass this large and diverse tradition.

- **Pacific and Indian Ocean Decadal Variability (D4):**

Better understanding of decadal and longer-term variability of ENSO has emerged as an important topic and there are interesting indications of signals in the mid and high latitude North and South Pacific. The North Pacific has a good tradition of sustained observations of the upper ocean and surface meteorology; however the organisations that fostered the collection and analysis of those observations have ceased to be active and several agencies have substantially reduced their support of these observations in recent years. There is a scientific community working on large-scale problems associated with the North Pacific, and the establishment of PICES shows that the nations surrounding the North Pacific have an interest in re-establishing the collaborative spirit that characterised the North Pacific Ocean community during previous decades. CLIVAR needs to identify a significant group of scientists or a national programme as a core of a Principal Research Area in the North Pacific.

## *12. Assessment of current status of Principal Research Areas*

The tropical Indian Ocean and western Pacific are regions that are important to the A-A monsoon and activities in this region will be co-ordinated by that panel. The size of the South Pacific and Indian oceans and the sparseness of the shipping routes makes a concerted attack on this region a daunting task although the drifting and profiling buoys offer some exciting new possibilities. Accordingly, the feasibility of making major advances is judged to be somewhat less at this time. Some small field programmes are being planned. The modelling and data analysis activities associated with the extended ENSO studies of NEG-1 and the Upper Ocean Panel are extending into the high latitude Pacific. These panels will provide a continuing oversight of issues related to the whole Pacific and Indian basins until CLIVAR develops a more appropriate coordination mechanism. Some aspects of this Principal Research Area may be addressed through G1.

- **Southern Ocean Climate Variability (D5):**

This region is difficult to observe systematically because of its remoteness and the resulting logistic difficulties. Historical data are few. This latter point makes it all the more important for some sustained activity in the area. The Southern Ocean does have an active scientific community that is used to working together on collaborative projects and will form the core of the CLIVAR planning and co-ordination activities in this Principal Research Area. The regular resupply of the Antarctic research stations offers good opportunity for annually repeated observations along particular longitudes. The WCRP has begun an initiative in Cryosphere and Climate as a broadening and follow-on to ACSYS which is likely to be very important for Southern Ocean studies.

- **Climate Change Prediction (A1):**

This is a key activity for the IPCC and is an extension of existing efforts. Through the WGCM, CLIVAR will coordinate and encourage the development, validation and intercomparison of coupled ocean - atmosphere climate models capable of simulating effects of both anthropogenic activities and natural variability. This activity has been under way in nations and within the WCRP since the beginning of 1990s and has contributed to both the 1990 and 1995 IPCC assessments. Placing this activity within CLIVAR strengthens the exchange of information between the modelling community and the communities that are examining the natural variability of the climate through empirical studies and focused observational programmes. CLIVAR expects the A1 activities to feed into the IPCC process and provide a solid scientific basis for their deliberations.

- **Climate Change Detection and Attribution (A2):**

This is another key activity feeding into the IPCC and is also an extension of existing activities. It encompasses development of techniques and databases to both detect climate change and determine whether part of those changes can be attributed to human activities. The latter requires definition of a climate signal to be expected from modelling studies. At present the community involved in these activities is relatively small; however, policy makers dealing with the climate change agenda really need this type of information. Aspects of this activity are concentrated within climate modelling groups so this can be considered a complement to A1 and contributions will come from the WGCM. The availability of data from a variety of coupled climate model runs, climate datasets and the availability of computer power to store and manipulate these large datasets suggest that this is an area of CLIVAR that has good potential for growth. A lot of this work will also occur in close collaboration with other groups (Commission for Climate Joint (with CLIVAR) Working Group on Climate Change Detection, CLIVAR/PAGES, etc.).



# APPENDIX 1

## 1. ACKNOWLEDGEMENTS:

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IV. Appendix

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## APPENDIX 2

### 2. LIST OF MEETINGS (June 1995 - May 1998)

- Fourth Session of the CLIVAR Scientific Steering Group, Hamburg, Germany, 12-16 June 1995
- First Session of the CLIVAR DecCen/ACC Numerical Experimentation Group (NEG-2), Hamburg, Germany, 11-13 September 1995
- CLIVAR/WOCE XBT/XCTD Panel, Ottawa, Canada, 13 October 1995
- Data Buoy Co-operation Panel (DBCP), Pretoria, South Africa, 17-19 October 1995
- First Session of the CLIVAR Upper Ocean Panel, La Jolla, USA, 18-19 December 1995
- Monsoon Planning Meeting, Honolulu, USA, 17-19 December 1995
- Executive Session of the CLIVAR SSG, Atlanta, USA, 2-3 February 1996
- WOCE Data Products Meeting, 9th Session, Brest, France, 5-9 February 1996
- First Session of the CLIVAR GOALS Numerical Experimentation Group (NEG-1), Montego Bay, Jamaica, 26-29 February 1996
- First Euroclivar Committee Meeting, Baarn, Netherlands, 1-2 April 1996
- Task Group of the WMO/CCL Working Group on Climate Change Detection, Geneva, Switzerland, 9-10 April 1996
- Euroclivar Workshop on cloud feedbacks and climate change, Bracknell, UK, 9 - 11 April 1997
- JCESS/CLIVAR Workshop on Decadal Variability, Columbia, USA, 22-24 April 1996
- Fifth Session of the CLIVAR Scientific Steering Group, Sapporo, Japan, 3-7 June 1996
- US Ocean CLIVAR Meeting, San Antonio, USA, 10-12 June 1996
- CLIVAR International DecCen Workshop on Atmosphere-Ocean Interactions and Their Influence on Decadal-Scale Climate Variability, Vancouver, Canada, 4-6 September 1996
- Second Session CLIVAR DecCen / ACC Numerical Experimentation Group (NEG-2), Victoria, Canada, 9-12 September 1996
- Second Euroclivar Committee Meeting, St. Lambert de Bois, 30 September - 2 October 1996.
- International CLIVAR Workshop on an Ocean Programme for DecCen Climate Variability, Villefranche-sur-Mer, France, 28-31 October 1996
- Workshop on an Assessment of the Pacific Observing System for Analyses, Model-Testing and El Niño; and Second Session of the CLIVAR Upper Ocean Panel, Villefranche-sur-Mer, France, 21-24 October 1996
- PAGES/CLIVAR Working Group, Villefranche-sur-Mer, France, 24-25 October 1996

#### IV. Appendix

- First Session of the Asian-Australian Monsoon Panel, Goa, India, 19-22 November 1996
- CLIVAR Implementation Plan Writing Group Meeting, Hamburg, Germany, 2-6 December 1996
- CLIVAR SSG Executive Session and Implementation Plan Writing Group Meeting, Boulder, USA, 10-14 February 1997
- Conference on American Monsoons, Mexico City, Mexico, 17-20 March 1997
- Third Euroclivar Committee Meeting, Vienna, Austria, 24 April 1997
- Sixth Session of the CLIVAR Scientific Steering Group, Washington DC, USA, 28 April-2 May 1997
- Second Session of the CLIVAR GOALS Numerical Experimentation Group (NEG-1), Hamburg, Germany, 12-15 May 1997
- UK CLIVAR Meeting, Southampton, UK, 5-6 June 1997
- Conference on the World Climate Research Programme, Geneva, Switzerland, 26-28 August 1997
- Euroclivar Workshop on Past Climate Data, Abisko, Sweden, 31 August-3 September 1997
- US Planning Meeting for a 'Pacific Basin-wide Extended Climate Study' , Miami, USA, 15-16 September 1997
- Fourth Euroclivar Meeting, Bologna, Italy, 9-10 October 1997
- Sixth Session of the TAO Implementation Panel, Reading, UK, 4-6 November 1997
- CLIVAR SSG, Executive meeting, Washington DC, USA, 14-16 January 1998
- US Atlantic Climate Variability Experiment, Dallas, USA, 2-4 February 1998
- Euroclivar Workshop on Climate Change Detection and Attribution, Bracknell, UK, 9-12 March 1998
- VAMOS/PACS Workshop on Field Programmes, São Paulo, Brazil, 30 March - 3 April 1998
- CLIVAR Upper Ocean Panel, 3rd Session, Toulouse, France, 27-29 April 1998
- Seventh Session of the CLIVAR Scientific Steering Group, Santiago de Chile, Chile, 27 April - 1 May 1998

## APPENDIX 3

### 3. PROGRAMMATIC INFRASTRUCTURE AND ORGANISATION

#### 3.1 IMPLEMENTATION AND OVERSIGHT STRUCTURES

The initial programmatic infrastructure of CLIVAR is shown in Fig. A.3.1. Under the scientific and programmatic oversight of the CLIVAR Scientific Steering Group (SSG) a number of standing committees, panels and working groups have been established to ensure an efficient co-ordination throughout the entire programme.

Some panels cut across the projects and time scales to integrate and co-ordinate the specific requirements of the CLIVAR Principal Research Areas. In particular, CLIVAR has set up panels dealing with numerical experimentation and modelling, and observations not specifically focused of one particular core project of CLIVAR.

Because modelling is of central importance to CLIVAR, two numerical experimentation groups (NEGs) have been formed. One will address issues and time scales relevant to GOALS (NEG-1), i.e. mainly the CLIVAR Principal Research Areas G1 to G4, while the other concentrates on issues and time scales relevant to DecCen and ACC. This group, named Working Group on Coupled Modelling (WGCM), operates under the joint oversight of CLIVAR and the Joint Scientific Committee of WCRP. The latter group also has strong links with WOCE for the oversight of ocean modelling, the Working Group on Numerical Experimentation of the JSC and with the appropriate bodies of IPCC. In this context, CLIVAR recently established a much closer co-operation with the Working Group on Climate Change Detection of the Commission on Climatology (of WMO) to co-ordinate the research efforts done under the core project A2. There will be a joint CLIVAR/CCI Working Group on Climate Change Detection.

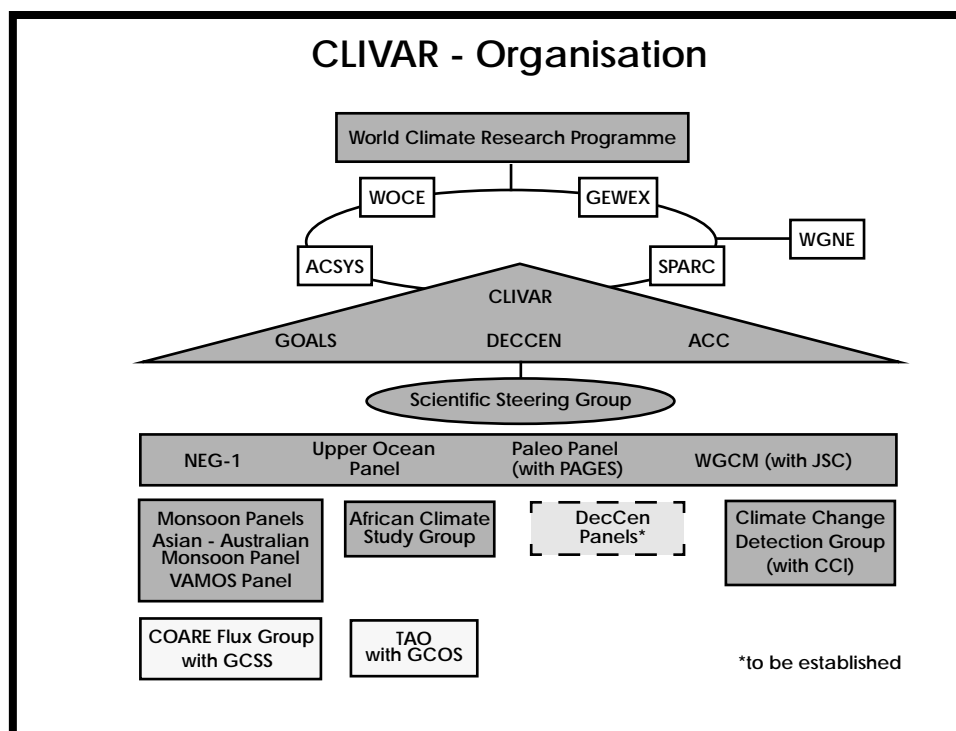


Fig. A.3.1: Schematic diagram of the CLIVAR organisation

#### IV. Appendix

In co-operation with the emerging oceanic components of the Global Climate Observing System under the Global Ocean Observing System (GOOS) (i.e. Ocean Observations Panel for Climate), and the ongoing WOCE (World Ocean Circulation Experiment), CLIVAR will address, through its Upper Ocean Panel, many issues associated with continuing and new requirements for ocean observations. This panel is, like the activities of the numerical experimentation groups, not specifically focused on one particular core project of CLIVAR but will cut across through the projects and time scales to integrate and co-ordinate the specific upper ocean observational requirements of the CLIVAR principal research areas. At its meeting in April 1998 the SSG also agreed to form a series of ocean basin panels to oversee detailed implementation. The UOP will provide an integration across these regional panels.

CLIVAR has established a further joint working group focusing on paleoclimatic changes, the generation and rescue of paleo and historical data relevant for different projects of CLIVAR. It was recognised that this activity, in co-operation with Past Global Changes (PAGES, a component of IGBP), is one of the few possibilities for the assessment and investigation of long-term climate variability on decadal time scales since the current observational record is and will during the lifetime of CLIVAR be too short for these purposes. The success of this project is critical for the guidance and evaluation of multi-decadal and multi-century global simulations of the climate system.

The variability of the monsoons is a major factor in year to year fluctuations of climate that affect large areas of the world and many millions of people. Thus, CLIVAR has established two initiatives on monsoonal climate variations. The Asian-Australian Monsoon Panel is mostly concerned with the 'classical' monsoon variability over the Asian and Australian region but will also address the global significance of the A.-A. monsoonal variations and place special emphasis on the role of the oceans. It will complement the activities of other international, regional and national programmes working in this area of research. The initiative will pay particular attention to the relationship between A.-A. monsoon systems and the El Niño/Southern Oscillation (ENSO) phenomenon.

Because of the different nature of the monsoonal circulations in the Americas a new initiative called "Variability of the American Monsoon Systems" (VAMOS) has recently been established. One of the main tasks of this panel is the co-ordination of the variety of ongoing activities and the identification of gaps in this sector.

Although the short-term climate variations over Africa affect the chances of survival of many people in Africa (e.g. Sahel rainfall), relatively little research attention has been paid to the African Climate System during the last decades. Therefore CLIVAR will, through the African Climate Study Group in close co-operation with other activities like START and the IHDP, try to establish a strong research project focusing on the various climate variations over Africa and the adjacent oceans. This group has been set up for limited term until 1999 to develop the scientific basis and infrastructure for the CLIVAR core project G4.

CLIVAR will be built largely on the legacies of TOGA and WOCE. The TOGA Coupled Ocean Atmosphere Response Experiment (COARE), a field programme to study the Warm Pool region of the Western Pacific, was carried out towards the end of the official TOGA decade (1985-1994). Hence, there is still much to expect from the ongoing research on the large amount of data collected during this experiment. CLIVAR will continue to monitor and foster the research and help bring the results of this enormous undertaking to bear on the problems of the future.

Beyond these panels and working groups directly operated under the auspices of CLIVAR, a number of committees, especially those concerned with ocean observations are of particular relevance to CLIVAR. To ensure a close co-ordination with these groups, namely the TAO Implementation Panel (TIP), the Ocean Observations Panel for Climate (OOPC), the Data Buoy Co-operation Panel (DBCP), the Mean Sea Level Group of GLOSS and the Ships-of-Opportunity Programme Implementation Panel of IGOSS, close liaison occurs with appropriate sub-bodies of CLIVAR (i.e. mainly to the Upper Ocean Panel). The exchange of information is either done through cross representatives in the membership on these various panels or via the co-ordination of the CLIVAR IPO.

The area of atmospheric observations is dominated by the operational observations for the purposes of weather prediction. CLIVAR's strategy in this area is to work with the Atmospheric Observations Panel for Climate (AOPC) under GCOS in a similar fashion to that given above.

This organisational structure will evolve over the next few years as the scope and character of the programme become clearer. Now that the key phenomena and projects have been identified, the SSG will ensure that they receive adequate scientific oversight and that effective advice on implementation can be generated. The terms of reference and membership of the CLIVAR Panels and working groups can be found in the CLIVAR Handbook issued by the International CLIVAR Project Office (CLIVAR IPO, 1998).

### **3.2 RESOURCE PLANNING AND CO-ORDINATION**

The success of CLIVAR will depend on the consolidation of a wide range of scientific activities as well as co-ordination of world-wide observing and data management systems, many of which are part of other international research and operational programmes. Co-ordination at the scientific level is carried out by the Scientific Steering Group and its sub-bodies. Ensuring that adequate resources are put forward by individual nations to implement the necessary observing and data management systems and working to co-ordinate and optimise resource planning amongst the many different agencies and countries involved will require additional effort. The SSG will consider various possible mechanisms for international resource co-ordination. An intergovernmental commitments conference is planned for December 1998, and consideration will also be given to the formation of an intergovernmental board and ad hoc meetings of funding agency representatives.

The CLIVAR IPO will work closely with the existing bodies, including GCOS and GOOS, which manage specific aspects of the observing systems required to monitor the climate, on the extent to which CLIVAR requirements as outlined in the initial implementation plan are being met. The IPO will keep detailed track of gaps and report these to the SSG and to the appropriate governmental bodies.

### **3.3 REFERENCES**

International CLIVAR Project Office, 1998: The CLIVAR Handbook. Available from the International CLIVAR Project Office, Hamburg, Germany, 35pp.



## APPENDIX 4

### 4. IMPLEMENTING A CLIVAR DATA RESOURCE MANAGEMENT

#### 4.1 PREFACE

##### 4.1.1 Purpose

CLIVAR is in the early design stage of the development of its data management concept. This section, therefore, will describe the general data resource management strategy to be adopted under the CLIVAR banner. More detailed plans for an overall systematic data management approach will have to be developed which focus on the outputs of the programme as well as its inputs, and which incorporate sufficient flexibility to enable the rapid development and dissemination of the expected, diverse line of products of the CLIVAR Principal Research Areas.

This document will:

- outline a general data resource policy based on the experience of earlier and existing research programmes;
- summarise the general nature of CLIVAR data requirements.
- describe the general structure of an effective data resource model for CLIVAR.
- identify where CLIVAR data management needs to interact efficiently with other programmes
- outline a general data management strategy for CLIVAR

##### 4.1.2 “CLIVAR data”?

All data that are produced by any part of the CLIVAR programme will be labelled “CLIVAR data”. This encompasses all data that would not exist without a CLIVAR programme.

Beyond this definition there may be data that are not generated by CLIVAR but are of importance for the overall success of the programme. The CLIVAR data management has to ensure that all data relevant to CLIVAR are accessible to the CLIVAR community.

##### 4.1.3 “CLIVAR data” resources:

In a very broad sense, the following “CLIVAR data” resources can be identified:

- Model Output

The various modelling intercomparison activities which have already been proposed or initiated by the two CLIVAR numerical experimentation groups will result in a large number of valuable data sets. The intercomparison projects are of importance for the assessment of the capability of models to simulate the natural climate variability and anthropogenic climate change as well as examining predictability on all timescales. In addition to the output from the modelling intercomparison projects, results from the long integrations of climate models with



specified forcings and numerical experiments to explore anthropogenic climate change are of interest to and in some cases sponsored by CLIVAR, so that groups will be encouraged to archive output for further analysis by the community. Typically, this will happen only after the principal investigators have had an adequate chance to publish their findings and complete their analysis. Moreover, these kinds of model data need to be analysed in the light of the model characteristics and experimental assumptions, and so adequate metadata about the simulations need to be archived.

- Observational Data

*Sustained measurements*

CLIVAR has to deal with a wide spectrum of different observational data sets. Apart from data available from other existing programmes, such as the (quasi-) operational programmes like WWW, GCOS, DBCP, IGOSS, etc.) and other research efforts (WOCE, GEWEX, ACSYS, SPARC, etc.), there will be a variety of data sets generated by sustained observational activities under CLIVAR. Although CLIVAR will work towards a (near) real-time data access, a number of data sets will only be available in delayed mode. CLIVAR has to ensure that these data are archived and accessible to the scientific community in an acceptable timeframe.

*Historical and paleo data*

Due to the limitations of the observational record in space and time CLIVAR will heavily rely on the extension of the data record into the past as far as possible. Analysis of historical data as well as generation of data sets from proxy data (e.g. coral cores, lake sediments, ice cores, tree rings, etc.) are of particular importance to CLIVAR.

- Reanalysis

Additionally, the ongoing and planned reanalysis efforts will be important cornerstones of the data sets needed for CLIVAR. Their multiple usability for modelling, diagnostic and empirical studies serve as an universal tool for the investigation of natural climate variability and anthropogenic climate change.

## **4.2 EXISTING STRUCTURES**

CLIVAR will, wherever possible, build on the data management structure of existing programmes. In this way duplication (data processing and storage) should be avoided and financial costs should be minimised. In this section existing data management concepts related to CLIVAR will be reviewed.

There were major differences in the data management philosophies of TOGA and WOCE and these deserve special attention. To simplify the presentation, the descriptions of the joint functions of TOGA/WOCE Data Centres appear under the section on WOCE Data Management.

### **4.2.1 TOGA data management concept**

From the outset of TOGA, and embodied in its implementation plan (ITPO, 1992), planned to collect and distribute data in realtime whenever possible. Data which were not available shortly after the time of observation were lost for operational analyses and therefore would only appear in a comprehensively assimilated form through a 'reanalysis' effort, perhaps not until many years after the original observation was taken. About half-way through TOGA it was recognised that it would be necessary to carry out a reanalysis

of the TOGA period, although this was also advocated in a wider context than the need to incorporate “missing” data. The ready availability of much of the original data and the original operational analyses, however, were valuable stimulants to research and probably accelerated the transition from research into useful, if only experimental, seasonal to interannual predictions.

TOGA realtime data (up to 30 days from the time of observation) are provided by the operational observing systems of WWW and IGOSS, and are available internationally as part of the existing data flow from the Global Telecommunication System (GTS).

TOGA delayed-mode data are acquired by centres up to several years after the time of observation. These may be data that have undergone quality control by specific investigators and are submitted to the relevant centre to replace corresponding real-time data. TOGA investigators are required to make such delayed-mode data sets available to the appropriate centre with the absolute minimum of delay. The Data Management Plan of TOGA mandated several different data centres. The main TOGA Data Centres were:

- ECMWF/WCRP Level III-A Atmospheric Data Archive, Reading, UK, for global analyses  
**<http://www.ecmwf.int/data/toga.html>**
- TOGA Global Sea-Surface Temperature Data Centre, NMC/CAC (now NCEP/CPC), Washington DC, USA  
**<http://nic.fb4.noaa.gov/>**
- TOGA Tropical Ocean Sub-Surface Data Centre at IFREMER, Brest, France  
**<http://www.ifremer.fr/sismer/program/gsdh/homepage.htm>**
- TOGA Tropical Sea-Level Data Centre, Hawaii, USA  
**<http://uhslc.soest.hawaii.edu/>**
- TOGA Marine Climatology Data Centre (UK Met. Office, Bracknell, UK)  
**[http://www.metoffice.gov.uk/sec5/CR\\_div/index\\_climate.html](http://www.metoffice.gov.uk/sec5/CR_div/index_climate.html)** (not specific TOGA, provide global SST analyses)
- TOGA Tropical Upper-Air Data Assembly Centre (IMD, New-Dehli, India)

For the most part, it is anticipated that the TOGA functions of these centres will continue under existing or new operational responsibilities. The TOGA WOCE Upper Ocean Thermal Data Centre at IFREMER/SISMER intends to contribute to CLIVAR by continuing its activity for assembling, controlling, archiving and disseminating the temperature profiles collected in the Atlantic Ocean and Mediterranean sea. Moreover, facilities are proposed to offer a supplementary backup site for the whole ocean data set previously validated in other regional scientific centres. This proposal represents a contribution to the forthcoming national scientific programmes in the Atlantic Ocean.

In addition to the named TOGA Data Centres above, there are other data centres which were considered important for TOGA, e.g.:

- Pacific Marine Environmental Laboratory (PMEL), Seattle - TAO array data management  
**<http://www.pmel.noaa.gov/toga-tao/home.html>**

- Drifter Data Acquisition Centre, Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami - drifter data management

<http://www.aoml.noaa.gov/phod/dac/gdc.html>

- Marine Environmental Data Services (MEDS), Ottawa - drifter data management

[http://www.meds.dfo.ca/Meds/e\\_inv.html](http://www.meds.dfo.ca/Meds/e_inv.html)

The Jet Propulsion Laboratory Distributed Active Archive Center (<http://podaac-www.jpl.nasa.gov/>) has produced a series of seven CD-ROMs of the first five years of the TOGA experiment (1985-90) containing *in situ* and numerical model data.

In using satellite measurements, TOGA and WOCE (see next section) were primarily interested in achieving global synoptic observations of ocean surface topography, sea surface temperature (SST), and surface winds. The following satellite missions were of highest importance for TOGA/WOCE investigators:

- GEOSAT (1985-89) ([http://podaac.jpl.nasa.gov/Geosat\\_Products.html](http://podaac.jpl.nasa.gov/Geosat_Products.html))

- TOPEX / Poseidon (since 1992), (<http://topex-www.jpl.nasa.gov/>, or

[http://podaac.jpl.nasa.gov/TopexPoseidon\\_Products.html](http://podaac.jpl.nasa.gov/TopexPoseidon_Products.html))

- ERS1 (since 1991-1996), and

- ERS2 (since 1995) (<http://www.esrin.esa.it/>, or

[http://www.esa.int/esa/progs/eo\\_over.html](http://www.esa.int/esa/progs/eo_over.html))

Note that, these data were not explicitly included in the TOGA data management, but nevertheless important for the overall success of the programme.

**TOGA COARE** data management (TCIPO, 1994) was a special case and while it was in operation, was co-ordinated by the International TOGA COARE Project Office in Boulder. With the cessation of the operations of that office, the bulk of remaining data management responsibilities carried out by that office for COARE have been transferred to the WOCE Data Information Unit at the University of Delaware. The World Data Center A for Meteorology at the National Climatic Data Center in Asheville (USA) (<http://www.ncdc.noaa.gov/coare/>) serves as the final archive for the TOGA COARE data.

#### 4.2.2 WOCE data management concept

As WOCE exceeds all previous oceanographic experiments in the scope of its goals and of the concerted fieldwork required to achieve them, it needed a data management system which explicitly addressed the unified nature of the programme and its products.

The goals of the WOCE data management system are:

- The creation of data sets for the critical assessment of theories and models.
- The creation of data sets to be used as boundary conditions for ocean models.

- The assembly of data sets to provide a comprehensive description of the global ocean circulation.
- The assembly of useful subsets of existing data for WOCE purposes.
- The creation of a comprehensive catalogue of these data sets.
- The dissemination of the data sets to the research community

WOCE data can be divided into two categories. The first are those data, mostly shared with TOGA, that are transmitted from observing location to processing centres in real-time or through quasi-operational mechanisms. The second category covers all data that require substantial postcruise/recovery processing to attain the data quality standards set by WOCE. In this category fall all hydrographic data, current meter observations, float data, and reprocessed, quality-controlled real-time data.

To achieve these requirements a data management system was established with a core of Data Assembly and Special Analysis Centres (DAC's and SAC's) distributed around the world. The data were further classified as coming from Operational Systems, which provide data important to WOCE but not wholly part of the programme (e.g. IODE, TOGA, VOS), or from research activities which include all data collected specifically for WOCE projects.

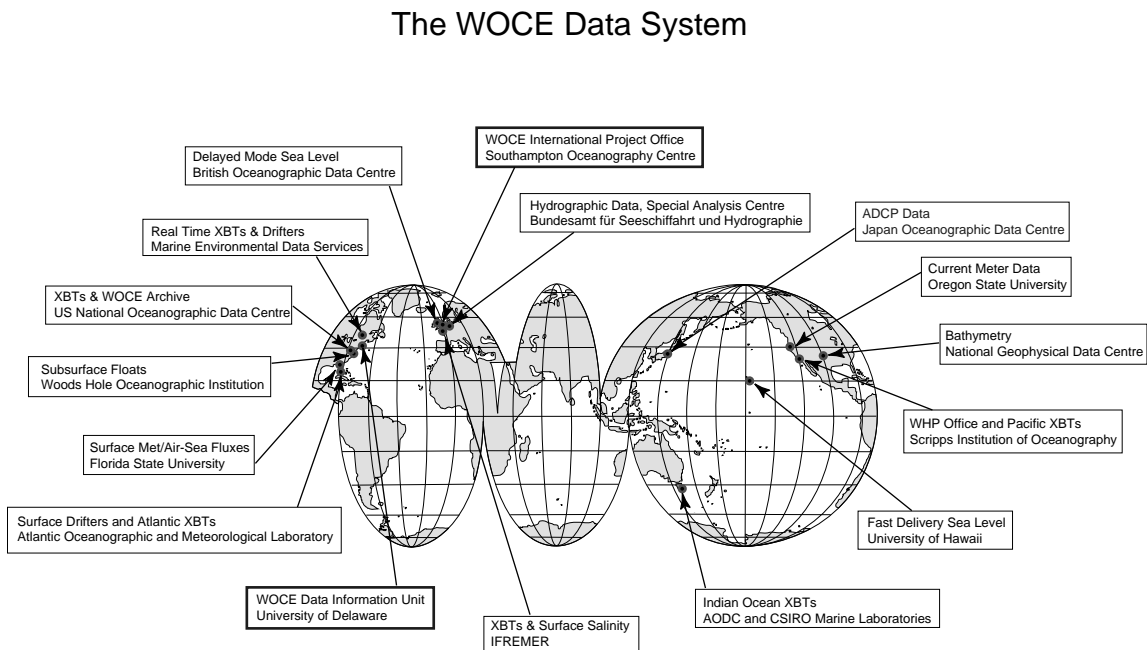


Fig. A.4.1: The WOCE Data System

All available WOCE and WOCE-related data are required to be submitted as soon as possible (according to the WOCE data sharing policy) (WCRP, 1988a, b) to the Data Assembly Centres. These DAC's assemble and quality control platform-specific data sets and together with the SACs generate large-scale data sets. At the present time there are 15 DAC's operating (Fig. A.4.1):

- Current meter data (Oregon State University, USA)

<http://kepler.oce.orst.edu/>

- Subsurface float data (Woods Hole Oceanographic Institution, USA)

**<http://wfdac.whoi.edu/>**

- Hydrographic data (Scripps Institution of Oceanography, USA)

**<http://whpo.ucsd.edu/>**

- Surface Drifter data (AOML (Quality Control), MEDS (Distribution/Archive))

**<http://www.aoml.noaa.gov/phod/dac/gdc.html>**

**[http://www.meds.dfo.ca/Meds/e\\_inv.html](http://www.meds.dfo.ca/Meds/e_inv.html)**

The Atlantic Oceanographic and Meteorological Laboratory (AOML) acquires drifter data directly from Service ARGOS for uniform processing, quality control and archiving. At 6 month intervals AOML transfers quality controlled data to MEDS for distribution and archival.

- Upper ocean thermal data (Global DAC: IFREMER, France and three regional DAC's: Pacific: Scripps IO, USA; Indian: CSIRO, Australia; Atlantic: AOML, USA)

**<http://www.ifremer.fr/sismer/program/gsdac/homepage.htm>**

The structure of the data assembly and archiving of WOCE (& perforce TOGA) upper ocean thermal data is complex. The system was designed to handle GTS and delayed mode data submitted through the existing systems. The regional centres concentrate on yearly quality control of the complete data set which includes delayed mode and realtime data. The Global Centre archives the data in a continuously updated data base which replaces realtime data with the equivalent delayed modes profile. Any realtime data not replaced are retained in the database.

Presently the UOT data centre at IFREMER holds about 460,000 profiles of XBT data (real-time and delayed mode) from 1985 to present. The average time lag between the receiving of real-time and delayed mode data is about three years. About 25% of the real-time profiles are never replaced by delayed mode data. Within the French scientific community the transition of this data centre into a CLIVAR subsurface data centre including the archiving of profiling float data was recommended.

- Sea level data (real-time: Univ. Hawaii, USA; delayed mode: British Oceanographic Data Centre (BODC), UK)

**<http://uhslc.soest.hawaii.edu/>**

**<http://www.nbi.ac.uk/bodc/woce/dmsldac.html>**

As the Hawaii centre also acts under the TOGA umbrella, sea level data are received in both real-time and delayed mode. The real-time sea level data from gauges with data distributed by satellite or other near real-time systems is done by the University of Hawaii (currently 101 stations) in a 1 to 3 months time frame.

The BODC assembles and services requests for fully quality-controlled sea level data FROM all gauges in the network within 18 to 24 months after data collection. Data assembly commenced in early 1991 and at present BODC is collecting data from approximately 130 tide gauge sites. More extended data sets are available through the co-located Permanent Service

for Mean Sea Level (PSMSL).

The BODC assembles and services requests for sea level data to full extent of quality control possible covering all gauges in the network within 18 to 24 months after data collection. Data assembly commenced in early 1991 and at present BODC is collecting data from approximately 130 tide gauge sites.

- Surface salinity data (ORSTOM, France)

**[http://www.ifremer.fr/orstom/sss/sss\\_dac/sss\\_dac.html](http://www.ifremer.fr/orstom/sss/sss_dac/sss_dac.html)**

The salinity data collected on WHP (WOCE Hydrographic Programme) cruises and Voluntary Observing Ships is archived at the global centre at ORSTOM, Brest, France. Only a rudimentary of quality control is performed.

- Surface meteorological data (Florida State University, USA)

**<http://www.coaps.fsu.edu/>**

Collects, checks, archives, and distributes surface meteorological data from vessels of the VOS fleet as well as from WOCE sponsored experiments.

- Acoustic doppler current profiler data (Japanese Oceanographic Data Centre, Japan)

**<http://www.jodc.jhd.go.jp/inf/data/current/shipboard-adcp.html>**

This DAC is responsible for the assembly and quality control of WOCE ADCP data (as well as for other non-WOCE data from Japanese vessels) in collaboration with the ADCP Archive Centre in Hawaii.

**<http://ilikai.soest.hawaii.edu/sadcp/>**

- Bathymetry data (NOAA/NGDC, USA)

**<http://www.ngdc.noaa.gov/mgg/mggd.html>**

The Special Analysis Centres perform data analysis and synthesis functions, including the generation of derived data sets and products. Special Analysis Centres (SAC) exist for:

- Hydrographic Data (BSH, Germany)

**<http://www.dkrz.de/~u241046/>**

The SAC has three goals:

- to produce data products exhibiting the oceanic mean state
- to investigate the short-term variability in the ocean circulation
- to provide a consistent oceanic data set to verify ocean models.

The SAC works in co-operation with the Max-Planck-Institut für Meteorologie, the Institut für Meereskunde, and the DKRZ.

- Air-Sea Fluxes (Florida State University, Florida)

**<http://www.coaps.fsu.edu/>**

The SAC for surface fluxes produces and analyses a set of regularly gridded products of the ocean surface forcing fields which would be suitable for use in numerical models as well as for intensive diagnostic studies. An historical data set (1961-89) for the Indian Ocean is available.

- Satellite Data

At the very heart of WOCE are the global measurements made by satellites. The primary interest for WOCE lies with satellite altimetry and its associated geophysical variables of sea level variability and wave height.

There have been 3 altimeters operating during the period of WOCE observations, the French/USA satellite TOPEX/Poseidon (since August 1992), and the European Space Agency satellites ERS-1 (from late 1991 until end of June 1996) and ERS-2 (since April 1995). In addition the US GEOSAT mission operated just prior to the WOCE field programme.

Also of relevance are wind fields from scatterometers (the NASA scatterometer NSCAT, and ERS-1 and ERS-2), sea surface temperature (the USA AVHRR or Advance Very High Resolution Radiometer) and water vapour content (TOPEX/Poseidon and the US Special Sensor Microwave Imager or SSMI). Most of these measurements will be required by CLIVAR as well.

The Satellite data are managed by a variety of agencies and data centres, so there are no specific WOCE satellite DACs. However data and products are available to users through the Internet. TOPEX/Poseidon data are in the public domain and not restricted, and while ERS-1 and ERS-2 data are available only to specified investigators, products from them are not restricted and are distributed on CD-ROM or exabyte tape. The Internet sites listed below offer a variety of high-level products including corrected and quality-controlled data and anomaly fields. They also contain high-quality images and discussion of the instrumentation and products available.

Introduction:

**<http://www.cms.udel.edu/woce/dacs.html>**

Altimetric sea level and wave height; scatterometer winds; AVHRR 'Pathfinder' sea surface temperature.

**<http://podaac-www.jpl.nasa.gov/>**

Altimetry, sea level, wave height

**<http://alti.cnes.fr>**

Altimetry, sea level, wave height, scatterometry, sea surface temperature

**<http://www.ifremer.fr/cersat/english/>**

ERS-1 and ERS-2 products and programme description

<http://www.esrin.esa.it/>

The WOCE Data Information Unit (DIU) at the University of Delaware, USA (<http://www.cms.udel.edu/woce/>) provides a source of information on the status of WOCE by tracking WOCE data collection, processing, and archiving activities. Most of the WOCE data products and/or a description of the data and the means of accessing them may be obtained on the World Wide Web. In addition, the DIU and the WOCE IPO have maintained and distributed a WOCE Data Handbook (WOCE, 1995) and published a “WOCE Data Guide” (WOCE, 1997; <http://www.soc.soton.ac.uk/OTHERS/woceipo/ipo.html>) summarizing the current status of the WOCE data.

So far, the WOCE data are mainly instrument-based, quality controlled Level IIB-data (i.e. all drifter data is sampled at one DAC, all mooring data at another DAC). During the AIMS phase WOCE will produce related data products (i.e. Level III-data) of WOCE and historical measurements (WOCE, 1998).

The WOCE Data system acts to provide timely access for all WOCE participants to the data identified according to the data sharing policy for WOCE. The World Data Centres (see 4.2.4) serve as a final permanent archive for WCRP data.

### 4.2.3 The GCOS programme

The Global Climate Observing System (GCOS) (GCOS, 1995a) is an international effort directed towards providing a systematic and comprehensive global set of observations

The scientific strategy of GCOS is based on the concept that analyses and models of the climate require an adequate observational base to be effective in addressing seasonal-to-interannual and decadal-to-centennial climate time scales. The quantity, quality, and continuity of observations required demand that a systematic global programme be implemented. The overall goal of GCOS is encapsulated in three objectives:

1. Design an effective operational climate observing system.
2. Establish, co-ordinate and manage the Initial Operational System (IOS) by integrating and enhancing existing components.
3. Develop new components to provide a comprehensive and responsive system to meet future needs.

The underlying strategy of GCOS information management (GCOS, 1995b) is to make maximum use of existing national and international facilities, i.e. the information system will be developed, implemented and operated by existing national and international organisations and programmes.

The first priority in the GCOS strategy is to define and develop an Initial Operational System (IOS) for observations and data.

The IOS will include a comprehensive data system which specifies procedures for collection, quality control, comparison of observations from different sources, dissemination, and utilisation of all data relevant to GCOS. This plan outlines the steps necessary to develop the IOS data system. Although, initial efforts will concentrate on the IOS, they must also contribute to realisation of the long-term goal for the GCOS data system: an international system of distributed data bases which provide for effective end-to-end management of all data and products pertinent to GCOS.

The GCOS data and information system should be developed to be a common system that accommodates data and products from the climate modules of the Global Ocean Observing System (GOOS), the Glo-



bal Terrestrial Observing System (GTOS), the World Hydrological Cycle Observing System (WHYCOS) and the World Weather Watch (WWW).

The primary emphasis of GCOS will be on co-ordination, integration and stimulation of these activities though definition of guidelines and policies for collecting, processing, and disseminating data pertinent to GCOS.

As already previously pointed out, CLIVAR expects that within GCOS/GOOS a number of climate observations will be carried out that will serve the needs for a number of scientific issues within CLIVAR. CLIVAR will, wherever possible, rely on these observations to achieve an optimal use of the resources available for observational climate.

#### 4.2.4 World Data Center system

The CSAGI, the Special Committee of the International Council of Scientific Unions (ICSU) for the International Geophysical Year of 1957-1958 established the World Data Center system to serve the IGY, and developed data management plans for each IGY scientific discipline. Because of its success, the WDC system was made permanent and used for post-IGY data.

Over the years the number of WDCs has changed. A comprehensive set of WDC-D was established in China in 1988. WDC-A in the U.S.A. has expanded and WDC-B in Russia is now operated by three different organisations. Some of the C, C1 and C2 centres in Europe and Asia have moved or have closed, but new centres have opened. All centres now have computer facilities and most use electronic networks to meet requests, exchange catalogue information and transfer data. Today the WDC system is healthy and viable. Most centres are maintaining their funding, though not a struggle. Data acquisition, storage and distribution are expensive, WDCs cost money, but they are cost-effective in transferring data to users, and their operational costs represent a tiny fraction of worldwide scientific activity.

Some data centres already serve as a final archive for research activities of the World Climate Research Programme (e.g. TOGA, WOCE).

The following World Data Center provide information relevant to CLIVAR:

World Data Center Homepage (<http://www.ngdc.noaa.gov/wdc/wdcmain.html>)

World Data Center A (USA):

(<http://www.ngdc.noaa.gov/wdc/wdca/wdca.html>)

- WDC-A Atmospheric Trace Gases, Oak Ridge TN
- WDC-A Glaciology, Boulder CO
- WDC-A Human Interactions in the Environment, Saginaw MI
- WDC-A Meteorology, Asheville NC
- WDC-A Oceanography, Silver Spring MD
- WDC-A Paleoclimatology, Boulder CO
- WDC-A Remotely Sensed Land Data, Sioux Falls SD

World Data Center B (Russia):

(<http://www.ngdc.noaa.gov/wdc/wdcb/wdcb.html>)

- WDC-B Meteorology, Obninsk Russia
- WDC-B Oceanography, Obninsk Russia

World Data Center C (Europe):

(<http://www.ngdc.noaa.gov/wdc/wdcc1/wdcc1.html>)

- WDC-C Glaciology, Cambridge England
- WDC-C Soils, Wageningen Netherlands

World Data Center D (China):

(<http://www.ngdc.noaa.gov/wdc/wdcd/wdcd.html>)

- WDC-D Glaciology and Geocryology, Lanzhou China
- WDC-D Meteorology, Beijing China
- WDC-D Oceanography, Tianjin China
- WDC-D Space Sciences, Beijing China

Note that there is at present time no central archive for meteorological or oceanographic satellite data. The data are being held and distributed (with different access restrictions) mostly by the space agencies (NASA, ESA, etc.). Satellite data products are produced and distributed by a number of research facilities (e.g. see Section 4.2.1, 4.2.2). GCOS puts some efforts through its Global Observing System Space Panel (GCOS, 1997) into the international co-ordination of climate related space-based observations.

### 4.3 GENERAL DATA MANAGEMENT REQUIREMENTS

The SSG has adopted the following general strategy with respect to data management:

- promote continuation of data management activities implemented under TOGA, and the maintenance of those components of the WOCE data management systems that will, if continued, support the scientific objectives of CLIVAR.
- develop a plan that will enable these activities to be reviewed in a timely manner and recommendations for enhancements to be made; these processes to be implemented through standing committees, workshops, assigning rapporteurs and co-operative activities with other WCRP and climate-related programmes.
- establish mechanisms whereby the outcome of these reviews and proposals for new activities can be presented for consideration by national and international scientific programmes.

The primary role of data management activities in CLIVAR should be high-level co-ordination to ensure that all activities feed into a global perspective. Therefore the overall data management policy for CLIVAR should provide both a global integrated data management approach as well as specific data management concepts appropriate for special focused research projects and field programmes under CLIVAR.

The access to CLIVAR data should in general be open and free. Any data generated within the CLIVAR programme should be made available as soon as possible. However, individual proprietary rights have to be respected.

One aim of the CLIVAR data management system is to provide high-quality data for synthesis and integration. This system should be built for the production of deliverables for the research community. This goal can be achieved by an integrative approach resulting in the development of a CLIVAR data resource.

A schematic diagram of the data resource management within the CLIVAR is displayed in Fig. A.4.2.

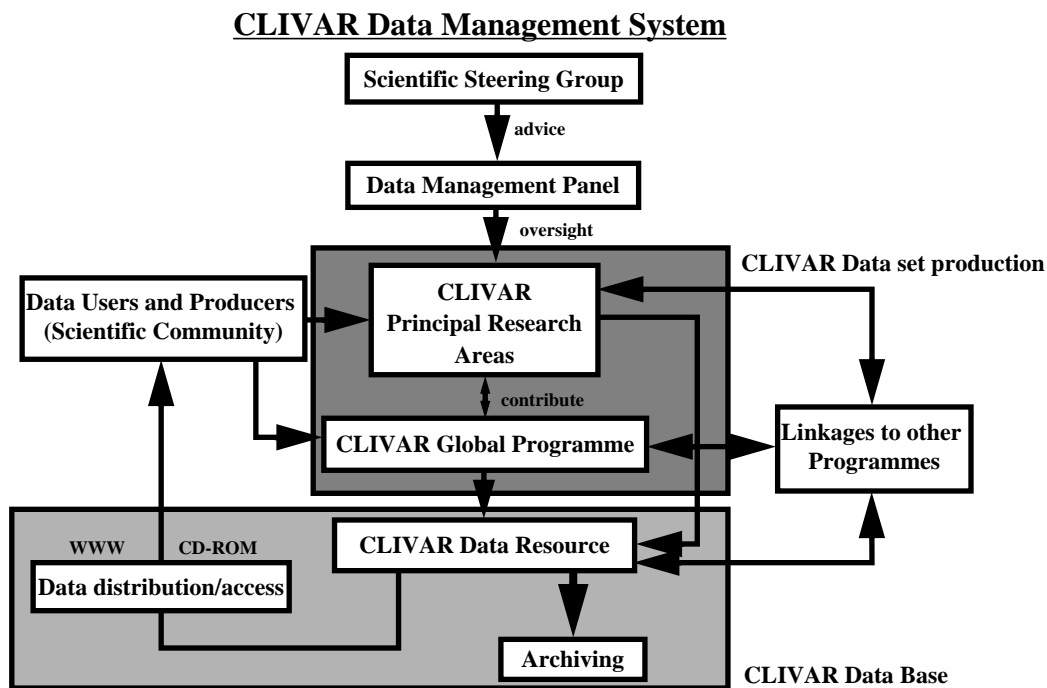


Fig. A.4.2: A schematic diagram of the data resource management within CLIVAR

The CLIVAR Scientific Steering Group gives advice to an oversight data management committee which is yet to be established. It should involve jointly scientists and data managers and concern itself with defining data products, data sharing, and data engineering. Additionally, the data management committee works on the transition from the former TOGA and WOCE data facilities to CLIVAR to agree on products of common interests that these facilities can produce.

The CLIVAR data set production will in general take place within each of the CLIVAR Principal Research Areas but with strong interaction to the global sustained observational programme of CLIVAR (“CLIVAR Global Programme” in Fig. A.4.2) which supports the specific needs of the individual research projects.

All the data produced by these main components combine to form the single CLIVAR data resource (i.e. merging of data into deliverables for the research community). This single data resource is the key element of the CLIVAR data management system.

To provide the CLIVAR data resource a CLIVAR information centre, clearinghouse, or product support centre has to be established. The activities of the centre could range from a small-scale effort (e.g. maintenance of a Web page with appropriate pointers) to a larger one which produces special integrated products with consistent quality control, packaging and distribution of data sets via CD-ROM, etc. Apart from this integrating facility CLIVAR has to consider the infrastructure for data assembly and production which currently is in place following the legacy of WOCE and TOGA. Apart from this integrating facility CLIVAR has to consider the infrastructure for data assembly and production which currently is in place following the legacy of WOCE and TOGA.

During the current implementation process of the programme the appropriate CLIVAR working groups and panels will review the current system resp. develop recommendation for a modified / new infrastructure needed to fulfil the CLIVAR needs. In particular, the proposed Data Management Panel has, apart from the very general statements of a CLIVAR data management strategy and issues of proposed infrastructure, to address a number of more specific items related to the different data types. More detailed descriptions for the various data types will be provided in a separate document serving as an implementation document for the CLIVAR resource management.

#### 4.4 REFERENCES

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WOCE International Project Office, 1998: WOCE AIMS Implementation Plan. Southampton, in press.

*IV. Appendix*

## APPENDIX 5

### 5. LINKAGES

#### 5.1 LINKAGES WITHIN THE WORLD CLIMATE RESEARCH PROGRAMME (WCRP)

##### 5.1.1 Global Energy and Water Cycle Experiment (GEWEX)

**WWW address: <http://www.cais.com/gewex/gewex.html>**

The Global Energy and Water Cycle Experiment (GEWEX) is a project initiated by the World Climate Research Programme (WCRP) to observe, understand and model the hydrological cycle and energy fluxes in the atmosphere and across the interface with the underlying surface. So complementary are GEWEX and CLIVAR that it will be essential for CLIVAR to develop close working relationships with all of the component projects of GEWEX, which are “process-related” projects, each of which also has the development of global data sets as a key ingredient.

GEWEX encompasses the following key activities:

##### Cloud studies

Cloud cover, its vertical distribution and optical properties, affects the total amount of solar radiation received at the Earth's surface, and thus, plays a key role in the Earth's water and energy cycles. An improved knowledge about cloud properties and subscale processes and their appropriate parameterisations in models are essential for the improvement of atmospheric resp. coupled models and therefore CLIVAR will heavily rely on the success of the following GEWEX projects:

- a. International Satellite Cloud Climatology Project (ISCCP)

**<http://www.cais.com/gewex/isccp.html>**

- b. GEWEX Cloud Systems Study Project (GCSS)

**<http://www.cais.com/gewex/gcss.html>**

##### Radiation

Another major problem in respect with atmospheric and coupled modelling are radiation schemes. In improve our knowledge on radiative processes GEWEX has set up the following projects:

- a. Surface Radiation Budget

**<http://www.cais.com/gewex/srb.html>**

- b. Baseline Surface Radiation Network

**<http://www.cais.com/gewex/bsrn.html>**

- c. Earth Radiation Budget Experiment (ERBE)

**<http://asd-www.larc.nasa.gov/erbe/ASDerbe.html>**

### Water Vapour

Water vapour, the most significant greenhouse gas, plays a fundamental role in the energy and water cycle processes that determine weather and climate. During the last year, it has been recognised that an improved knowledge about water vapour is necessary for the improvement of atmospheric models. The accurate global measurement, modelling, and long-term prediction of water vapour is the primary goal of the GEWEX Water Vapour Project (GVaP).

**<http://www.cais.com/gewex/gvap.html>**

### Precipitation

Accurate modelling and prediction of global monthly precipitation have been extremely difficult because precise climatological data on the worldwide distribution of precipitation do not exist. In two projects GEWEX tries to improve our knowledge about precipitation and the global runoff for the development and verification of atmospheric and hydrologic models.

- a. Global Precipitation Climatology Project (GPCP)

**<http://www.cais.com/gewex/gpcp.html>**

- b. Runoff - Global Runoff Data Centre (GRDC)

**<http://www.cais.com/gewex/grdc.html>**

### Land Surface Characteristics

International Satellite Land Surface Climatology Project (ISLSCP)

Climate models as used in CLIVAR require worldwide information about terrestrial changes that are responsible for interactions between the atmosphere and land-surfaces. It is the goal of all activities within ISLSCP to assess these changes in terms of the physical and biological quantities, which can be related to the exchange of energy and water between the surface and atmosphere.

**<http://www.cais.com/gewex/islscp.html>**

### GEWEX Continental Scale Experiments

GEWEX is also sponsoring several continental scale projects for which more comprehensive data sets at finer spatial resolution are becoming available, e.g. for the Mississippi and MacKenzie River Basins in North America (GCIP & MAGS), the Baltic Sea region in Northern Europe (BALTEX), the Amazonian Basin (LBA) and several areas in the Monsoon regions of Asia (GAME). It is expected that some of the CLIVAR core projects closely co-operate with these continental scale projects (e.g. G2 (Asian-Australian Monsoon) with GAME, G3 (American Monsoon) with GCIP).

**GCIP: <http://www.cais.com/gewex/gcip.html>**

**MAGS: <http://www.cais.com/gewex/mags.html>**

**BALTEX:** <http://www.cais.com/gewex/baltex.html>

**LBA:** <http://www.cais.com/gewex/lambada.html>

**GAME:** <http://www.cais.com/gewex/game.html>

### 5.1.2 World Ocean Circulation Experiment (WOCE)

WOCE measurements made between 1990 and 1997 will provide a global, high quality data set of the distribution of physical and chemical properties in the major open basins of the world's oceans. These measurements have doubled the number of available deep sea ocean stations and, by virtue of their high quality, provide a baseline against which future changes in oceanic properties may be assessed. They have already been compared with previous high-quality sections in order to quantify changes in water mass properties over the past few decades. They therefore present another important part of the base upon which CLIVAR can build. While the assessment of variability (the main focus of CLIVAR) was given only limited emphasis in setting the original WOCE goals, the results of WOCE research will address variability issues. In particular a number of time-series stations and repeated sections have been maintained by WOCE and these have been valuable in documenting seasonal and interannual changes in water column properties. Continuity of time-series is a strong motivation for maintaining this programme of measurements when WOCE ends. At longer (decadal) time scales the comprehensive WOCE measurements of transient tracers provide evidence of the pathways and rates of the thermohaline circulation. Basin-wide and global circulation schemes will be deduced from the hydrographic measurements through their combination with satellite altimetry, *in situ* current measurements from moored arrays, floats and drifters and from the assimilation of all these data into eddy-resolving models. From these circulation schemes and property distributions, the basin-scale fluxes of properties within the ocean will be estimated. They will also be estimated from individual trans-ocean hydrographic sections and their associated moored arrays. WOCE had only limited success in supporting seasonal repeats of sections that allow meridional flux variations to be determined. Opportunities for remedying this are embodied in CLIVAR's thermohaline studies (D3 and D5).

WOCE AIMS is the Analysis, Interpretation, Modelling and Synthesis phase of the World Ocean Circulation Experiment. WOCE AIMS follows the field phase of the programme (1990-97) and will last to the year 2002. The objective of the AIMS phase is to meet the goals of WOCE, which in summary are to improve our understanding and modelling of the global ocean circulation, the role of the ocean in the Earth's climate and to increase skill in climate prediction.

A major scientific thrust for the remaining years of WOCE is to assess which ocean processes are important for climate prediction thus for CLIVAR. To have predictive value, models must accurately describe the present ocean state. In particular, which processes below the surface layer must be observed and modelled and at what minimum resolution in space/time to increase predictive skill?

Three overlapping activities are recognised in WOCE AIMS:

- **analysis:** which includes the synthesis of data with simple ocean models,
- **model development:** which includes the comparison of models and data, and
- **assimilation:** which combines data with models directly.

These activities all presuppose the existence of a comprehensive WOCE data set, which results from the assembly of quality-controlled data from disparate sources, its documentation, the ready and widespread access of this data set and ultimately its secure archival.

**WOCE:** <http://www.soc.soton.ac.uk/OTHERS/woceipo/ipo.html>



### 5.1.3 Arctic Climate System Study (ACSYS)

Sea ice has strong influence on the sensitivity of climate in high latitudes, as well as on the formation of deep water. ACSYS will improve the understanding of sea ice processes and their interaction with atmosphere, ocean and global climate, via modelling and process studies, the establishment of an Arctic basin-wide sea ice climatological database and ice thickness monitoring. ACSYS will also compile Arctic hydrological databases on precipitation (Arctic Precipitation Data Archive) and runoff (Arctic Run-off Database). CLIVAR will take advantage of the results of the ACSYS programme, esp. of the modelling efforts and the two buoy programmes IABP (International Arctic Buoy Programme) and IPAB (International Programme for Antarctic Buoys) under the wings of ACSYS and DBCP.

**ACSYS:** <http://www.npolar.no:80/acsys/>

### 5.1.4 Stratospheric Processes and their Role in Climate (SPARC)

Atmospheric chemistry may lead to significant changes in concentrations of radiatively active gases, including stratospheric ozone. In particular, it is uncertain whether or not variations in solar output lead to significant changes in stratospheric ozone, perhaps in a way that amplifies the climate response. Through its modelling activity, SPARC will attempt to resolve several critical issues important for CLIVAR that relate to stratospheric/tropospheric interactions, e.g. there is strong evidence that in order to understand the North Atlantic Oscillation, the stratospheric forcing of tropospheric circulation must be well modelled. The Quasi-Biennial Oscillation in the mean zonal (east-west) direction of lower stratospheric equatorial zonal winds also has been known for over 35 years, and the suggestion of its forcing by waves of tropospheric origin remains accepted to this time. Many problems remain, however, in a fuller understanding of the processes in the QBO. It is unclear to what extent the stratospheric QBO is coupled to tropospheric and sea surface temperature variations. The manner in which the tropical stratospheric QBO couples to higher latitudes in the stratosphere is not completely clear either, and no theoretical framework exists to explain the correlation between the frequency of Atlantic hurricanes and the phase of the QBO.

**SPARC:** <http://www.aero.jussieu.fr/~sparc/>

## 5.2. THE INTERNATIONAL GEOSPHERE BIOSPHERE PROGRAMME (IGBP)

The International Geosphere-Biosphere Programme (IGBP) is an interdisciplinary scientific activity established and sponsored by the International Council of Scientific Unions (ICSU). The goal of the IGBP is to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions. As the computer-based models of the climate-earth system become more comprehensive and inevitably more complex, it is becoming commensurably important for the scientific disciplines associated with the many components of the system to work together to ensure realistic couplings of those systems within the models. The IGBP is comprised of eight broadly discipline-oriented projects covering such topics as atmospheric science, terrestrial ecology, oceanography, hydrology, and links between the natural and the social sciences that are critical to CLIVAR's success in ensuring that its global coupled climate models will provide useful predictions of climate variability on seasonal to interannual time scales and accurate simulations of the climate system under a wide range of forcing scenarios. Three framework activities on data, modelling, and regional research, facilitate incorporating scientific results into a holistic picture IGBP Programme Elements.

**IGBP:** <http://www.igbp.kva.se/>

IGBP research currently focuses on six key questions that are addressed by eight Core Projects:

1. *How is the chemistry of the global atmosphere regulated and what is the role of biological processes in producing and consuming trace gases?*

IGBP core project: International Global Atmospheric Chemistry Project (IGAC) jointly with the International Commission on Atmospheric Chemistry and Global Pollution (ICACGP)

2. *How will global changes affect terrestrial ecosystems?*

IGBP core projects:

a) Global Change and Terrestrial Ecosystems (GCTE)

b) Land-Use and Land-Cover Change (LUCC) jointly with the International Human Dimensions Programme (IHDP) on Global Environmental Change

3. *How does vegetation interact with physical processes of the hydrological cycle?*

IGBP core project: Biospheric Aspects of the Hydrological Cycle (BAHC)

4. *How will changes in land-use, sea level and climate alter coastal ecosystems, and what are the wider consequences?*

IGBP core project: Land-Ocean Interactions in the Coastal Zone (LOICZ)

5. *How do ocean biogeochemical processes influence and respond to climate change?*

IGBP core projects:

a) Joint Global Ocean Flux Study (JGOFS) jointly with the ICSU Scientific Committee on Oceanic Research (SCOR)

b) Global Ocean Ecosystem Dynamics (GLOBEC) project, in collaboration with SCOR and the Intergovernmental Oceanographic Commission (IOC), with the International Council for the Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES) as regional co-sponsor.

6. *What significant climate and environmental changes have occurred in the past and what were their causes?*

IGBP core project: Past Global Changes (PAGES)

**<http://www.ngdc.noaa.gov/paleo/pages.html>**

The integration of IGBP Core Projects is assisted by three cross-cutting Framework Activities:

1. IGBP Data and Information System (IGBP-DIS)
2. Global Analysis, Interpretation and Modelling (GAIM)
3. Global Change System for Analysis, Research and Training (START), addressing regional research initiatives and needs, jointly with the IHDP and WCRP.

CLIVAR's coupled modelling programme and IGBP's core project on Global Analysis and Interpretation Modelling (GAIM) will interface across a widening range of topics as the pace quickens to develop fully integrated climate-earth system models. Early topics for collaboration include

- Carbon cycle model intercomparisons
- Terrestrial/Land Modelling (together with GEWEX)
- Predictions or forward calculations of CO<sub>2</sub>, looking at the problems of model initialisation and spin-up, and the ties to how carbon is cycled through processes in the oceans.

The development of a comprehensive paleoclimatic record at an annual resolution, or better, for a large part of the globe provides one of the centrepieces of co-operation between CLIVAR and the IGBP core programme PAGES (Past Global Changes).

Specifically, the collaboration involves the following three actions:

1. A detailed study of the climatic variability of the last 400 years (globally) and the last 1000 years (where possible). The goal here is to provide the first comprehensive understanding of natural (non-anthropogenically-forced) seasonal to interdecadal variability, and to put the last 100 years in the context of the last 1000. Where possible, the emphasis will be on deriving and using global fields of multiple climatic parameters (e.g. temperature, precipitation, sea-ice), and on the combined use of reconstructed time-series of both climate observations and climatic forcing (e.g. SST, volcanic activity - optical depth, solar radiation, trace-gases, and aerosols).
2. A comprehensive study of climate variability given climatic states and forcing that are significantly different from today. The primary objective acknowledges that fact that global climatic forcing is changing dramatically, and that this means that future climatic variability could be distinctly different from any of the last 150 years. The paleoclimatic record suggests that each of the above-mentioned key phenomena may have been significantly different during the mid-Holocene and Last Glacial Maximum. Thus, specific attention should be given to reconstructing, understanding and modelling climate variability of 6,000 and 21,000 years before present.
3. A detailed investigation of major abrupt transient climatic events of the Holocene and Pleistocene. The focus here is on climatic events of the past that, if they were to occur today, would have profound impact on human societies. Past abrupt changes occurred on seasonal to decadal time scales, and provide key insights into how the coupled climate system may respond to altered climate forcing in the future. This recommended PAGES/CLIVAR action is aimed at avoiding devastating climatic "surprises" in the future, and should be aimed ultimately at developing a predictive ability to simulate major abrupt changes in climatic variability.

### **5.3 INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC)**

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to assess the most up-to-date scientific, technical and socio-economic research in the field of climate change. The IPCC is organised into three working groups: Working Group I concentrates on the climate system, Working Group II on impacts and response options, and Working Group III on economic and social dimensions. The need to investigate the responses of the physical climate system to changes in external forcing factors, such as the concentration of greenhouse gases and atmospheric aerosols, is a major thrust behind CLIVAR. CLIVAR will provide both the raw climate model results and the scientific insight needed to assess both the scope of possible future climate changes and the physical impacts of such changes. CLIVAR is therefore expected to constitute the principal WCRP project underpinning its collaboration with the IPCC. The main interactions at the working will occur between CLIVAR-ACC and IPCC Working Group I through:

- a) The Working Group on Coupled Modelling (WGCM), a joint panel of the Joint Scientific Committee for the WCRP and CLIVAR will be the key vehicle for ensuring that the best, impartial expertise is brought to bear on the scientific aspects of the politically, economically and socially important issue of anthropogenic climate change.
- b) The joint CLIVAR/CCI working group on Climate Change Detection Group focusing on the fundamental aspects of Climate Change Detection and Attribution most relevant to the CLIVAR core project A2.

**IPCC:** <http://www.ipcc.ch/>

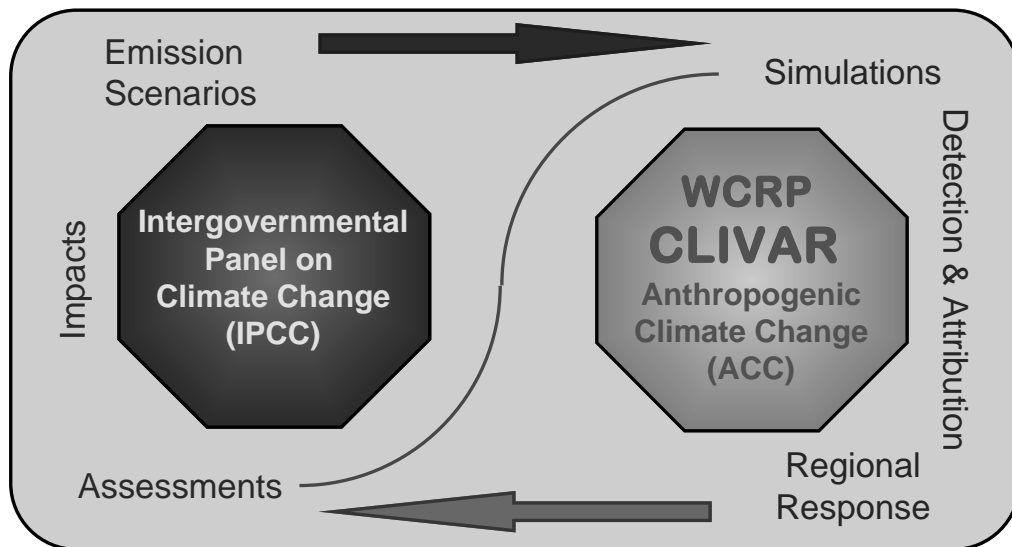


Fig. A 5.1: Relationships between CLIVAR ACC and the IPCC.

## 5.4 “CLIMATE” OBSERVATIONS PROGRAMME

There are a number of existing and planned activities concerned with atmosphere and oceanic observations which are carried out for different purposes but will overall be useful for climate studies as recommended by CLIVAR. We will only describe the connections to these programmes very briefly as they are referenced already a number of times throughout the plan.

### 5.4.1 The Global Climate Observing System (GCOS)

The Global Climate Observing System was established in 1992 by four international organisations: the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the United Nations Environment Programme (UNEP), and the International Council of Scientific Unions (ICSU). Although mainly set up for operational purposes, CLIVAR expects that main parts of the basic observing system needs are carried out under the auspices of GCOS and GOOS.

The Atmospheric Observations Panel for Climate (AOPC) and the oceanic counterpart the Ocean Observations Panel for Climate (OOPC) will co-ordinate the observations relevant for CLIVAR, i.e. CLIVAR has to ensure a close co-operation with those panels to get a maximum benefit from the observations carried out by those programmes.

**GCOS:** <http://www.wmo.ch/web/gcos/gcoshome.html>

### 5.4.2 The Global Ocean Observing System (GOOS)

There exists as yet no internationally co-ordinated system to observe the ocean on a global-scale, to define the common elements of regional marine environmental problems or to provide data and products on which collective national response or improvement can be built. The Global Ocean Observing System (GOOS), initiated by IOC in co-operation with WMO, UNEP and ICSU, will meet this need.

In a sense, GOOS serves as the oceanic counterpoint to GCOS. In terms of the climate module it overlaps with the ocean component of GCOS. The OOPC, see above, will co-ordinate the joint GCOS/GOOS efforts which are relevant to CLIVAR as well.

**GOOS: <http://www.unesco.org/ioc/goos/iocgoos.htm>**

Additionally, to GCOS/GOOS the CLIVAR will observational programme rely on a number of activities mainly serving the operational needs but also providing useful measurements for climate observations needed in CLIVAR. Amongst them the most important are:

- Integrated Global Ocean Services System (IGOSS)

**<http://www.unesco.org:80/ioc/igoss/igoshome.htm>**

- Global Sea Level Observing System (GLOSS)

**<http://www.unesco.org/ioc/goos/gloss.htm>**

- International Oceanographic Data and Information Exchange (IODE)

**<http://www.unesco.org:80/ioc/oceserv/iode/iodehome.htm>**

### 5.5 INTERNATIONAL HUMAN DIMENSIONS OF GLOBAL ENVIRONMENTAL CHANGE PROGRAMME (IHDP)

The purpose of this programme, conducted by Unesco's International Social Science Council (ISSC), is to advance research on topics that are critical for understanding both the human role in global environmental change and the implications of the change for society. Since it addresses processes that transcend political and cultural boundaries, it requires international co-operation. IHDP contributes to global change research by providing mechanisms to foster collaboration among natural and social scientists, develop compatible and comparable data sets, elaborate common methodologies, and exchange research results. Climate research fostered by CLIVAR will provide an important base for the interactions between WCRP, IGBP and IHDP, within the framework of the System for Analysis, Research and Training (START). The IHDP sponsored programme on Land-Use Cover Changes will in turn provide useful information on projections of changes in land cover due to human activities which must ultimately be incorporated in global climate change models. The establishment of appropriate linkages to the International Human Dimensions of Global Environmental Change Programme (IHDP) and the Intergovernmental Panel on Climate Change will ensure that the results of CLIVAR-related research is applied in the most effective manner and that CLIVAR itself benefits from the critical feedback from the activities of these programmes.

**IHDP: <http://ibm.rhrz.uni-bonn.de:80/ihdp/>**

## APPENDIX 6

### 6. ACRONYMS

AABW	Antarctic Bottom Water
AAIW	Antarctic Intermediate Water
AAMIP	Asian-Australian Monsoon Implementation Plan
AARAM	Andean Amazon Rivers Analysis and Monitoring Project
AAN	Asian AMeDAS network
ACC	Antarctic Circumpolar Current
ACC	Anthropogenic Climate Change
ACC E	Atlantic Circulation and Climate Experiment
ACMAD	African Centre for Meteorological Applications and Development
ACSYS	Arctic Climate System Study (WCRP component)
ACW	Antarctic Circumpolar Wave
ADCP	Acoustic Doppler Current Profiler
AMeDAS	Automated Meteorological Data Acquisition System (Japan)
ADEOS/NSCAT	Advanced Earth Observing Satellite/NASA Scatterometer
AGCM	Atmospheric General Circulation Model
AIMS	Analysis, Interpretation, Modelling, and Synthesis (WOCE)
ALACE	Autonomous Lagrangian Circulation Explorer (Float)
AMI	Active Microwave Instrument
AMIP	Atmospheric Model Intercomparison Project
AMSR	Advanced Microwave Scanning Radiometer
AOML	Atlantic Oceanographic and Meteorological Laboratory (NOAA)
AOPC	Atmospheric Observations Panel for Climate (GCOS)
ARM	Atmospheric Radiation Measurement
ARTIST	Arctic Radiation and Turbulence Interaction Study
ARTS	Annual Records of Tropical Systems
ASAR	Advanced Synthetic Aperture Radar
ASCI	Air-sea convective intraseasonal interaction
ASPECT	Antarctic Sea-Ice Processes and Climate
ATLAS	Autonomous Temperature Line Acquisition System
ATSR	Along-track scanning radiometer
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biospheric Aspects of the Hydrological Cycle (IGBP)
BALTEX	Baltic Sea Experiment (GEWEX)
BECS	Basin-wide extended climate study
BEST	Benguela Sources and Transports (programme)
BMRC	Bureau of Meteorology Research Centre (Australia)

#### IV. Appendix

BODC	British Oceanographic Data Centre (UK)
BP	before present
BPPT	Agency for the Assessment and Application of Technology (Indonesia)
BSH	Bundesanstalt für Seeschifffahrt und Hydrographie (Germany)
BSN	Basic Synoptic Network of World Weather Watch
CARDS	Comprehensive Aerological Reference Data Set
CAS	Commission for Atmospheric Sciences (WMO)
CBS	Commission for Basic Systems
CCCCO	Committee on Climate Changes and the Ocean
CCI	Commission on Climatology (of WMO)
CCSR	Center for Climate System Research (Japan)
CDAS	Climate Data Assimilation System
CDW	Circumpolar Deep Water
CEOF	Complex Empirical Orthogonal Functions
CGCM	Coupled General Circulation Model
CLIPS	Climate Information and Prediction Service
CLICOM	Climate Computing Project (World Climate Data and Monitoring Programme)
CLIVAR	Climate Variability and Predictability (WCRP component)
CM	Current Meter
CMIP	Coupled Model Intercomparison Project
CNES	Centre National d'Etudes Spatiales (France)
COADS	Comprehensive Ocean-Atmosphere Data Set
COARE	Coupled Ocean Atmosphere Response Experiment (TOGA)
CORC	SIO-LDEO Consortium on The Ocean's Role in Climate (NOAA)
COWL	Cold Ocean Warm Land
CPC	Climate Prediction Center (NCEP)
CRC	Climate Research Committee (USA)
CSIRO	Commonwealth Scientific and Industrial Research Organization (AUS)
CT	Cold Tongue
CTD	Conductivity Temperature Depth (instrument)
CWSVPPC	CLIVAR/WOCE Surface Velocity Programme Planning Committee
CWXXPPC	CLIVAR/WOCE XBT/XCDT Programme Planning Committee
DAC	Data Assembly Centre (WOCE)
DAO	Data Assimilation Office (NASA)
DARE	Data Rescue
DBCP	Data Buoy Co-operation Panel (WMO/IOC)
DCP	Data Collection Platform
DecCen	Decadal to Centennial Climate Variability (CLIVAR component)
DIMP	Data and Information Management Panel (GCOS)

## 6. Acronyms

DIS	Data and Information System (IGBP)
DIU	Data Information Unit (WOCE)
DKRZ	Deutsches Klimarechenzentrum (German Climate Computing Centre)
DMC	Drought Monitoring Centre, Harare, Zimbabwe
DMPC	Deep Moored Profiling CTDs
DPC	Data Products Committee (WOCE component)
DWBC	Deep Western Boundary Current
EAC	East Australian Current
ECLAT	Etudes Climatiques dans l'Atlantique Tropical
ECMWF	European Centre for Medium Range Weather Forecasts (UK)
ENSIP	ENSO Intercomparison Project (CLIVAR NEG-1)
ENSO	El Niño Southern Oscillation
ENVISAT	Environmental Satellite
EOF	Empirical Orthogonal Functions
EOS	Earth Observatory System
EPOCS	Eastern Pacific Ocean Climate Studies
ERBE	Earth Radiation Budget Experiment
ERS	ESA Remote Sensing Satellite
ESA	European Space Agency
ESOP	European Subpolar Ocean Programme
ESTOC	Estación de Series Temporales Oceánicas de Canarias (Time series station, Canary Islands)
EUC	Equatorial undercurrent
EU	European Union
FANGIO	Feedback Analysis of GCMs and in Observations (WGNE component)
FOCAL	Programme Français Océan et Climat dans l'Atlantique Equatorial
FRAM	Fine Resolution Antarctic Model
FSU	Florida State University, Tallahassee, FL, USA
GAIM	Global Analysis, Interpretation and Modelling (IGBP Task Force)
GAME	GEWEX Asian Monsoon Experiment
GAW	Global Atmosphere Watch
GCIP	GEWEX Continental Scale International Project
GCM	General Circulation Model
GCOS	Global Climate Observing System (IOC/WMO/ICSU/UNEP)
GCSS	GEWEX Cloud System Studies
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GEOSAT	Geostationary Satellite
GEWEX	Global Energy and Water Cycle Experiment (WCRP component)
GFDL	Geophysical Fluid Dynamics Laboratory (USA)
GISP	Greenland Ice Sheet Project



#### IV. Appendix

GISS	Goddard Institute for Space Studies (of NASA, USA)
GLOBEC	Global Ocean Ecosystem Dynamics
GLOSS	Global Sea-level Observing System
GMPP	GEWEX Modelling and Prediction Panel
GOALS	Global Ocean Atmosphere Land System (CLIVAR component)
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GODAE	Global Ocean Data Assimilation Experiment
GODAR	Global Oceanographic Data Archaeology and Rescue
GOES	Geostationary Operational Environment Satellite
GOOS	Global Ocean Observing System (IOC)
GOS	Global Observing System
GOSTA	Global Ocean Surface Temperature Atlas
GPCP	Global Precipitation Climatology Project (GEWEX)
GPI	Global Precipitation Index
GR	Global Residual
GRACE	Gravity Recovery and Climate Experiment (NASA mission)
GRDC	Global Run-off Data Centre
GRID	Global Resources Information Database (UNEP)
GRIP	Greenland Ice-Core Project
GSN	GCOS Surface Network
GTOS	Global Terrestrial Observing System
GTS	Global Telecommunication System
GTSP	Global Temperature and Salinity Project
GUAN	GCOS Upper-Air Network
GVaP	GEWEX Water Vapour Project
HC	Hadley Centre for Climate Prediction and Research (UKMO)
HIRS	High-resolution Infrared Radiation Sounder
HOTS	Hawaii Ocean Time-Series
HWR	Hydrology and Water Resources (W)
IABP	International Arctic Buoy Programme
IAI	Inter-American Institute for Global Change Research
iAnZone	International Antarctic Zone
IAS	Intra-American Seas
ICACGP	International Commission on Atmospheric Chemistry and Global Pollution
ICES	International Council for the Exploration of the Seas
ICPO	International CLIVAR Project Office
ICSU	International Council of Scientific Unions
IFMH	Institut für Meereskunde, Hamburg, Germany
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer (France)
IGAC	International Global Atmospheric Chemistry Programme

## 6. Acronyms

IGBP	International Geosphere Biosphere Programme
IGOSS	Integrated Global Ocean Services System
IHDP	International Human Dimensions of Global Environmental Change Programme
IIOE	International Indian Ocean Expedition
IMR	Institute of Marine Research (Reykjavik, Iceland)
INDOEX	Indian Ocean Experiment
INSAT	India's Geostationary Meteorological Satellite
IOC	Intergovernmental Oceanographic Commission
IODE	International Oceanographic Data and Information Exchange
IOS	Initial Operational System (GCOS)
IPAB	International Programme for Antarctic Buoys
IPCC	Intergovernmental Panel on Climate Change
IRI	International Research Institute
ISLSCP	International Satellite Land Surface Climatology Project (GEWEX)
ISCCP	International Satellite Climatology Project (GEWEX)
ISO	Intra-Seasonal Oscillation
ISOS	International Southern Ocean Studies
ISSC	International Social Science Council (UNESCO)
ITCZ	Inter-Tropical Convergence Zone
ITPO	International TOGA Project Office
JAMSTEC	Japan Marine Science and Technology Center
JASON	proposed TOPEX/Poseidon follow-on satellite (NASA)
JCESS	Joint Center for Earth System Science
JCOMM	Joint Commission for Ocean and Marine Measurements (GCOS/GOOS)
JGOFS	Joint Global Ocean Flux Study
JODC	Japanese Oceanographic Data Centre
JPL	Jet Propulsion Laboratory (NASA)
JSC	Joint Scientific Committee for the World Climate Research Programme
KERFIX	KER for Kerguelen and FIX for fixed station (Time series station, Kerguelen islands)
KNMI	Koninklijk Nederlands Meteorologisch Instituut (The Netherlands)
KORMEX	Korea Monsoon Experiment
LBA	Large-Scale Biosphere-Atmosphere Experiment in Amazonia
LDEO	Lamont-Doherty Earth Observatory, Palisades, USA
LLT	Long term trends (GLOSS data set)
LMD	Laboratoire de Météorologie Dynamique (France)
LOICZ	Land-Ocean Interactions in the Coastal Zone (IGBP)
LODYC	Laboratoire d'Océanographie Dynamique et de Climatologie (France)
LSW	Labrador Sea Water

#### IV. Appendix

LUCC	Land-Use and Land-Cover Change (IGBP)
MAFF	Ministry of Agriculture, Fisheries and Food (UK)
MAGS	Mackenzie GEWEX study
MARVOR	French Subsurface Float, contraction from old Breton language: “MARCH” (horse) and “VOR” (sea)
MAST	Marine Science and Technology Programme (European Union)
MEDIAS	Regional Research Network Mediterranean Basin (MEDI) and Subtropical Africa (AS) (France)
MEDS	Marine Environmental Data Services (Canada)
MIT	Massachusetts Institute of Technology
MJO	Madden-Julian Oscillation
MOC	Meridional Overturning Cell
MODIS	Moderate-resolution Imaging Spectrometer
MOS	Model output statistics
MRI	Marine Research Institute (Helsinki, Finland)
MSD	Mid-Summer Drought
MSLP	Mean sea level pressure
MSU	Microwave Sounding Unit
MWS	Meridional wind stress
NAC	North Atlantic Current
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Space Development Agency of Japan
NADW	North Atlantic Deep Water
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research (USA)
NCDC	National Climate Data Center (USA)
NCEP	National Center for Environmental Prediction
NDVI	Normalised Difference Vegetation Index
NECC	North equatorial countercurrent
NEG	Numerical Experimentation Group
NEP	Numerical Experimentation Panel
NGDC	National Geophysical Data Center (NOAA component)
NMC/CAC	National Meteorological Center / Climate Analysis Center
NOAA	National Oceanic and Atmospheric Administration (USA)
NOS	National Ocean Service (NOAA, USA)
NRC	National Research Council
NSCAT	NASA Scatterometer
NSF-ONR	National Science Foundation-Office of Naval Research
NWP	Numerical Weather Prediction
OCTS	Ocean Colour and Temperature Sensor

## 6. Acronyms

OGCM	Ocean General Circulation Model
OLR	Outgoing Longwave Radiation
OMIP	Ocean Model Intercomparison Project
OOPC	Ocean Observation Panel for Climate (GCOS/GOOS/WCRP)
OOSDP	Ocean Observing Systems Development Panel (CCCCO/JSC)
OSSE	Observing System Sensitivity Experiments
OWS	Ocean Weather Ship
PACS	Pan American Climate Studies (US-GOALS)
PAGES	Past Global Changes (IGBP component)
PALACE	Profiling ALACE floats
PBL	Planetary boundary layer
PCMDI	Program for Climate Model Diagnosis and Intercomparison (USA)
PDF	Probability density function
PICES	North Pacific Marine Science Organization
PILPS	Project for Intercomparison of Land-Surface Parameterisations (GEWEX)
PIRATA	Pilot Research Moored Array in the Tropical Atlantic
PMEL	Pacific Marine Environmental Laboratory (USA)
PMIP	Paleoclimate Modelling Intercomparison Project
PNA	Pacific North American
PRA	Principal Research Area
PSMSL	Permanent Service for Mean Sea Level
PV	Potential vorticity
PSA	Pacific South American
QBO	Quasi Biennial Oscillation
RAFOS	SOFAR (Sound Fixing and Ranging Float) spelled backwards
REVIZEE	Avaliação de potencial sustentável de Recursos Vivos na Zona Economica Exclusiva
SAC	Special Analysis Centre
SACZ	South Atlantic Convergence Zone
SAMW	Subantarctic Mode Water
SAR	Second Assessment Report (of IPCC)
SAR	Synthetic Aperture Radar
SAT	Surface Air Temperature
SCAR	Scientific Committee on Antarctic Research
SCOR	Scientific Committee on Oceanic Research
SCORPIO	Oceanographic Cruise in the South Pacific, 1968, USA
SCPP	Seasonal-to-interannual Climate Prediction Program (NOAA)
SCSMEX	South China Sea Monsoon Experiment
SEACAT	recording CDT product of SeaBird (Seattle, USA)
SEC	South equatorial current

#### IV. Appendix

SEQUAL	Seasonal Response of the Equatorial Atlantic
SeaWiFS	Sea-viewing Wide Field-of-view Sensor (NASA)
SHEBA	Summer Heat Budget of the Arctic
SIE	Sea Ice Extent
SIMW	Subtropical Indian Mode Water
SIO	Scripps Institution of Oceanography, La Jolla, USA
SLP	Sea level pressure
SMIP	Seasonal Prediction Model Intercomparison Project
SO	Southern Oscillation
SOC	Southampton Oceanographic Centre, UK
SOI	Southern Oscillation Index
SPALACE	Salinity Profiling ALACE
SPARC	Stratospheric Processes and their Role in Climate (WCRP component)
SPCZ	South Pacific Convergence Zone
SSG	Scientific Steering Group
SSH	Sea Surface Height
SSM/I	Special Sensor Microwave/Imager
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
START	Global Change System for Analysis, Research & Training
STOIC	Study of Tropical Oceans in Climate Models (CLIVAR NEG-1)
SVP	Surface Velocity Programme (former WOCE component)
TAO	Tropical Atmosphere Ocean (TOGA moored array)
TBO	Tropospheric biennial oscillation
THC	Thermohaline circulation
TIP	TAO Implementation Panel (GCOS/GOOS/WCRP)
TOGA	Tropical Ocean Global Atmosphere (WCRP component)
TOPEX/POSEIDON	Ocean Topography Experiment (NASA/CNES Satellite Programme)
TOP	Top of the atmosphere
TRITON	Triangle Trans-Ocean Buoy Network
TRMM	Tropical Rainfall Measuring Mission
TWXXPPC	TOGA / WOCE XBT / XCDT Planning Committee
UD/EB	Upwelling Diffusion-Energy Balance Model
UKMO	United Kingdom Meteorological Office
ULS	Upward Looking Sonars
UNDP	United National Development Programme
UNEP	United Nations Environment Programme
UOP	Upper Ocean Panel (CLIVAR)
VAMOS	Variability of the American Monsoon Systems
VCP	Voluntary Cooperation Programme (WMO)

## 6. Acronyms

VEINS	Variability of Exchanges in Northern Seas
VOS	Volunteer Observing Ships
WCDMP	World Climate Data and Monitoring Programme
WCRP	World Climate Research Programme
WDC	World Data Center
WGCM	Working Group on Coupled Modelling (JSC/CLIVAR)
WGNE	Working Group on Numerical Experimentation (WCRP/CAS)
WHP	WOCE Hydrographic Programme
WHPPC	WOCE Hydrographic Programme Planning Committee
WHYCOS	World Hydrological Cycle Observing System
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment (WCRP component)
WWW	World Weather Watch (WMO)
WWW	World Wide Web
XBT	Expendable Bathythermograph
XCTD	Expendable Conductivity-Temperature-Depth Instrument

*IV. Appendix*