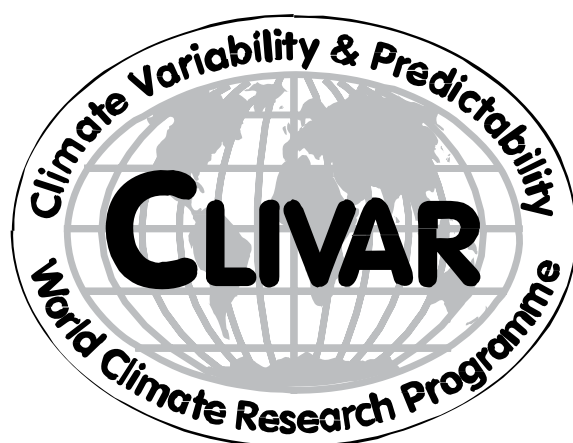


INTERNATIONAL  
COUNCIL FOR  
SCIENCE

INTERGOVERNMENTAL  
OCEANOGRAPHIC  
COMMISSION

WORLD  
METEOROLOGICAL  
ORGANIZATION

## WORLD CLIMATE RESEARCH PROGRAMME



### CLIVAR Pacific Implementation Workshop Report

February 5-8, 2001  
East-West Center, Univ. of Hawaii

JULY 2001

WCRP Informal Report No. 12/2001

*ICPO Publication Series No. 51*

CLIVAR is a component of the World Climate Research Programme (WCRP), which was established by WMO and ICSU, and is carried out in association with IOC and SCOR. The scientific planning and development of CLIVAR is under the guidance of the JSC Scientific Steering Group for CLIVAR assisted by the CLIVAR International Project Office. The Joint Scientific Committee (JSC) is the main body of WMO-ICSU-IOC formulating overall WCRP scientific concepts.

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Figures included in this report and additional information are available to download on the CLIVAR website  
- <http://www.clivar.org/organization/pacific> under publications



## **1. Meeting Objectives**

The goals of the implementation workshop were to bring together atmospheric and oceanic scientists from the Pacific nations to exchange information on the CLIVAR Principal Research Areas in the Pacific and to advance the process of the collaborative implementation of those plans. The science problems in the Pacific identified by CLIVAR span a range of time scales, and the issue at hand was to define and initiate a coherent approach to work in the Pacific. The legacies of the workshop will be an international CLIVAR Pacific Implementation Workshop Report and an international CLIVAR Pacific Sector Panel.

Participants were asked to bring to the meeting national and personal plans for field work; information about timing, locations, and methods of planned measurements; requests and requirements for international coordination; indications of interest or commitments to take on elements of the broadscale, regional, and process study work to be done in the Pacific. The intent of the meeting was to begin to develop timelines and tables and to begin the drafting of an International Implementation Plan for Pacific CLIVAR. Discussions at the meeting were to address key issues for implementing Pacific CLIVAR, including issues of readiness and priority; of partnerships to be developed between CLIVAR and, for example, the global carbon and water cycle programs; and of the extent to which the planned observations meet the needs of the modeling and data assimilation efforts and of the interactions between observing, assimilation, and modeling elements of Pacific CLIVAR.

Working Groups were set up during the workshop to begin to develop descriptions of the cooperative, international approach to the broadscale ocean and atmospheric sampling, to the regional studies, and to the process studies and draft time tables for these efforts. Discussions were also aimed at developing a list of action items, including the steps that must be done next to successfully implement Pacific CLIVAR.

## **2. Organizing Committee Members**

At the CLIVAR SSG in Hawaii in 2000, a preliminary planning meeting was held to discuss organizing to hold a Pacific Implementation Workshop. This original group (list names) was subsequently developed into an Organizing Committee for the workshop.

The final make up of the Organizing Committee was:

Robert Weller, Chair

Jose Rutllant

Rit Carbone

Mansour Ioualalen

Y. H. Ding

Richard Johnson

Yoshi Kuroda

George Kiladis

Pablo Lagos\*

Roger Lukas

Phil Sutton

## **3. Plenary Presentations**

A number of invited overview presentations were spread over the first two days of the workshop. The speakers had been asked to provide a summary of the science issues, the work that was in progress or planned, and of the challenges in each of their respective areas. Tony Busalacchi, co-Chair of the CLIVAR SSG, was asked to start with an overview of the CLIVAR science issues in the Pacific basin. Dean Roemmich and George Kiladis followed with talks on broadscale ocean and atmospheric sampling, respectively. Roger Lukas gave a presentation on regionally enhanced sampling, where the sampling would be more intense than under the broadscale coverage. Ocean, atmospheric, and coupled model development were presented in turn by Andreas Schiller, Mitch Moncrieff, and Bryant McAvaney. Russ Davis provided a presentation on ocean process studies, and Chris Bretherton provided a presentation on atmospheric process studies. Michael Ghil talked about atmospheric data assimilation, and Detler Stammer talked about oceanic data assimilation.

### 3.1 Overview of CLIVAR Pacific science (Tony Busalacchi)

The objectives of CLIVAR have been well developed and stated in the CLIVAR science documentation. Relevant to this Pacific Implementation Workshop are the following CLIVAR Principal Research Areas:

G1 ENSO – extending and improving predictions, advancing understanding and observations of climate variability associated with El Niño-Southern Oscillation (ENSO) and global teleconnections to improve prediction and applications. Questions that need to be addressed include: What governs the onset, amplitude, and duration of ENSO events? To what extent and how can ENSO lead time predictions be extended? Role of high frequency and stochastic forcing? What determines the apparent decadal modulation of ENSO? Is there a more appropriate measure than Niño3? Role of Indonesian Throughflow and western boundary circulation?

D4 Pacific and Indian Ocean Decadal Variability – 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. The possibility of ocean-atmosphere interactions outside the tropics has been hypothesized for decades.

However, considerable uncertainty remains regarding the mechanisms of Pacific decadal variability and the geographic centers of ocean-atmosphere coupling. Possible coupled modes: (1) unstable air-sea interaction between the subtropical gyre circulation in the North Pacific and the Aleutian low pressure system, (2) decadal variability originating in the tropics with higher latitude variability resulting from ENSO-like atmospheric teleconnections, (3) air-sea coupling in the northeastern subtropics that involves transport variations of the North Pacific Subtropical Cell, (4) decadal variability set by subduction time scale, (5) Pacific decadal variability as a result of global ocean-atmosphere interactions.

With regard to the first of these hypotheses, the following issues should be addressed in the implementation of Pacific CLIVAR: Role of advection of mean temperature by anomalous currents versus anomalous temperature by mean currents; How significant is the response of the atmospheric circulation to midlatitude SST anomalies? AGCM experiments suggest that the midlatitude response to SST is modest compared to atmospheric internal variability. May have complex seasonal and nonlinear dependencies, and varies among models; Weng and Neelin (1988) suggest the period of the coupled oscillation is sensitive to the length scale of feedback from the atmosphere, i.e., coupled Rossby mode; SST anomalies in the equatorial Pacific are of opposite sign relative to the main anomaly in the North Pacific and "relatively" weak, which suggests that the decadal model has its origin in midlatitudes; subtropical circulation cells do not play an active role in this mechanism for decadal variability.

Considering how decadal variability in the tropics may couple to the midlatitudes raises the following issues to be dealt with in the implementation of Pacific CLIVAR: What causes the decadal variability in the tropics, possibly coupled interaction between the tropics and mid-latitudes? What sets the time scale; are is a subharmonic of ENSO? Subsurface propagation of North Pacific temperature anomalies, which do not appear to propagate to the subsequent equatorial thermoclines to initiate the subsequent phase. The strengthened Aleutian low in response to tropical SST has not been rigorously diagnosed.

Developing a better understanding of tropical — midlatitude coupling requires that the implementation plan provide the means to address the following questions: What is the relative importance among transport changes, temperature advection, and forcing originating from the tropics? What is the relative role of northern versus southern hemisphere contributions? What are the related changes in water mass attributes, and are they significant? What is the relative importance of the influence of mid-latitude vs tropical SST on the mid-latitude atmosphere? What is the atmospheric response to SST variability induced by the STCs?

Moving forward to implement CLIVAR in the Pacific, we should benefit from national implementation plans, already proposed fields programs, the Working Group on Coupled Modeling and its Workshop on Decadal Predictability, the CLIVAR Workshop on Shallow Tropical-Subtropical Overturning Cells and their Interaction with the Atmosphere, the CLIVAR/NASA/IPRC Workshop on Decadal Climate Variability, various satellite missions (TRMM, altimetry, SST), the TAO array and other observing elements already in place.

The implementation of Pacific CLIVAR should: not be a simple extension of TOGA or WOCE, should not be U.S. centric, should develop a strategy for air-sea fluxes, should fight against parochialism, should incorporate paleodata, should fight against a northern hemisphere bias, may require new structures to organize themselves, must link process study scales to basin scale. Integrate remote sensing. This workshop show work toward strategies that will lead to: (1) improved understanding of tropical-extratropical decadal coupled process, (2) refinements and improvements in our ability to understand and predict coupled

processes on seasonal and interannual timescales and to exploit this understanding, and (3) commitments and creation of an appropriate international structure to permit these improvements to be achieved. It is anticipated that the workshop will result in the formation of a standing CLIVAR Pacific Implementation Panel to: (1) recommend and oversee the implementation of observations in the Pacific Ocean sector, in order to meet the objectives outlined in CLIVAR's Science and Implementation Plans, particularly with respect to the Principal Research Areas G1 (ENSO: Extending and Improving Predictions) and D4 (Pacific and Indian Ocean Decadal Variability), (2) collaborate with the JSC/CLIVAR Working Group on Coupled Modeling and CLIVAR Working Group on Seasonal to Interannual Prediction, in order to design appropriate numerical experiments, and to be aware of requirements set by these groups for data sets needed to validate models, and (3) liaise with the CLIVAR Ocean Observations Panel, TAO/TRITON Implementation Panel, Ocean Observations Panel for Climate, ARGO, and GODAE.

### **3.2 Broad scale ocean sampling (Dean Roemmich)**

Roemmich gave an overview talk on broadscale ocean sampling in the Pacific, identifying objectives, explaining the OceanObs99 (St. Raphael, France, 1999) planning process, reviewing the ENSO observing system and extensions to it needed by Pacific CLIVAR, and pointing out additional new broadscale sampling elements needed in the Pacific.

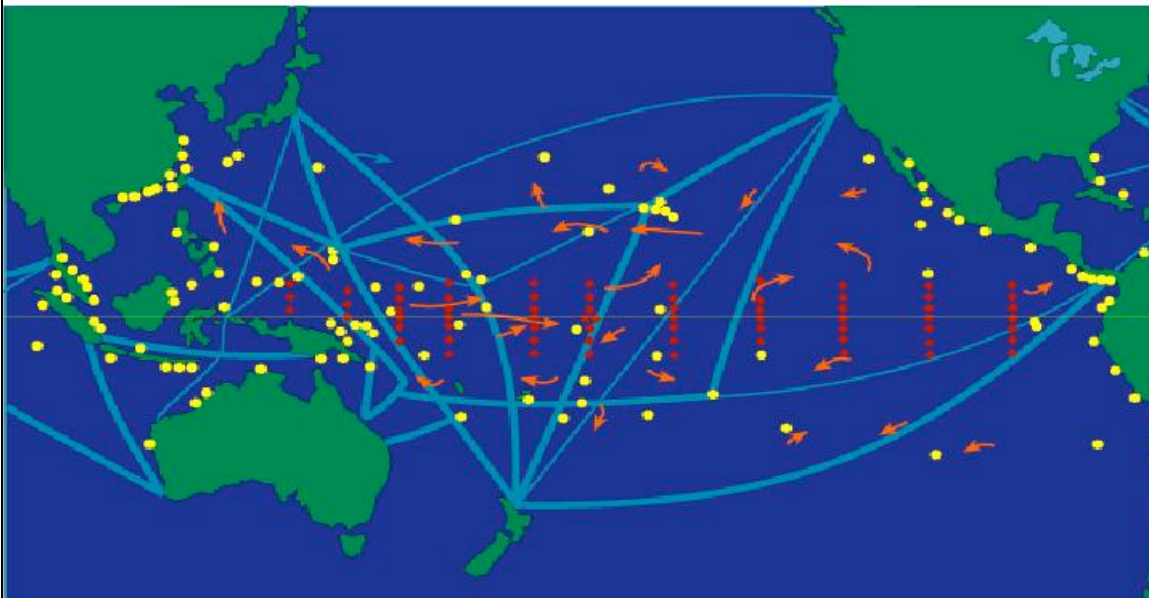
The objectives of the broad-scale sampling in CLIVAR are to:

- 1) Provide a basic description of the climate system including its variability on seasonal and longer time scales.
- 2) Improve our understanding of the climate system by revealing physical processes that influence climate on long time-scales.
- 3) Provide the large-scale context for regional process studies of limited duration.
- 4) Provide the required data sets for data assimilation and (seasonal and longer) forecast model initialization.
- 5) Complement the satellite remote sensing systems with data needed for validation, calibration, and interpretation.

At OceanObs99 the CLIVAR UOP and the OOPC brought together expert groups for all elements of the ocean observing system. Each group was tasked with describing the status and objectives and with providing a practical plan for implementation. Several of the papers from OceanObs99 are relevant to the Pacific CLIVAR implementation process and can be found in *Observing the Ocean in the 21st Century* (2001).

A central element in the broad-scale Pacific observing system is the ENSO observing system (Fig. ?). It has been recommended that additional salinity, and velocity observations be made and that four of the TAO buoys be upgraded to observe the surface meteorology needed to compute the air-sea fluxes of momentum, heat, and freshwater.

**The ENSO Observing System *includes:*  
Moored buoys, Tide gages, Drifting buoys, VOS network**



**To measure: Sea level, thermal profiles, surface velocity, surface fluxes.  
For: better understanding and improved prediction of ENSO phenomena.**

**The ENSO observing system.**

It is noted that the sea level gage network is global and that surface drifters have been deployed globally, though it is likely that without action the number of drifters in the extratropical Pacific will decline. The broad-scale thermal network is global north of 30°S and must be maintained until ARGO is fully deployed. After that the broadscale XBT sampling would be phased out and resources focused on the high density (HRX) and frequently repeated (FRX) XBT lines. An additional recommendation is that more attention be paid to sea surface salinity (SSS).

The in-situ sea level gage network is essential to ground-truthing and correcting the calibration on the satellite altimeters. Surface drifters provide a global data base for calibration of satellite sea surface temperatures (SST), description of the mean and variability of the near-surface circulation, and testing models of the surface layer. The broad-scale XBT network focuses on upper ocean heat content and on the thermal variability on seasonal and longer time scales. The upper ocean thermal network was reviewed in August 1999 (Smith et al, 2001). This review developed the recommendation to shift resources, as ARGO was deployed, to the HRX and FRX lines.

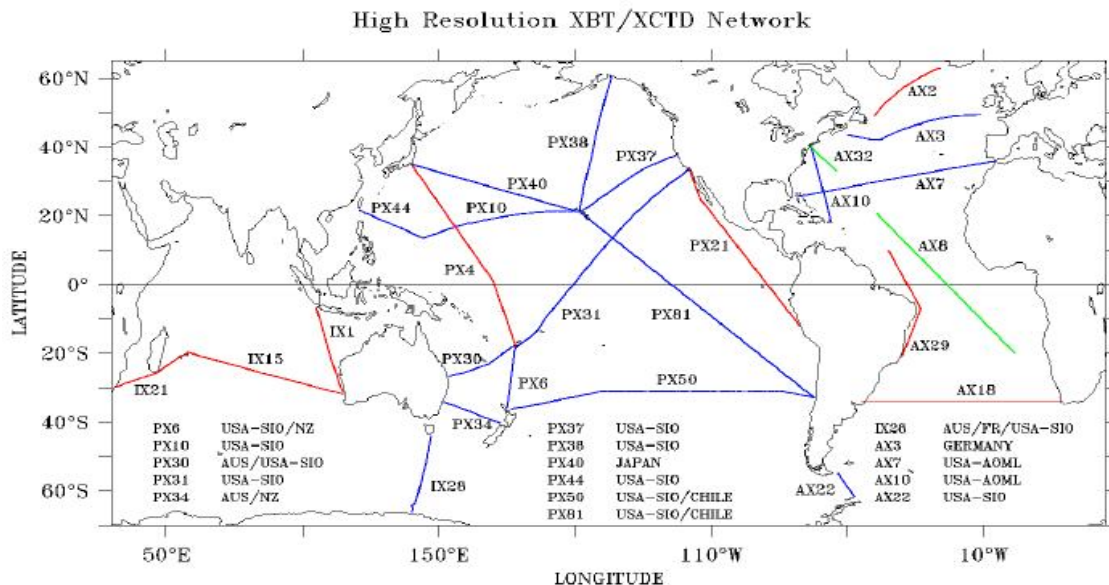
Deployment of ARGO will provide the T,S profiles and reference velocity globally. International commitments for ARGO are growing and were summarized by Roemmich. As of late 2000 622 floats had been funded and 2,219 were proposed over the next three years. Different nations have targeted different locations for their floats, and of concern for Pacific CLIVAR is that floats deployed over the whole Pacific basin as part of a global deployment rather than being restricted to specific regions. Deep ocean repeat hydrography (CTD, nutrients, oxygen, geochemical tracers) is also needed. Reoccupation of the WOCE lines in cooperation with the carbon community is the goal for implementation of repeat hydrography in the Pacific.

Time-series stations (CTD, nutrients, oxygen, bio/geochemical measurements and flux reference sites) are needed. The surface flux reference sites have been identified with input from the numerical weather prediction community, and a planning meeting will be held in early 2001 to firm up the selection of the other sites for time series stations. Basin-scale air-sea fluxes will come from the flux reference sites in combination with data from VOS equipped with improved meteorological sensors. HRX lines will be used to provide basin-wide XBT/XCTD section with good spatial resolution and this basin-wide transports. The goal is to occupy all the HRX lines in the Pacific. Transects make typically 300 profiles, with spacing as close as 10 km near boundaries. XCTDs are dropped infrequently along the track, and climatology is used to



infer salinity in between the XCTD profiles. Present XBTs go to 800m, but 2000m probes are being tested. These HRX lines would be outfitted with IMET sensors and provide data for basin-scale surface meteorology and air-sea fluxes.

Boundary current measurements will come from direct velocity observations due to the need for good space and time resolution. A number of strategies are possible, including; moored arrays, repeat hydrography with ADCP, high resolution XBT sampling, gliders, and tomographic arrays. Regionally appropriate plans are needed for each boundary current that are cost effective and address both calibration and sustained measurement issues. Acoustic tomography can provide integrated signals. Both basin-scale and regional tomographic arrays have been discussed. The planning is most advanced for a tomographic array as part of KESS.



Presently sampled lines are shown in blue.

Objectives are to measure seasonal to interannual variability in transport of mass, heat and salt as well as accurate determination of mean fields and statistics of variability.

Recommended HRX lines.

For Pacific CLIVAR the high priority set of sustained observations need to be agreed upon. These will probably include:

- 1) Maintaining existing high priority time-series
- 2) Deployment of ARGO
- 3) Implementation of a strategy for basin-wide improved air-sea fluxes, using surface flux reference sites and VOS.
- 4) Regional enhancements.

### 3.3 Broad scale atmosphere (George Kiladis)

An overview of the state of the current atmospheric observing system was provided. This was followed with discussion of what atmospheric observations are needed in the Pacific for: (1) Process studies, (2) Data assimilation for analyses, coupled modeling research, and (3) ENSO and long-range forecasting.

The existing observing system includes:

- 1) Permanent island installations, which include surface stations, radiosonde sites, and profilers, for operational and climate monitoring purposes.
- 2) TAO array and other moorings

- 3) Volunteer Observing Ships (VOS) and XBT lines
- 4) Satellite observations
- 5) Aircraft observations
- 6) Observations from field programs

The land-based stations provide surface observations (once or twice daily at relatively low horizontal resolution; temperature, precipitation, pressure, humidity, wind, radiation). They are also where radiosonde observations are made (once or twice daily, high quality, high vertical resolution observations of temperature, pressure, humidity, and wind). These are cost-effective and automated operation is possible for remote sites. However, there has been a dramatic decrease in coverage over the last decade. Profilers can provide with high vertical and temporal resolution wind, vertical motion, and precipitation. Aerosondes can also provide high temporal resolution; several could provide good spatial coverage. These are potentially very cost effective for field efforts or for operational purposes. They measure temperature, pressure, humidity, wind, and radiation.

Moored and drifting buoys. The TAO array provides surface meteorology, daily data, and good horizontal resolution along the equatorial wave-guide. Many sites have temperature, humidity, and wind, SST. Four sites also have shortwave radiation, pressure. Some sites have precipitation. As part of various research programs buoys have been fielded by WHOI and other institutions that were fully equipped (incoming shortwave and longwave radiation, wind, air temperature, SST, humidity, precipitation, barometric pressure) to measure the air-sea fluxes of heat, freshwater, and momentum using bulk formulae. Along the coast there are the National Data Buoy Center buoys in the U.S. and similar buoys from other countries. Drifting buoys are also able to carry some surface meteorological sensors.

Volunteer Observing Ships (VOS) and XBT lines. Some ships have been equipped with IMET (Improved METeorological packages) to provide high quality, high temporal resolution of the complete set of surface meteorological observations needed to measure air-sea fluxes. The high-resolution XBT lines are an attractive subset of lines for these upgrades. Routine observations are less complete, less often, and of lower quality. Surface observations are also taken from the ships servicing the TAO/TRITON arrays; these could also be used for launching radiosondes. The coverage by ships is limited (see figure below) to the where the ships go and is thus biased toward the northern hemisphere. Drifting buoys do provide a means of more limited observations in areas less heavily travelled by ships.

Satellite missions that will support Pacific CLIVAR include: scatterometry, cloud winds, atmospheric profilers (temperature, humidity, radiance), and ozone mapping.

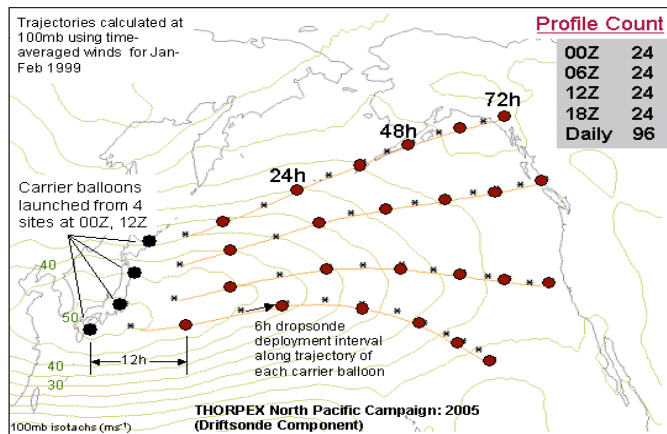
Aircraft can provide high temporal resolution along flight paths. Research aircraft can be well equipped. Efforts to add sensors to commercial aircraft are underway. Research aircraft provide temperature, humidity, pressure, wind, radiation, and cloud observations; they also can deploy dropsondes. Small, unmanned aircraft such as the aerosonde may offer an alternate method for sampling.

Observations from other Proposed Field Efforts:

EPIC is the Eastern Pacific Investigation of Climate Processes in the Coupled Ocean Atmosphere SYstem. Enhanced measurements include additional surface moorings in the TAO array and an IMET mooring under the stratus clouds at 20°S, 85°W and additional radiosonde sampling from TAO service ships and land in Central and South America. In the October 2001, extensive ship and aircraft –based process studies will be conducted along 95°W from the ITCZ, across the equator and then into the coast of Chile.

THORPEX – The Hemispheric Observing System Research and Predictability Experiment will deploy additional soundings in targeted regions of the Pacific where such observational enhancements may lead to improved predictability over North America. The concept of a large balloon that can deploy dropsondes and XBTs is being looked into, with prototype testing planned for 2001-2004 and regional campaigns for 2003-2005.

Fig. 5: Driftsonde profile coverage at one assimilation time, after 3 days of deployment from 4 launch sites in Japan – each dot represents a separate carrier balloon / gondola and GPS dropsonde profile location at 00Z (or 12Z) - stars are profile locations at 06Z or 18Z



GAINS – Global Air-Ocean IN-situ System is planning constant pressure-latitude system of 100 to 400 balloons with dropsondes, air chemistry, and ocean sondes. Proof of concept tests to be conducted in 2001-2003.

#### Island Enhancements

Maintenance of existing land stations and enhancements to some should be considered, with the re-establishment of at least three island-based radiosonde sites to be considered seriously.

San Cristobal, Galapagos (1°S, 90°W). Already manned by experienced observers, would be very cost effective.

Midway Island (28°N, 177°W). An ecotourist destination, has fully manned airport, essentially no cost for personnel involved.

Wake Island (19°N, 168°E). Has a long historical record, airstrip, but little in the way of air traffic at the moment.

Other possibilities: Johnston Island (17°N, 170°W). Christmas Island (1°N, 158°W). Kiribis government would provide trained personnel.

Other line islands: Fanning (4°N, 160°W), Washington (5°N, 160°W), Palmyra (6°N, 162°W) Would provide a convenient land-based transect from the dry zone to the ITCZ for field experiments.

#### General Recommendations

- Optimization of existing land-based observing platforms, with enhancements of surface and radiosonde observations.
- Enhancements of surface met observations on VOS lines, upgrading 3-5 TAO moorings to measure all parameters needed to infer fluxes, establishing 4 extra-tropical IMET moorings.
- Consider the possibility of operational aerosonde observations from land- and ship-based locations.
- Ensure that all observations from all available platforms are made immediately available for assimilation and research.
- Central archiving of historical and real-time data gathering is crucial.

### 3.4 Regionally enhanced (Roger Lukas)

Roger Lukas gave a plenary presentation on regionally enhanced observations in the Pacific basin. The purpose was to inform attendees about ongoing and planned regional projects, to solicit and integrate new information, and to suggest strategy for Pacific CLIVAR implementation.

Regional enhancements would be additions to the basin-scale sampling. They would be done to provide additional space and time resolution as needed in special physical regimes, such as boundary currents, subduction regions, and the equatorial waveguide. The bifurcations and convergences associated with the eastern and western boundary currents would be addressed by regional sampling, but the implementation plan would need to be developed for each region to address the dynamics and logistics of the site.

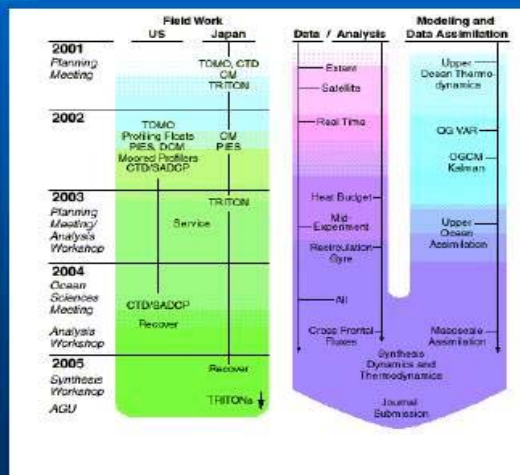
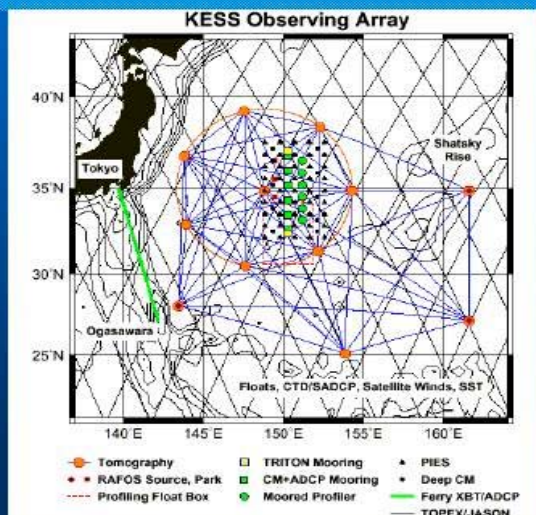
The observations needed are of velocity, transport, mixing, and eddy diffusion. In some sites (Kuroshio extension), intense air-sea interaction would be an observational target. Concentrated meridional/vertical fluxes would be targeted in the westernboundary current and along the equator.

Partitioning of transport, recirculation, and redirection would need to be examined in bifurcation and confluences.

In cases where the approach to a region is not yet clear, it is recommended that CLIVAR Pacific carry out pilot studies. In addition, it is anticipated that process studies done in CLIVAR Pacific will have a regional character, with their focus directed toward learning more about process and improving predicting by making more detailed observations in a region. An outcome of the pilot and process studies would be the understanding of what regional enhancements should remain in place for the duration of Pacific CLIVAR in order to, for example, measure transports in key boundary currents.

Regional programs already underway include EPIC (Eastern Pacific Investigation of Climate) in the eastern Pacific cold tongue, ITCZ, and stratus cloud areas, KESS (Kuroshio Extension System Study) in the Kuroshio extension, KOP (Kuroshio Observation Program) in the Kuroshio, ITF-Arlindo in the Indonesian throughflow, and SAGE in the subpolar gyre.

## Kuroshio Extension Study





# Kuroshio Observation Project by FORSGC/JAMSTEC

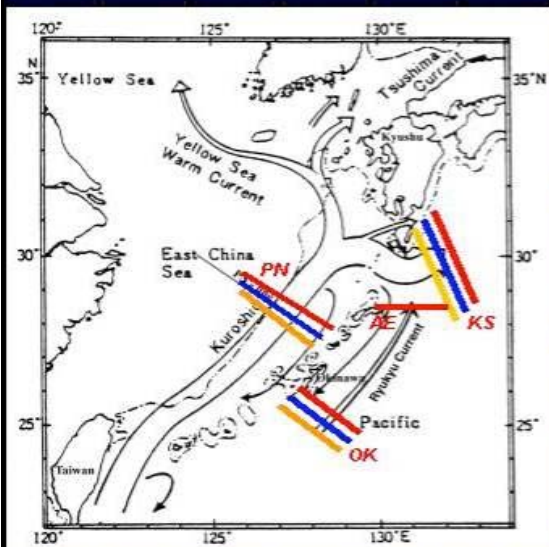


Fig. 1. Map of planned observations and the Kuroshio current system chart (Nitani 1972).

## Objectives / Sites

- \* The Kuroshio structure  
KS and PN
- \* Meandering of the Kuroshio in the  
East China Sea  
PN
- \* Ryukyu Current  
AE and OK
- \* The Kuroshio recirculation gyre  
AE and KS + altimetry
- \* Mesoscale eddies east of the Ryukyus  
AE, KS, and OK + altimetry

## Dynamic Height and Velocity

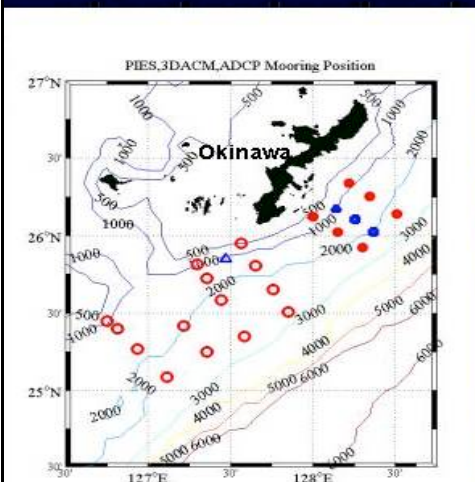
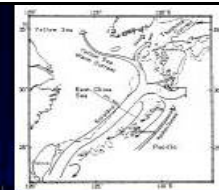


Fig. 2. OK-array after deployment planned for 2001. Filled marks - instruments deployed in 2000.

- \* PIES (●) → acoustic travel time
- \* Acoustic travel time → specific volume anomaly,  $\delta$ , profile
- \* Horizontal gradients of  $\delta$  → baroclinic velocity
- \* 3DACM (■) and ADCP (▲) → reference velocity
- \* Baroclinic velocity + reference velocity → absolute velocity profile
- \* PIES observations of the dynamic height will be combined with the TOPEX/POSEIDON and ERS altimeter data.



## Timetable of the KOP

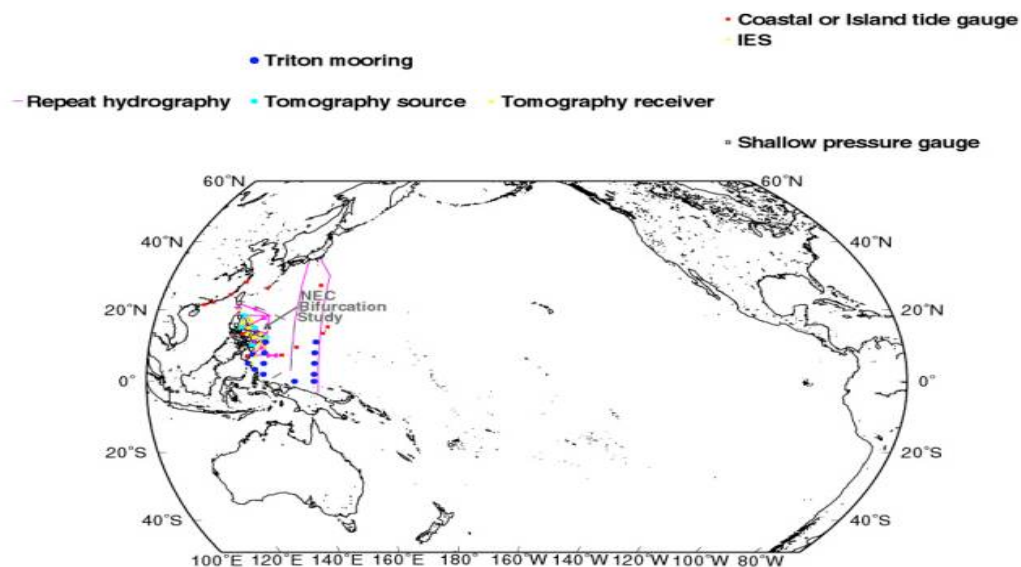
Task	Site	Phase I: Process Study					Phase II: Monitoring
		FY 00	FY 01	FY 02	FY 03	FY 04	FY 05 – 09
PIES mooring	OK	10	20	20	20	20	
	AE-KS			12	12	12	
	PN			5	16	16	
Lowered ADCP/CTD casting	OK	15/25	30~/30~	40~/40~	40~/40~	40~/40~	
	AE-KS	16/26	20~/20~	25~/25~	25~/25~	25~/25~	
	PN	4/14	10~/10~	20~/20~	30~/30~	30~/30~	
Upward Looking ADCP mooring	OK	1	2	2	2	2	
	AE-KS			1	1	1	
	PN (trawl resistant)				1	1	
3D ACM mooring	OK	2	2	4	4	4	
	AE-KS			2	2	2	
	PN			4	4	4	
XBT/XCTD casting	OK	9/8	20~/10~	20~/10~	20~/10~	20~/10~	
	AE-KS	6/1	10~/10~	20~/10~	20~/10~	20~/10~	
	PN			10~/5~	10~/5~	10~/5~	
WOCE drifter	Subtropical gyre	7	8~	10~	12~		

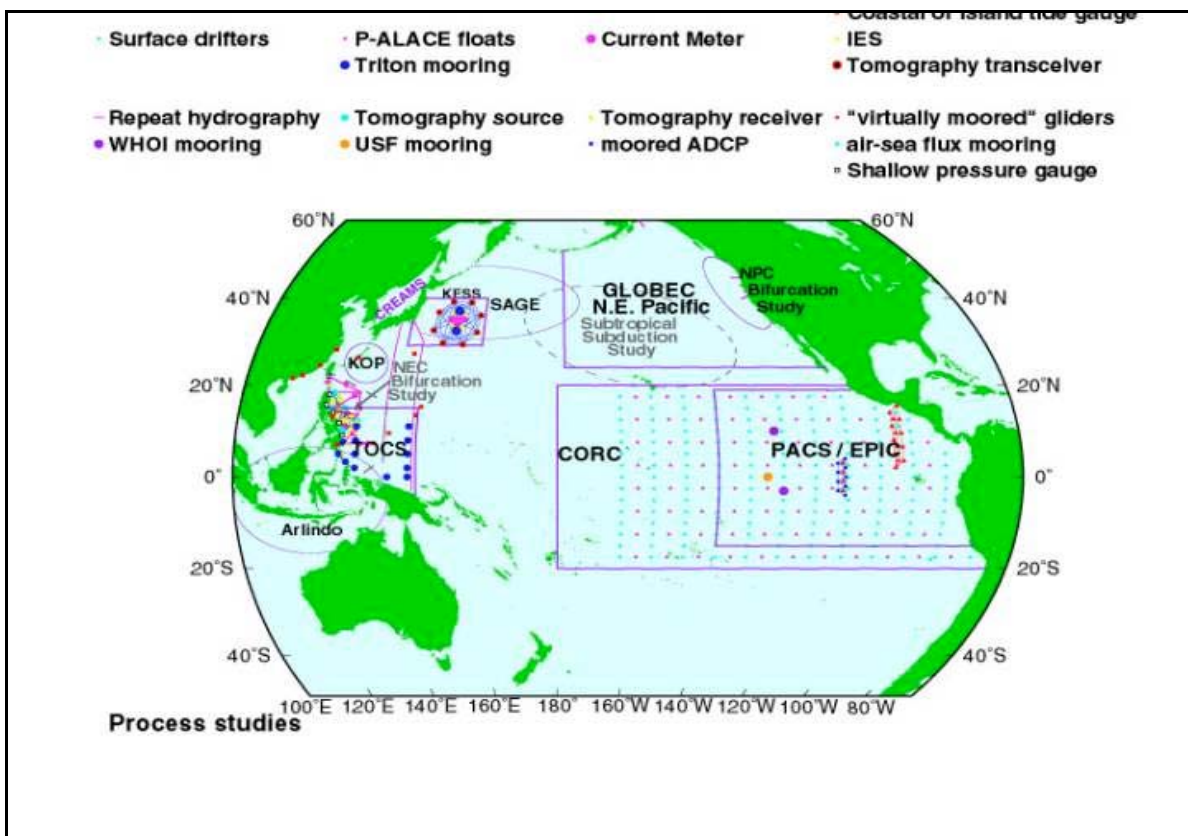
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Proposed or under consideration are more work in KESS and ITF-Arlindo, a subduction process experiment, a NEC bifurcation study, a NPC bifurcation study, a study of equatorial upwelling, and VAMOS-EPIC (VEPIC), an international follow on to EPIC.





Challenges for Pacific CLIVAR include finding resources, coordination, including among other WCRP and IGBP programs, and integration, including understanding systems and cooperation at programmatic margins.

### 3.5 Ocean model development (Andreas Schiller)

The ultimate goal is to develop better models to explain climate dynamics and to predict climate variability. This presentation summarized present status and challenges, identified modeling issues: resolution, parameterizations, and forcing, and addressed the observational efforts needed to improve ocean models.

Some questions for models and observations:

- What are the sources for and rates of subduction of tropical and subtropical waters that contribute to shallow cells?
- What are the equatorial and coastal upwelling rates of waters that contribute to shallow cells?
- What are the water mass properties in the thermocline of the tropical and subtropical oceans?

Modeling issues:

#### 1) Resolution.

A basic choice to be made in ocean general circulation modeling concerns integration time in two classes of models:

- a) Models aiming at solutions in thermodynamic equilibrium that require compromise in spatial resolution (plus models used to carry out multiple simulations in order to explore sensitivity to model parameterizations, initial conditions and forcing fields).
- b) Models aiming at an accurate depiction of the actually observed flow fields that require a compromise in the adjustment to a full equilibrium state.

Gap remains between those models developed and used primarily for oceanographic applications (ocean-only models), and those used as components in climate system models.

Most type of multi-decadal and longer model studies are limited to intermediate resolution ( $1^{\circ}$ – $2^{\circ}$  horizontal resolution).

Choice of model spatial resolution affects parameterization and biases.

#### 2) Parameterizations

Challenges for modeling equatorial dynamics:

- a) High velocity shear in upper ocean.
- b) Strong vertical advection and vertical mixing impact on mixed layer dynamics.
- c) Penetration of solar shortwave radiation.
- d) Barrier layer formation.
- e) Mixing due to tropical instability waves.
- f) Tidal mixing.

All existing ocean models have substantial biases at least somewhere between the surface and thermocline (unrealistic stratification, unrealistic depth of thermocline, unrealistic currents). Furthermore, ocean models do not properly represent the mean subsurface currents and western boundary current system.

Explicit/implicit free surface methods (Blumberg and Mellor, 1987; Dukowicz and Smith, 1994; Killworth et al., 1991).

Mixed layer formulations (Large et al., 1994; Chen et al., 1994).

Parameterization of eddy-induced mixing (Gent and McWilliams, 1990; Gent et al., 1995). Improvement in coarse-resolution ocean models with respect to thermocline sharpness, confinement of deep convection regimes, and elimination of spurious diapycnic convection regimes, and elimination of spurious diapycnic mixing through parameterization of mesoscale eddies. BUT: scheme strongly damps fronts in addition to grid-scale structures.

Parameterization of bottom boundary layer (Beckmann and Döscher, 1997).

Parallel computing technologies.

### 3) Modeling issues: surface forcing

Knowledge of the fluxes of heat, freshwater (E&P), and momentum (wind stress) at the air-sea interface is central: (a) improving ocean and atmosphere component models, and (b) to better understanding ocean-atmosphere coupling in coupled forecast models.

Mixed layer turbulence depends on wind stress and buoyancy fluxes (surface heat and freshwater fluxes).

Wind stress is the major forcing field for ocean current variability on intraseasonal to interannual time scales (reasonable accuracy).

Solar radiation is least accurately known heat flux component.

### 4) Observational efforts needed to improve ocean models

OGCMS will require improved data to identify (increasingly subtle) model problems.

Model problems can result from any of the following:

- a) Erroneous dynamics
  - missing physics
  - inappropriate parameterizations
  - lack of spatial/temporal resolution
- b) Forcing and boundary data
- c) Initialization data

Basin-scale issues:

- a) Continuity of satellite measurements is essential for climate modeling. Measurements should include SST, scatterometer winds, sea level, rainfall, insolation and ocean color (penetrative convection).
- b) Satellite missions for remote sensing of global surface salinity, 70 - 100 km spatial resolution, accuracy of 0.1 psu [buoyancy fluxes, barrier layer, salinity budget].
- c) ARGO floats [circulation, heat and freshwater storage].
- d) Representative high accuracy surface flux measurements.
- e) New climatology (hydrographic atlas) based on in-situ and remote sensing data for improved initialization?

Equatorial dynamics issues;

- a) MJO of 40- to 60-day period and tropical instability waves of 20- to 30-day period: provide benchmarks for model validation
- b) Extended TOGA Observing System:
  - Data from below thermocline (TAO array does not provide data at these depths)[N/S ACCs, reversing jets, TC/STC].
  - More salinity sensors deployed on platforms of the ENSO observing system, e.g., moorings and drifters.
  - Gliders to supplement TAO array.



- Deployments of surface flux (reference) stations in regions of equatorial subduction and upwelling.

Subtropics and western boundary current issues:

Improvement of parameterizations of mixing by deployment of surface and subsurface stations in regions and subtropical subduction (and upwelling).

WBCs: Pressure and temperature gauges at bottom for continuous monitoring of boundary currents (opposite coastal sea-level stations).

Surface forcing issues:

Improved and enhanced meteorological observations from moored buoys and vessels of opportunity.

Required accuracy:

- Net heat flux better than  $10 \text{ W m}^{-2}$ .
- Precipitation to better than 20%.
- 10% in wind stress for monthly mean fields.

All data:

- Temporal (spatial) resolution is as important as accuracy.

### 3.6 Atmospheric model development (Mitch Moncrieff)

Mitch Moncrieff gave an overview talk on atmospheric model development and how Pacific CLIVAR would interact with this activity. He summarized challenges in atmospheric modeling, discussed the path to model improvement, and offered guidance to and identification of challenges for CLIVAR Pacific observational efforts that would lead to model improvement and validation.

During the CLIVAR era, major model developments are anticipated, paced by improvements in computer architecture and in science. By 2015 global NWP models will have 10 km horizontal resolution. This will impact how parameterization is perceived, if not practiced. We need to anticipate this evolution and GEWEX and CLIVAR need to collaborate more effectively to accomplish this.

Different kinds of atmospheric models will be used: climate (century-long runs at low resolution of 300-400km), seasonal forecasting (ensemble approach, with 100 km resolution), cloud resolving models (CRM) (resolution 1 km, domains 1000's km), and large-eddy simulation (LES) (boundary layer, treating convection and boundary layer circulations explicitly so that convective parameterizations are not needed because the convection is resolved). All CRM and LES have nonhydrostatic cores. While CRMs are presently used for research, they will eventually replace traditional AGCMs.

Challenges facing AGCMs include: sub-grid scale parameterization (convection, boundary layer, radiation and clouds, surface exchange, gravity wave drag), physical initialisation including data assimilation, orography (e.g., sub-grid scale and resolved scale), and numerics (e.g., grid geometry, coordinate system, discretization, upper boundary condition). NWP models will need to consider governing equations in a nonhydrostatic formulation (e.g. elastic versus anelastic). Use of AGCMs to address climate will not be operational in the Pacific within 15 years unless the nonhydrostatic formulation proves to have a distinct computational benefit.

WGNE recently held a workshop at BMRC on systematic errors in models, and some of the conclusions are summarized here. Sub-grid scale variability may influence large-scale variability and mean error to a significant degree (requiring nonlocal and stochastic parameterisations). Examination of sensitivity at high frequency revealed non-physical behavior (e.g., ECMWF and NCEP reanalyses). Present treatment of clouds and radiation in models is a fundamental source of error. Parameterizations tend to be model dependent. Confidence in regional climate models is compromised by systematic errors in the global models that drive them.

When TOGA COARE was planned (late 1980's, early 1990's) atmospheric modelling was underway in two separate communities, the small and mesoscale (process) study investigators and those working on regional and global prediction. At the start of CLIVAR, these communities overlap. This has resulted because faster computers have led to higher resolution, longer integrations and larger domains and has been driven by the need to quantify the role of convection and cloud-radiation interaction in climate. This progress gives the prospect for advancing knowledge of how small and large scales interact, and thus leading to more accurate prediction.

In efforts to understand the physical processes responsible for climate variability, CRMs used in conjunction with observations will be a powerful tool for examining the basic aspects: boundary layers

(ocean and atmosphere), cloud-radiation interaction, convection, dynamical coupling among cloud systems (e.g., stratocumulus, deep convection and orographic effects), and ocean-atmosphere coupling at fine scales. To be pursued are answers to how convection, radiation, microphysics, boundary layer and surface processes collectively affect the large scales. This will require explicit numerical solutions, observational evaluation, and physically based parameterisations, with 1 km a crucial scale of coupling. Resolved convection will be compared to parameterisations, such as the Kain-Fritsch (K-F) parameterization used in models with 15 km grid. Strengths of K-F are the downdraft, CAPE-closure, prognostic liquid and ice microphysics at mesoscales. Deficiencies are associated with the single entraining plume model used in K-F.

Work has been done on the representation of cloud clusters in the Western Pacific super-clusters seen in TOGA COARE. Month-long CRM simulations were forced by observed SST and large-scale advection of temperature and moisture. The same forcing was used in the NCAR CCM3 single-column model (SCM). The CCM3 radiation scheme was used in both CRM AND SCM. It was found that distribution in time and altitude of condensates were very different in the different models which in turn significantly affects the radiative transfer (Wu and Moncrieff, 1999).

Atmospheric radiative heating was compared in COARE, using month long simulations, and contrasting ECMWF, observed radiation, CRM, and SCM. There was a significant spread of  $22 \text{ W m}^{-2}$ . The CRM values were within  $5 \text{ W m}^{-2}$  of observed. SCM radiation was too low because cloud condensate too small, as was the case for ECMWF. The surface energy budget was also compared. The CRM was accurate to about  $5 \text{ W m}^{-2}$ . Net flux results from the difference of large values (latent heat, shortwave), so the error in the difference can be large and compensating errors in shortwave and latent heat flux may be obscured in the net heat flux. Another focus for Pacific CLIVAR should be on ocean-atmosphere interaction at mesoscales, making use of the improved characterization of the surface fluxes and their spatial variability from CRMs. This will lead to fully-coupled ocean-atmosphere simulations, longer integrations, improved SCMs, and coupled 3-D simulations.

Tropical intraseasonal oscillations are one example of convection-wave interaction. Multiscale issues should be addressed by Pacific CLIVAR, as recently it has become practicable to simulate multiscale convection and tropical wave interactions (e.g., MJO, westerly wind bursts, superclusters). This is necessary because high-resolution global models have difficulty with convection organized on mesoscales because it is partly parameterized and partly explicitly treated, causing model error (Moncrieff and Klincker, 1997). Synoptic weather systems may also cause trouble (e.g., tropical easterly waves in the ITCZ).

Key issues:

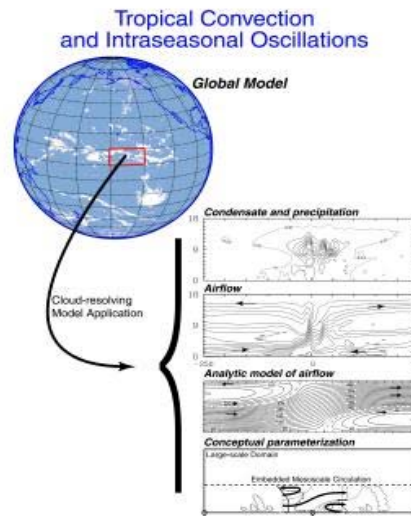
- 1) Climate models have difficulty in realizing transient motion in the tropics, even if the means state is reasonably correct, and even if the transients have a large enough scale to be resolved (in principle).
- 2) Because most tropical cloud systems are convectively driven, convective parameterization is a key issue.
- 3) While tropical convection is observed to be organized on mesoscales (1 km – 1000 km), the concept of organization is ignored in parameterization.
- 4) Cloud distribution is a fundamental uncertainty in radiative transfer.

Such issues must be understood if climate models are ever to be physically realistic.

CRMs do have some success with producing realistic convection. A 20,000 km, 40-day cloud-resolving simulation shows eastward-moving super-clusters, westward moving mesoscale convective systems, but does not get the correct propagation speed and amplitude of MJO. This is not possible yet with present convective parameterization methods.

## Archetypal MJO

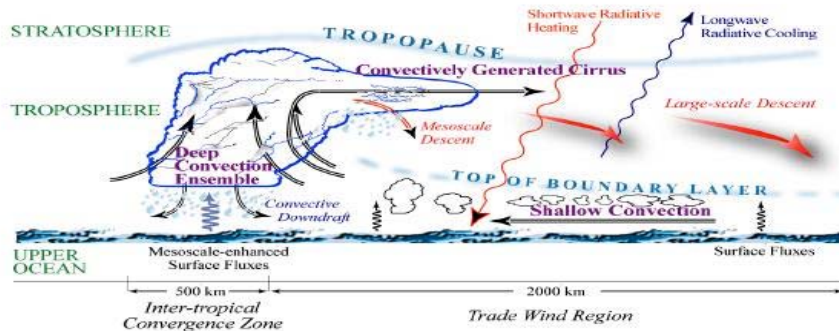
- **SST gradients not necessary for MJO, ppmodulate wave amplitude**
  - **West-moving organized mesoscale convective systems (MCS) are a key element**
  - **Momentum transport generates shear – a positive dynamic feedback**
  - **Convective downdrafts trigger convection, maintain MCS activity**
  - **Surface fluxes in dry region maintain convectively coupled Kelvin wave**
- (Grabowski & Moncrieff 2000)**



The next steps in MJO studies should include: three-dimensional CRM simulations, evaluation of CRM results against observations (analysis of TRMM and Cloud Sat data), ground-based observations, and derivation of physically based parameterisations, including of organized convection.

Another target for Pacific CLIVAR should be CRM simulations of the ITCZ, shallow convection and the upper-ocean complex in the eastern Pacific in conjunction with EPIC. The Hadley circulation and the ITCZ are central feature of the atmosphere in the Pacific. The Hadley circulation consists of deep precipitation convection as well as shallow convection and clear air in trade-wind regions. Thus, it is an example of coupling between primary cloud systems, both of which are parameterized separately in climate models. Simulation of this coupled system is explicitly tractable using modern computers. It is not yet, however, treated accurately in global prediction models.

## Cloud systems, atmosphere-ocean interaction and the Hadley circulation



Schematic of the ITCZ and Hadley circulation.

In general, the synergy between modelling and observation in CLIVAR Pacific will be extensive and string. The long-term monitoring and intensive observing periods (IOPs) of process studies will together provide data of unprecedented dynamic range. The combination of cloud-resolving models and new, higher resolution global NWP models with observations will provide a key resource, and new profiling satellites now being planned will fly.

One will look to the atmospheric modelling in Pacific CLIVAR to: bridge the gap between process studies and the large-scale modelling (CRMs and high-resolution NWP models), quantify effects of clouds on the surface energy balance, quantify mesoscale organization (scale-separation assumption in convective parameterization), and quantify the complexity needed in cloud-microphysical parameterisations (radiative aspect). By 2015 10 km resolution AGCMs will be available, and CLIVAR Pacific will face new issues, e.g., formulation of nonhydrostatic global models, consistent resolved and parameterised convection, and data assimilation at convective scales. Links to GEWEX have been implicit in this presentation, particularly with the GEWEX Cloud System Study (GCSS) on cloud resolving modelling, field experiments and parameterization development and with the GEWEX Radiation Project (GRP) on clouds and radiation, satellite analysis and modelling including CloudSat.

In summary, CLIVAR Pacific presents new opportunities for atmospheric model development, as unprecedented advances in computer architecture and speed and in remote sensing will pace the development of the next generation of atmospheric models. It is recommended that Pacific CLIVAR conduct the following studies involving multiscale modelling and observations:

- 1) Understanding the mechanisms that couple convection with tropical waves (i.e., MJO, westerly bursts). Do small scales hold the key? What are the implications for El Niño onset ?
- 2) Atmospheric and oceanic boundary layers explicitly coupled at convective scales.
- 3) Cloud-radiation interaction, effects of clouds and precipitation on the surface energy budget.
- 4) Dynamical coupling among distinct cloud systems (EPIC).

During Pacific CLIVAR the atmospheric component of coupled AGCMs should be improved, global NWP models which are now at 40 km resolution will improve to 15 km resolution, and cloud-resolving modelling on the Pacific basin scale will be feasible. There are measurement-related challenges: the large-scale advective forcing derived from sounding data (even during IOPs) is usually of inadequate accuracy, adequate evaluation data (broadband top of atmosphere fluxes and profiles of the three phases of water are needed, and the dynamical range of observational data needs to span 1 km through 10,000 km with an emphasis on integrated IOPs and satellite observations ever more important for CRM evaluations.

Additional studies during Pacific CLIVAR should address:

- 5) Physically based parameterisations of convection and clouds for climate models from validated CRMs.

- 6) Field experiments (SCSMEX II, EPIC, ...) for model evaluation, also extended observations (E.G., profilers).
- 7) Dynamic range of modern cloud-resolving models (1 km to 10,000 km and seconds to months) require new evaluation strategies (in-situ and remote sensing).
- 8) Prepare for 10 km resolution global NWP models by the end of CLIVAR era (explicit and parameterised convection).

To do this, linkages are needed. GEWEX has an interest in the high-frequency and CLIVAR in lower frequencies. Cloud-resolving modelling should be directly interconnected to observational studies. Satellite measurements (e.g., TRMM, CloudSat) need attendant field studies and modelling. Model development and observations in Pacific CLIVAR should be integrated with three foci: cloud resolving models with a Pacific basin model by the end of CLIVAR, physically based parameterisations, and field and satellite measurements. An integrated observational and modelling strategy will quantify the multiscale dynamical interactions among process in cloud systems and thus accelerate the improvement of weather and climate prediction models.

### ***3.7 Coupled model development (Bryant McAvaney)***

The talk went over: model components, present state of the art, what is needed, how model development should be attempted, computing issues, data issues, and diagnostics and visualization.

Coupled models include atmospheric, ocean, land surface, and sea ice modules and couplers. There have been a number of intercomparisons of coupled models, for example during the IPCC process, where model climatology is the basis for comparison and assessment of performance. One can also choose specific phenomena as the gauge of model performance: NAO, ENSO, MJO, Paleo-monsoon, monsoons. Extremes in model simulations can also be examined: rainfall, temperature, storms (extratropical and tropical). Periods of past climate can be examined: mid-Holocene, last glacial maximum, last millennium.

Initialization of coupled models.

Things that need to be addressed: marine stratus, heat fluxes over oceans, diurnal cycle, other.

Model design issues: regional versus global focus, horizontal and vertical resolution, suitability of numerics, exploration of model uncertainties, data handling.

Model development needs: comprehensive diagnostics, optimal experimental design, phenomena selection, closing the loop.

Model-model-data comparisons: These would be the benefits of such comparisons: standard experimental design, gross outliers, insufficiency of data, building confidence, incentive for model improvement, greater openness. However, it can be argued that the comparisons are unfocussed, add to the work load, fail to find 'reasons' for problems, fail to improve models directly, and have 'fixed' experimental design. Thus, when considering comparisons, they might be: process focused, have a global focus, require defined diagnostics, and be inclusive.

The WGCM CMIP 2+ initiative is to compare control and 1% increase in CO<sub>2</sub>, with high frequency output (daily) and diagnostic sub-projects. The CMIP3 Phase 1 program focuses on the climate of the 20th century. Start with 1850 (1700?), initialize with 'current control run', use standardized forcing (GHGs, solar, volcanic), monthly averages, high frequency during 'SOPs', diagnostic sub projects involving numerical experimentation. CMIP3 Phase 2 focuses on the climate of the past 1000 years. This is supported by the paleo community, is a 'grand challenge', and offers a look at the internal variability of the coupled models.

Computing issues: module architecture (algorithms, domain decomposition), resolution, length, ensembles, distributed computing.

Analysis and visualization: analysis environment (data search and query, local versus remote), analysis tools (local versus remote processing), visualization tools.

Data storage: local versus geographically distributed, web accessible issues.

Where do we go from here: MIPS (relevance), data issues, process issues, computing issues.

### ***3.8 Ocean process studies (Russ Davis)***

A process study is defined to be a field program in a localized region employing special instrumentation for a finite duration to examine a specific set of processes. For Pacific CLIVAR priority is placed on processes that are: (1) important to understanding or modeling climate phenomena, (2) inadequately parameterized or treated in models, (3) general enough that results from one region can be applied elsewhere or (1) important to interpreting sustained observations, (2) are not well enough known to

adequately use these observations, (3) general enough that results from one region can be applied elsewhere or provide quantitative description of rates and mechanisms and have impact on models.

Kuroshio Extension System Study (KESS)

Climate problem:

Impact of Latif-Barnett type mid-latitude feedback between SST, wind stress and ocean transport on variability like the Pacific Decadal Oscillation.

General Processes:

The role of the Kuroshio Extension and Kuroshio Recirculation on mid-latitude air-sea interaction. How changes in these regions impact SST.

Specific processes:

- Mixed layer evolution in the mode water in the recirculation
- Impact of surface buoyancy flux on the dynamics of the recirculation and extension
- Role of recirculating mode water in sequestering anomalous waters from year to year
- Role of mean and eddies in variations of SST
- Role of cross-stream eddy transport of potential vorticity on the recirculation
- Mechanisms and magnitudes of cross-frontal transport of PV, heat and salt

General approach:

Joint U.S. and Japan planning and implementation. Accurate mapping of T, S, u in  $10^\circ \times 20^\circ$  region of extension and recirculation analyzed inside data-fitting models and data-assimilation models and interpreted with the assistance of process modeling.

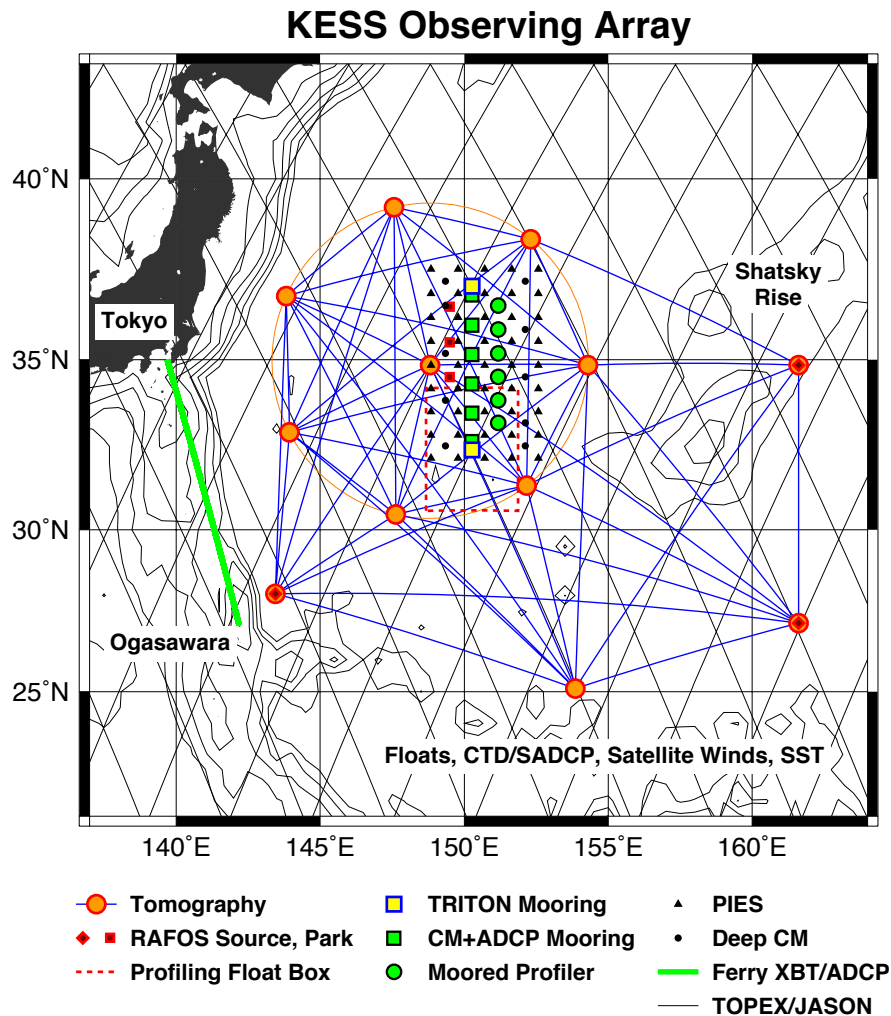


Figure 10: Proposed US-Japan observing array. Key at base of diagram indicates the suite of instrumentation. Straight black lines indicate T/P ground tracks, blue lines indicate tomographic ray paths, and the green line indicates the TOPEX Ogasawara ferry route. Profiling T,S floats will be deployed within the region outlined by the red dashed line. CTD/SADCP stations and ship tracks are not included in the diagram. Satellite winds and SST will be obtained for the entire region. The “high-resolution array” is the set of PIES, CM + ADCP, DCM and MP moorings. The “regional array” is the set of tomographic moorings.

C-10

#### KESS Method and Status:

- Satellite altimetry and SST – heat storage, shallow advection – US & J
  - TRITON moorings and CNEP analyses -surface fluxes – J
  - T, S profiling floats – heat and freshwater storage, mixed-layer evolution – US
  - Ocean tomography – heat storage in recirculation, absolute velocities – J&US
  - Pressure and Inverted echo sounders – eddy fluctuations – US
  - Moored profilers – T, S, and u profiles – storage, advection eddies – US
  - Current meter moorings – details of currents from Eulerian perspective – US
  - RAFOS floats – details of flow from Lagrangian perspective – US
  - ADCP & XBT repeat sections – Ferry over Izu Ridge – J
  - Ships with CTD and ADCP – 3 broad-scale surveys – US & J
  - Data assimilation models – Quasi-geostrophic and sigma-coordinate – J& US
- Timing:

Planned for a 2-year duration; next chance is 2003. Note: US CLIVAR has recommended combining KESS plans with additional program (including moorings) to measure air-sea fluxes associated with SST variability.

## EPIC

Climate problem:

Ocean-atmosphere processes in eastern Pacific and their affect on climate, climate variability, and models of climate in this region.

General processes:

Ocean-atmosphere processes responsible for structure and evolution of heating gradients in the eastern Pacific cold tongue and Inter-Tropical Convergence Zone (ITCZ).

Dynamical, radiative and microphysical processes in boundary layer clouds in southeasterly trades and cross-equatorial flow regimes.

Specific foci (Ocean):

- Mechanisms governing the temperature and salinity evolution across the oceanic cold tongue and ITCZ.
- Maintenance of oceanic cold tongue, eastern Pacific warm pool, and fronts in between including the role of advection, mixing, upwelling in the oceanic heat budget.
- Role of SST and ocean heat budget in modulating tropical winds.
- Role of air-sea fluxes in maintenance and modulation of stratus clouds.
- Dynamics of annual cycle of coupled ocean-atmosphere system and reasons for its large-scale variability.
- Parameterization of oceanic mixing in climate models
- The observations needed to initialize and validate coupled models for prediction of seasonal-to-interannual variability
- Impact of coastally trapped disturbances on continental weather

General approach (ocean):

- Monitoring of surface and upper ocean conditions with moorings
- Two intensive ocean field campaigns imbedded in atmospheric studies

Method and present status:

- 7 enhanced and 3 new TAO moorings with upgraded surface observations on 95°W from 8°S to 12°N (2000-2003).
- 1 IMET mooring with surface and upper ocean observations at 20°S, 85°W (2000-2003).

## Phase I (U.S., April–May 2001)

Surface and upper-ocean sections from VOS

50 x 50 km intensive ocean survey aimed at upper ocean heat budget near 8°N, 95°W

Seasoar – high resolution structures especially at fronts

Shipboard ADCP – advection and inferred upwelling

Turbulent mixing – diapycnal eddy fluxes and entrainment

High resolution physical/optical property profiles – advection, radiation

Ship and moored-buoy surface observations – air-sea fluxes

## Phase II (U.S., 2003)

Twice per year research-cruises with ocean profiling, surface fluxes, and possibly mixing measurements to observe seasonal/interannual changes in structure and process during 2001–2004.

Possible additional 50 x 50 km surveys to define dominant process in heat

Budget

Potential additions aimed at equatorial upwelling,

Near-equatorial mixing,

Contribution of coastal upwelled water to cold tongue,

Role of air-sea exchange in cold tongue,

Processes that set thermocline depth

## VAMOS EPIC

Peru-Chile Undercurrent - structure, mixing, carbon-nitrogen cycling (France, Chile)

Pacific Basin Extended Climate Study (PBECS)

General Problem:

Develop quantitative description of the large-scale process governing climate variability.



Specific foci:

- PDO and other decadal variability
- ENSO and ENSO decadal modulation

General method:

- Sustained (15 year) observations to develop picture of basin-scale evolving climate state.
- Data assimilative modeling to quantify processes and test hypotheses.

Components of PBECS:

- Air-sea fluxes (momentum, heat, water)
  - Satellite winds and radiation
  - Reference surface observations (wind, T, humidity, radiation)
  - Numerical weather prediction type assimilation
  - Ocean assimilation testing/correction
- Basin-scale storage and flow
  - Altimetry
  - ARGO

Repeat hydrography (decadal)

- Lateral transport
  - High-resolution XBT/CTD, Repeat hydrography (decadal)
- Equator – small y scale, short time scale
  - ENSO observing system including TAO
  - More TAO velocity for meridional flow
- Western boundary currents - ocean teleconnections
  - Mindanao
  - New Guinea CC/UC
  - Kuroshio
  - East Australian
- Eastern boundaries - areas of important variability
  - Methods??
    - Current meters, tomography, glider, repeat hydrography
- Conventional process experiments
  - Sub-basin-scale

Experiments suggested by PBECS:

Focus: shallow (<1000 m) meridional overturning that links subtropics and equator

- Diapycnal fluxes in the daily cycle below the equatorial mixed layer
  - Diapycnal fluxes are critical to maintenance of equatorial SST
  - Diapycnal fluxes produced by stratified turbulence below the equatorial surface layer must be parameterized for use in climate models

No satisfactory parameterization exists and even the mechanisms are not agreed upon

Daily cycle, mean shear and internal waves are essential elements to mixing

Further coordinated experiments and synthesis of equatorial mixing is needed

- Understanding and parameterizing diapycnal mixing at low latitude
  - Diapycnal fluxes central to overturning circulation and upper ocean heat budget
  - Climate models do not now include accurate estimates of  $K_p$
  - Sources of sub-mixing
    - internal waves
    - salt fingering
    - thermohaline intrusions

Midlatitude mixing can be estimated from internal wave properties

Internal wave properties should be mapped by CLIVAR

Relation of low-latitude mixing and internal waves should be determined

Low-latitude importance of internal waves should be determined by comparing tracer release mixing to internal wave parameterizations

Thermohaline intrusions may also be a main source of diapycnal mixing. This needs to be evaluated and perhaps parameterized.

- Generation of subducted temperature-salinity anomalies
  - Subducted T-S anomalies are potentially an important tropical-subtropical connection
  - Properties are set in the mixed layer and potentially transmitted along neutral surface
  - Experiment is needed to determine how T-S anomalies are created and modified
- Process of subtropical-tropical exchange
  - The transmission of subducted spiciness and/or potential vorticity (PV) anomalies from the subtropics to equator is central to some models of decadal ENSO modulation
  - Passage from North Equatorial Current to North Equatorial Counter Current is key
  - Quantification of mixing along path is needed
- North equatorial current bifurcation study
  - Bifurcation of the North Equatorial Current near the Philippines is critical juncture in path of anomalies from subtropics to equator where they can affect ENSO and to the Kuroshio where they may affect the Pacific Decadal Oscillation
  - Dynamics of the western boundary current are complex and poorly treated in models
  - Bifurcation is potentially sensitive to atmospheric forcing and remote subtropical influences, building in new feedbacks
  - A process experiment is needed to begin understanding causes of change in the process and for the design of a long-term measurement plan
- Equatorial upwelling and emergence of subtropical anomalies
  - Equatorial upwelling is the choke point of meridional overturning where water subducted in subtropics emerges and strongly affects the atmosphere
  - The vertical transport and source of upwelling are central to predicting impact
  - Models do not handle upwelling or maintenance of the equatorial thermocline well
  - It is not feasible to directly measure vertical velocities for sustained periods so monitoring ultimately depends on models constrained by diverse data types
  - A process study is needed to develop and test ways of observing large-scale upwelling and to examine the processes by which it affects equatorial SST
  - This experiment must account for processes that affect equatorial SST anomalies:
    - anomalous spiciness that can make temperature a passive tracer
    - uncompensated anomalous temperature that also affects density and flow
    - anomalous advection that generates SST anomalies
- Vertical structure of horizontal currents
  - Upper ocean circulation is key in determining the SST that affects the atmosphere
  - Ageostrophic transport is significant in upper ocean heat budgets
  - Observed transport extends deeper than the mixed layers in which models confine it
  - An experiment examining the horizontal momentum, heat, and salt budgets of the upper ocean is needed to unravel the mixing processes below the mixed layer and understand the full structure of the upper ocean
- A field program to study mixed layer and thermocline processes that cause surface waters to be subducted into the thermocline. Regionally, this study should take place of the stratus deck region of the Northeast or Southeast Pacific and address coupled ocean-atmosphere interactions involved in production of subducted water masses.
- A field program to determine rates, source waters, and dynamical controls on equatorial upwelling. A similar experiment for coastal upwelling would be desirable.
- A field program to study the bifurcation of the North Equatorial Current and its time-varying contribution to the Kuroshio and Mindanao Currents. Connectivity of the Indonesian Throughflow to these currents should be addressed as well.
- A field program to study the termination of major zonal currents in the thermocline along the eastern boundary, and the fate of water masses in those currents. This study should include an investigation of the equatorial 13°C water and its relation to the Tsuchiya Jets.

### 3.9 Atmospheric process studies (Chris Bretherton)

There is a need in Pacific CLIVAR to do process studies. The reasons are that:

- Many deficiencies of coupled models can be traced to shortcomings in their simulation of atmospheric processes and circulation, particularly in the tropics.
- These same problems seriously affect atmospheric reanalyses, especially over the tropics.
- They affect the ability of coupled models to simulate climate variability/change from the seasonal scale on up.
- Particularly serious simulation issues include boundary layer cloud and its radiative effects, space-time distribution of deep tropical convection, cloud radiative forcing in regions of deep convection, aerosols, and land-surface interaction.
- These issues have been studied for some time; further progress will require a blend of diagnostics analysis of observations and models, and new process studies. Pacific CLIVAR needs to foster all of these.

Examples of problems. In NCAR CCM, insufficient stratocumulus and too bright shallow cu. There is complex spatial distribution of cloud everywhere. Plus there is high temporal variability (weather) that sets climate. Getting cloud top boundary layer forcing processes correct is another challenge. Large differences of precipitation noted in MIPs; specific issues include topographic effects and impact of tropical convection on global atmosphere. Getting tropical deep convection right is a major challenge with the following associated issues: (1) monsoons; land surface feedbacks, (2) Madden-Julian oscillation and time-space variability, (3) mesoscale organization, (4) downdrafts and surface fluxes, (5) ice-phase microphysics, (6) cloud population/vertical distribution (feedbacks with lower troposphere relative humidity and shear), (7) cloud-radiation interaction, (8) vertical momentum transport, (8) upper troposphere humidity. Planned process studies:

#### EPIC 2001

Sept -Oct 2001, based along 95°W

Combines ship-based and aircraft observations

Atmospheric science goals:

- Initiation of deep convection in the E. Pacific warm pool, and its association with easterly waves.
- Interaction of convection, synoptic scale dynamical forcing and lower tropospheric humidity field
- Boundary layer evolution in cross-equatorial flow across cold tongue
- Surface wind stress, the vertical structure of the PBL, and clouds
- Exploratory SE Pacific stratus cruise
- Relate changes in cloud morphology/thickness to underlying sea-surface fluxes, precipitation processes, aerosol, entrainment. Is cloud basically controlled by entrainment drying, or is precipitation often important.

#### DYCOMS-II

July 2001, off Baja California

Accurate aircraft measurements of entrainment rate into nocturnal stratocumulus clouds and its relation to turbulent eddy structure within the boundary layer.

#### Possible future process studies

- VEPIC - interaction of Pacific circulation and low cloud with S. American deep convection.
- A joint effort of US CLIVAR and VAMOS, in planning stages.
- Science focus: Interaction between deep convection over S. America and circulation/low cloud over the Pacific on synoptic to interannual time scales; is that interaction important?; is it two way?; are these components adequately simulated by models?
- Methodology
- Preliminary diagnostic and modeling studies over the ocean
- New sustained observational components over the ocean
  - Buoy array off the west coast of South America
  - IMET buoy at 20°S, 85°W
  - Ceilometer at San Felix Is.
  - Chilean cruises to Easter Is.

- Pilot experiments, possibly followed by an international field experiment off Peru/Chile around 2005
  - Kuroshio extension and midlatitude low cloud feedbacks
- Work by Norris et al (1998) suggests large covariability of SST and low cloud in this area.
- Science issue: What is the corresponding surface radiative flux change? Is it simulated by AGCMs?

Does it contribute significantly to interannual persistence of SST anomalies in this region?

Methodology: Flux buoy, satellite and reanalysis data, possible aircraft profiles

Timing: both winter and summer scenarios of interest

- Deep convective cloud radiative forcing study
- Tropical convective cloud radiative forcing in both shortwave and longwave is large, though they largely cancel in current climate.
- Satellite observations do not completely tell us the height distribution of this forcing, since cirrus anvils block lower clouds. The height distribution of cloud radiative forcing is both a useful constraint on models, and may be a part of climate change.
- Upcoming satellites (CLOUDS/PICASSO) may give us some ability to see through upper tropospheric cirrus anvils.
- Simultaneous aircraft observations of radiative fluxes at multiple levels would complement the satellite information, might also constrain the still unsettled 'anomalous absorption' debate, thus would be a better version of CEPEX
- Trade cumulus study
- Trade cumulus are ubiquitous over the tropical Pacific.
- They moisten the lowest 1.5 km of the atmosphere, invigorating the Hadley circulation.
- However, they are a challenge to current AGCMs because of:
  - lateral entrainment and detrainment processes averaged over cloud lifecycle
    - role of precipitation in updrafts
    - mixing processes at cloud tops
    - momentum and radiative fluxes
- Most cumulus parameterizations represent trade cumulus quite poorly. Many GCMs underestimate trade cumulus activity, leading to a dry bias at 850 mb (the trade inversion). Large-eddy simulations seem to do much better.
- Strategy: Use two mm-wavelength Doppler radars combined with aircraft penetrations to compare trade cumulus cloud statistics of cloud fraction, turbulent moments, reflectivity-derived precipitation etc. to large-eddy simulations
- Continuing diagnostic work (models, reanalyses, observations) on the sensitivity of the midlatitude and subtropical circulation to midlatitude vs. tropical SST anomalies of large geographic extent
- Tropical deep convection
- Surface fluxes

Conclusions:

- CLIVAR should support a balanced program of diagnostic studies of observations and models, refinement of model parameterizations, and new process studies
- Particular foci should be deep convection and boundary layer clouds
- Land-ocean interaction is clearly also a particular problem for GCMs
- A few process studies have been suggested, but as focus studies need to be dictated by focussed, current, and inspiring scientific questions, more will emerge as CLIVAR progresses

### **3.10 Atmospheric data assimilation (Michael Ghil)**

This overview talk on atmospheric data assimilation (see <http://www.atmos.ucla.edu/tcd> for references and colleagues) began with a review of data availability, looked at the beginnings of data assimilation and numerical weather prediction, reviewed basic ideas about combining data and models, then looked at advanced ideas, and finally provided some conclusions.

The motivation for why you would assimilate data: because you have incomplete and inaccurate data, imperfect models, greater computer power or novel observing systems. Then examples of the type of atmospheric data that are available and the coverage of each were shown. Satellites, radiosondes, ships, buoys, and aircraft were pointed to as sources of atmospheric data. The distribution of data availability in time and space was discussed.

Estimation methods were reviewed: filtering, smoothing, and prediction. The main issues to be dealt with include: (1) The fluid atmosphere has temporal as well as spatial variability. (2) There are two types of information, direct (from observations) and indirect (inferred using dynamics determined from past observations; both have uncertainties. (3) The two need to be combined in an optimal manner. (4) Advanced data assimilation methods provide such means using sequential estimation (the Kalman filter) and control theory (the adjoint method). (5) The two types of methods are essentially equivalent for simple linear systems (the duality principle). (6) Their performance differs from large nonlinear systems in accuracy and computational efficiency. (7) Study optimal combination(s), as well as improvements to currently operational methods (OI, 4-D Var, PSAS). Examples of data assimilation and sequential estimation were presented and illustrated with a barotropic model.

Computational advances that have helped include; hardware (CPU, memory), software (better algorithms, automatic adjoints).

What is the mix of assimilation and forecasting? Design integrated forecast-assimilation systems.

Observing system design: (a) need to be more (independent) observations than degrees of freedom to be tracked. Data assimilation should be included in observing system design experiments. (b) all observations should be brought in, including satellite images and 4-D data sets.

Parameter estimation discussion.

Conclusion: No observing system without data assimilation and no assimilation without dynamics.

### **3.11 Ocean data assimilation (Detlef Stammer)**

An overview of motivation, approaches, examples, applications, anticipated results, and problems.

Motivation:

- The ocean circulation shows vigorous variability which poses serious problems in observing it.
- Much emphasis needs to be placed therefore on numerical models in simulating and understanding the ocean and in interpreting diverse data sets.
- However, both show substantial uncertainties.
- Combining ocean data sets with ocean models (data assimilation) in a rigorous way is intended to produce the best possible and dynamically consistent estimate of the time-varying ocean circulation.
- Uncertainties of both the data and the model need to be specified a priori.
- Uncertainties of results need to be provided.

Applications:

- Estimates of major ocean transport pathways.
- Heat and freshwater flux divergences.
- Similar for tracer and oxygen, silica, and nitrate.
- Locations and rate of ventilation, mixing, convection.
- Dynamics of ocean response to atmospheric variability.
- Design efficient and cost-effective climate observing systems.
- Improve estimates of gravity field.
- Initialisations of climate models.

Approaches:

- 1) Empirical methods such as Optimal Interpolation and 'nudging'. They especially involve heat sources and sinks within the ocean interior that would render analyses of ocean heat transport difficult.
- 2) Rigorous methods solve the estimation problem in a dynamically and statistically consistent way. They include the Kalman Filter-Smoother and the adjoint method, both of which are computationally demanding.

Elements of ocean state estimation:

- Model-data comparison
- Prior data and model error evaluation
- The estimation procedure
- A-posteriori evaluation of results
- Oceanographic applications

The effort at SIO, MIR, JPL was discussed. This is the NOPP-funded consortium for Estimating the Circulation and Climate of the Oceans (ECCO) whose goals are to bring ocean state estimation from its current experimental status to a quasi-operational tool and to study large-scale ocean dynamics, design observing strategies, and examine the oceans role in climate. Technical goals are global ocean estimation

over 15+ years with  $1/4^\circ$  horizontal resolution and regional eddy-resolving experiments embedded in global runs with combination of all available data. This work will support WOCE-AIMS, CLIVAR, and GODAE.

#### Models:

- 1) The forward model  
2° resolution, 23 level  
+/- 80° latitude range  
start from Levitus T, S fields  
Daily NCEP surface momentum, heat and freshwater forcing  
Implicit free surface
- 2) The adjoint model  
Obtained from the Tangent-linear and Adjoint Model Compiler (TAMC)  
Flexible to changes in forward model and cost function  
Adjoint component requires about 2 times the CPU of the forward
- 3) Next step  
1° resolution  
KPP mixed layer model  
GM parameterisation

Discussion of results so far. Data used include altimetry, scatterometry, SST, PALACE, TAO array, XBTs, hydrography, surface drifters, tomography, and moorings. ECCO's strawman list of products:

- Monthly mean model state (u, v, w, T, S, density, ps) over full water column.
- Associated surface fluxes of momentum (wind stress), heat and freshwater, which have been adjusted during the assimilation procedure and are consistent with the estimated ocean state.
- Time series of the full model state at specific positions (e. g. time series stations) with daily resolution.
- Likewise with daily resolution: estimates of horizontal transports of mass, heat and freshwater across nominal zonal and meridional lines.
- Meridional overturning stream function with daily resolution
- Simulated float trajectories and profiles as they will follow from an ARGO float network.
- SSH and bottom pressure fields with daily resolution.
- Mixed layer depth and vertical viscosity and diffusivity fields on a monthly basis.

ECCO will be working on: (1) 1° global WOCE synthesis with KPP, GM, eddy coeff., all WOCE data. (2)  $1/4^\circ$  global 85 to present estimation. (3) 1° global over past 50 years. (4) Embedded high-res approaches in the Pacific and Atlantic. For the CORC (Consortium on the Oceans Role in Climate) assimilation the work will be on: (1) Region model and its adjoint set up in the tropical Pacific over +/- 20° latitude, (2) boundaries implemented as open, (3) synthesis of TAO, altimeter, scatterometer, ARGO and CORC data into dynamically consistent analysis by optimising the model initial and boundary conditions to fit the observations, (4) dynamical balances for surface currents near the equator, especially what determines SST and upper ocean heat and salt variability in the Indo-Pacific area, (5) Parameterisation of instability wave mixing for coarser-resolution models, (6) Estimation of diffusion, viscosity, (7) how do we optimally combine altimeter and in situ data in this area? Where do we need measurements? (8) Error covariance functions in this region? Model systematic errors.

IPRC activities: (1) a steady-state inversion of the North Pacific circulation (3D var assimilation of surface flux data, drifters, WOCE climatology and T/P altimetry into large scale geostrophic model), (2) 4d var assimilation of a seasonal cycle in the North-western Pacific into a GCM with KPP parameterisation of the upper mixed layer (same types of data), (3) 4d var assimilation of the acoustic tomography and T/P altimetry into an ocean-ocean QG model (Kuroshio Pilot Study experiment); 4d synthesis of the tomography, altimetry and in situ data (CTDs, ADCPs) is now underway, (4) Going to develop a version of a SEEK filter to assimilate surface and in situ data into POM + continue 4d var research in the regions of the Kuroshio extension and North/Subtropical Pacific.

#### Summary:

- Models show (in certain aspects) a surprising degree of realism
- Present results demonstrate that global ocean state estimation has become feasible as a tool to synthesize diverse ocean data sets

- We don't see a fundamental obstacle for an elaborate in-situ and remote sensing data synthesis for both near-real time applications and climate-oriented reanalysis projects.

However:

- We are just at the beginning and MANY improvements of the model and the statistical assumptions are necessary to approach a useful result.
- Computer resources are an issue similar to their importance in atmospheric analyses and re-analyses activities.

Problems:

1. Theory: bias in data, models
2. Estimation of solution errors
3. Estimation of data and model errors
4. Model improvements and adjoint model developments
5. Data distributions: sensitivity studies

#### 4. Working Groups

The plenary talks were used as a jumping off point for further discussion by working groups. The charge to these working groups was to:

- Based on Pacific CLIVAR science objectives, identify what is needed in an implementation plan to meet these objectives.
- Take the plenary talks and their recommendations as a starting point.
- Identify missing elements and point to:
  - Recommended national contributions
  - Critical issues
  - Items requiring action
- Develop timelines
  - Consider priority, readiness, and international links
- Discuss evolution and evaluation of Pacific activities in light of
  - New Techniques
  - Value and impact
  - Intercalibration and operational coordination
- Data
  - What exists, is it available
  - CLIVAR action needed?
- Activities now underway
  - Provide information to ICPO (K. Bouton) and post summaries and inventories to Pacific website
- Draft
  - Recommendations
  - Lists of national contacts
  - Time lines

##### ***4.1 BROADSCALE OCEAN - CHAIRED AND SUMMARIZED BY JOHN GOULD AND GREG JOHNSON***

The group heard input from:

- Yoshifumi Kuroda on Japanese plans for the Triton buoy array and for Argo floats
- Andreas Schiller concerning Australian plans for maintaining XBT and CTD sections
- Bernie Kilonsky concerning the availability of sea level data in very near real time
- Peter Niller on the ways in which drifter data sets might be improved.

The conclusions of the WG were as follows:

##### **Moored arrays.**

COOP and OOPC will jointly review the TAO Triton array during 2001 with the aim of optimizing array design within a fixed budget.

The WG concluded that the measurement of salinity in the TAO/Triton array had the potential for delivering improved dynamical information. As well as observations from the moorings, thermosalinographs on VOS

were a likely source of surface information but the WG understood that while France was continuing with this activity, the USA had abandoned it through cost considerations.

A satellite salinity mission is proposed for launch in 2006 and would have the potential for new information although resolution and accuracy may be problematical in much of the open ocean.

There appeared to be no plans for extra-tropical extensions (as called for by Pirata in the ATLANTIC) except for flux reference sites and the OSEPA/VEPIC sites in The Eastern Pacific and for any moored sites that might be called for or currently in place as part of process studies (although these would not be "sustained").

#### **Profiling floats**

The WG was concerned that resource limitations would presently not allow both the N and S Pacific to achieve 3° resolution coverage in the foreseeable future. The Argo Science team should work through CLIVAR panels and working groups to make the scientific case for the resources to achieve global Coverage.

#### **Drifters**

It was the view of the WG that CLIVAR should work through the DBCP to promote the need for drifter measurements of surface velocities and near surface properties (T/S) and SLP. An immediate issue was the attempt to form an N Pacific drifter consortium. (ask Niiler to write draft)

#### **XBT**

High-density lines (identified in the Upper Ocean Thermal review) have strong support in their own right and as a complement to Argo (especially as a means of measuring near-boundary regimes). The WG saw a need for resources to be found to support the "Tasman Box" observations.

The WG was concerned that the broadcast mode XBTs were declining before Argo would replace them.

#### **Satellites**

Satellite coverage should not be taken for granted; of particular concern and need for Pacific CLIVAR are: altimetry (Geoid), surface winds, SST, ocean color (in its own right and as a means, with SST, of getting upper ocean heat absorption).

#### **Hydrography**

The group was encouraged by evidence presented in plenary by Dean Roemmich that a basic grid of Pacific Hydro sections was likely to be occupied in the near future and also heard on plans by Australia and NZ in the SW Pacific.

CLIVAR needs to work with the Carbon community to develop a combined observational strategy with appropriate temporal/spatial resolution AND immediately to ensure carbon measurements of CLIVAR cruises e.g. 32°S in Indian. The group did not discuss tracer observations due to lack of expertise represented there. It was noted that CO2 budgets need (1) storage (2) air-sea flux and (3) ocean transport estimates.

#### **Sea level**

Real time (1hr delay) data are now possible. Is there a CLIVAR need?

#### **Boundary currents**

The WG did not discuss Boundary currents in detail but there is a need for the CLIVAR Pacific panel to identify key locations and methods. The group was informed of the 6-year time series N of PNG and was concerned that this might terminate due to a relocation of the two buoys.

There is a need to identify key locations and the appropriate observational techniques to monitor boundary currents (and recirculation regimes). This should coordinated with the identification of contacts in relevant countries.

#### **Acoustic thermometry**

A source will remain for the next 5 years and CLIVAR should evaluate these integral measurements.

### ***4.2 BROADSCALE ATMOSPHERE - chaired by Dick Johnson and Jose Rutllant, summary contributed by Dick Johnson, Jose Rutllant, Chris Bretherton, Rit Carbone, George Kiladis, Bryant McAvaney, Mitch Moncrieff, Sumant Nigam***

#### **Background**

A sustained (15-yr), broadscale atmospheric observing system is essential to achieve the following objectives of Pacific CLIVAR:

- The dynamics and predictability of ENSO
- Coupling of the ocean-atmosphere system on seasonal to interannual time scales
- Decadal variability of El-Nino Southern Oscillation (ENSO)



- Decadal variability in the North Pacific (Pacific Decadal Oscillation or PDO)
- Processes that govern the heat storage, vertical and horizontal mixing in the upper 1500 m of the Pacific and its coupling to the overlying atmosphere
- Improved parameterization of physics within atmospheric general circulation models (AGCMs)
- Improved coupled ocean-atmosphere models.

These goals depend crucially on the availability of quality atmospheric observations for data assimilation and modeling. Implementation of new observing systems, and maintenance and enhancement of existing atmospheric observations in the Pacific are proposed to address these scientific issues. One focus of CLIVAR Pacific is on decadal or multi-decadal oscillations pertaining to ocean and atmosphere circulations in the North Pacific and ENSO. Several hypotheses have been advanced for decadal variability of these phenomena, but as of yet there is no consensus on the relevant processes. However, in virtually all theories it is argued that decadal variability involves coupling between the ocean and the atmosphere in the tropics, subtropics and midlatitudes. Therefore, broadscale atmospheric sampling is essential to document, monitor, and ultimately understand decadal variability. Other important scientific issues involve variability and predictability of ENSO, and climate change in the Pacific Basin (which may be manifested as long-term variations in rainfall, water vapor, stratocumulus clouds, etc.). Atmospheric processes relevant to CLIVAR Pacific are: atmospheric convection; precipitation; air-sea fluxes of heat, momentum, and moisture; cloud radiative forcing; boundary-layer clouds and radiation; and atmospheric circulation and transport.

Optimum sampling strategies for the range of scientific issues for CLIVAR Pacific require consideration of existing theories and conceptual models. However, also needed are: (1) input derived from process studies (e.g., EPIC, KESS, NAME), and (2) Observing System Simulation Experiments (OSSEs). An initial broadscale observing plan should be established now, but it will be refined based on findings from both process studies and OSSEs.

*The following sustained, broadscale atmospheric observing network for the Pacific is proposed:*

Initial broadscale atmospheric network (existing technologies)

Atmospheric Rawinsonde Network

- Sounding sites in the Pacific region within the World Weather Watch Global Observing System, including the entire GCOS Upper-Air Network (GUAN) in the Pacific Region with 1/day launch frequency (see Action Item below regarding GCOS network). Owing to the scarcity of soundings in the eastern Pacific, special emphasis is given to restoring soundings at Galapagos and Easter Islands to 1/day frequency.
- An additional sounding site with 1/day launches at Midway Island (28N, 177W)

Surface Observations

- Surface observing stations of the World Weather Watch Global Observing System including GCOS Surface Observing Network in the Pacific Region (see Action Item below regarding GCOS network).
- TAO-TRITON Array (SST, temperature, relative humidity, precipitation, pressure, radiation). Measurement technologies for some of these fields (e.g., pressure, precipitation, radiation) are still under development by NOAA PMEL - CLIVAR Pacific strongly endorses this activity.
- Surface observations by VOS, XBT lines

Atmospheric Profilers

- Continued operation of NOAA's Trans-Pacific Profiler Network (from Biak in the west to Piura, Peru in the east)
- 915 MHz wind profiler at San Felix Island (27S 80W) [will support VEPIC, but also needed for long-term monitoring of climatologically significant stratocumulus regime]

Surface Flux Instrumentation

- Pacific moored surface flux reference site array
- Observations sufficient to obtain bulk fluxes from VOS and XBT lines
- TAO-TRITON Array

Satellite Observations

- Scatterometer surface winds, temperature, water vapor profiles, precipitation, cloud distributions and properties, integrated water vapor, cloud-drift winds, aerosols

#### Backscatter lidars

- Measurements of aerosols (Christmas Island, Nauru, Manus)

#### Aircraft Observations

- Commercial aircraft reports, PIREPs

#### Enhanced broadscale atmospheric network (emerging technologies)

##### Driftsondes (dropsondes launched from high-altitude balloons)

- Assess feasibility and cost-effectiveness of driftsonde technology to fill gaps in Pacific atmospheric sounding network based on THORPEX Atlantic pilot in 2003 and Pacific THORPEX in 2005. Conduct OSEs related to driftsonde technology for the Pacific (NASA DAO and/or NRL)

##### Aerosondes (lower-tropospheric remotely piloted aircraft)

- Assess feasibility and cost-effectiveness of aerosonde technology for boundary-layer and lower-tropospheric measurements of thermodynamics and wind based on 2001 EPIC

##### Rocket Soundings

- Assess feasibility and cost-effectiveness of autonomous rocket soundings from VOS

##### Moored Wind Profiler

- Assess feasibility and cost of moored 915-MHz wind profiler at 0N 125°W to fill gap in TPPN in eastern Pacific

#### Action items

- Work with GCOS community to ensure implementation of GCOS upper-air (1/day frequency) and surface networks in the Pacific. Task CLIVAR Pacific Panel to establish linkages with appropriate groups to see that implementation is successful.
- Establish Midway Island sounding site (estimated cost \$70-100K per year)
- Initiate a program of Observing System Simulation Experiments (OSSEs) to refine and optimize the broadscale atmospheric observing network. OSSEs should be directed toward seasonal-to-interannual variability of ENSO and decadal variability throughout the Pacific, with particular attention to optimizing observational strategies for the free troposphere, boundary layer, and surface fluxes.
- Work with Pacific countries, operational forecast centers, and the WMO to ensure that all GCOS observations, as well as all other sounding and surface observations in the Pacific region, are available in real time on the GTS for assimilation into operational models. Task CLIVAR Pacific Panel to see that this action is accomplished.
- Assess feasibility and cost-effectiveness of emerging technologies listed above, as well as other new technologies, for sustained, large-scale atmospheric monitoring of the Pacific
- Establish within CLIVAR a data center for collection, archival, and dissemination of all broadscale atmospheric sampling data.
- Establish and enhance the historical atmospheric dataset for the Pacific for diagnostics, reanalyses, and other studies. Sounding data at some sites in the Pacific are not entered onto the GTS and reside only in raw or incompletely processed form at observing sites. An inventory of historical sounding data in the Pacific is needed along with estimates of the cost and effort (time) required to recover and digitize these data.

**References:** International/US CLIVAR Implementation Plans; Ch. 10 of PBECS Plan

#### ***4.3 Regionally Enhanced observations - chaired by Billy Kessler and Yihui Ding, summary contributed by Roger Lukas***

Roger Lukas provided a summary. In South America there is a good sense of cooperation among Columbia, Ecuador, Peru, and Chile. Some of these countries have had success in obtaining World Bank funding for instrumentation. Ecuador, Mexico, Peru, and Chile are working together on upwelling studies as part of EPIC. Columbia, Ecuador, Peru, and Chile have an annual regional cruise. Plans are for 2 TAO-type buoys off Ecuador, moored arrays off Colombia, Peru, and Chile. Peruvian plans include coastal stations,

wind profilers, additional meteorological/hydrological stations, four offshore buoys with T, S, and oxygen down to 500 m. This is a 10-year program, with the goal of 25 or more regional buoys and hydrographic lines extending offshore between 5.5°S and 16°S. Chile has also developed a national plan for a moored array and is working to secure funding.

Canada occupies line P three times per year and line Z occasionally in coordination with the Japanese (Oshoru Maru). P1 may be repeated in coordination with the Japanese. There is at present no mooring at Station P (Papa). French work out of Noumea will focus on the warm pool and three-dimensional structure of the front, on the barrier layer, and on salinity. Hydrographic lines along 165°E and possibly the dateline will be sampled yearly. SSS data is collected using VOS.

Japanese efforts are on KESS (2001-2005, JAMSTEC) and KOP (with the intent of developing real-time data links from the array to ship or shore). Work in the Indonesian throughflow has been proposed by U.S. and Indonesian investigators. China plans for a South China Sea Monsoon Experiment (SCSMEX-2) in 2003. The onset of the monsoon is the focus. Twenty ARGO floats will be deployed. Flux observations will be made from three towers. In the planning stage is a new ocean observation program for the Philippine Sea, with buoys and floats being discussed.

Lynne Talley and other have advocated a regional focus on subduction and mode water formation in the Southeast Pacific, in particular the area off southern Chile where intermediate waters are formed. This could be done in conjunction with Southern Ocean process studies and draw data from two XBT lines, ARGO, ADCP sampling an a 30°S repeat hydrographic section.

One focus for regional studies will be the western boundary currents. Except for the Kuroshio, though, plans are not yet well developed. The NGCC is monitored by JAMSTEC as part of TRITON/TOCs with two moorings since 1995. Australian boundary currents have been measured using XBTS along three lines, but only quarterly. Enhancements to sampling in the equatorial region have been called for to improve observations of the wind-driven flow (upper 50 m) and its divergence. It is also desirable to be able to identify the depth from which water upwells at the equator. Observational gaps at present include the Southwest Pacific boundary region and regions where subduction occurs.

Regional enhancements will be of use to data assimilation and model development efforts in Pacific CLIVAR, but will require a minimum of three to four years of sampling. The sampling plan in space may rely on nested schemes. For budget studies in the Pacific, though, the sampling should have a duration of fifteen years.

#### ***4.4 Numerical Modeling within CLIVAR Pacific - chaired by Magdalena Balmaseda and Pablos Lagos, summary contributed by Paul Schopf, Magdalena Balmaseda, Pablo Lagos, Mitch Moncrieff,***

The relationship between numerical modeling and CLIVAR Pacific is multi-faceted. The modeling community is looking to CLIVAR Pacific to help improve coupled and component models while at the same time contributing to CLIVAR Pacific through numerical experimentation and theoretical hypothesis testing. An integral part of CLIVAR Pacific is the development of an ocean analysis system, fusing an advanced numerical model with the observational data to make optimal state estimates for the Pacific Ocean during the CLIVAR observing period. Thus the models embrace the complete range of theoretical studies, state initialization for prediction, prediction on interannual to decadal scales, and reanalyses. The needs and implementation strategy related to such models are thus equally varied.

In addition, the nature of the problems facing CLIVAR generally imply that modeling issues are global and generic to all regions, so that many of the challenges facing modelers are being addressed within the larger CLIVAR context through such groups as the JSC/CLIVAR Working Group on Coupled Modeling, the CLIVAR Working Group on Seasonal-to-Interannual Prediction, and the PAGES/CLIVAR Working Group. Nonetheless, there are particular problems and opportunities that appear to arise more clearly in the Pacific basin, and it is the aim of CLIVAR Pacific's modeling implementation to ensure that those specific issues be addressed.

The following sections outline the technical and science issues facing modeling, the data requirements for advancing the modeling, strategies for model development, plans for theoretical studies and numerical experimentation, and linkages with other groups.

Data assimilation and its specific needs for PBECS is being addressed in a separate section given below.

## Technical and Scientific Issues

This section outlines the most important model-specific problems facing CLIVAR Pacific studies. We focus here on specific details that seem more pressingly in need of specific attention. All of the following focus areas relate to the broad modeling themes of CLIVAR Pacific, namely

### *Air-Sea Interaction.*

From small scale coupled boundary layer processes to large scale mid-latitude atmospheric response to SST.

### *Clouds, precipitation and radiation.*

How do diabatic processes affect the atmospheric state, the surface energy balance and atmosphere-ocean interaction and its variability?

### *Stochastic processes.*

Can high frequency processes (perhaps purely random "weather noise", perhaps organized phenomena such as the Madden-Julian Oscillation (MJO) or westerly wind bursts) have a non-linear effect on the Pacific system which causes low frequency variations?

### *Atmospheric teleconnections.*

Does an atmospheric "bridge" operate between the tropics and sub-tropics?

### *Ocean pathways through shallow tropical/sub-tropical cells.*

Can a preferred frequency for low frequency Pacific variation be due to transients propagated through the upper ocean thermocline?

The work of the CLIVAR Workshop on Shallow Tropical/Subtropical Overturning Cells and Their Interaction with the Atmosphere held in Venice, October, 2000 ([http://www.clivar.org/organization/atlantic/STC/STC\\_rep0801.pdf](http://www.clivar.org/organization/atlantic/STC/STC_rep0801.pdf)) (hereafter referred to as the STC Workshop) lays out a series of questions of interest to CLIVAR Pacific and gives a more extensive view of observational and modeling problems. The questions posed in that report were:

- Q1. Do STCs play a role in seasonal to centennial climate variability, and if so, how?
- Q2. What are the sources and pathways of the STCs, including other features such as the Tsuchiya Jets and the Indonesian Throughflow?
- Q3. How do surface fluxes affect subduction processes and the three-dimensional ocean circulation within the STCs?
- Q4. What are the relative mean and time-variable contributions of the northern and southern hemisphere STCs to the equatorial circulation.

## Boundary Layers

### *Surface Boundary Layers*

The key role played by surface boundary layers in determining and modulating the fluxes and communication between the ocean and atmosphere has long been appreciated and extensive research has been done over the past 25 years or more to understand and accurately model the behavior of the surface layers. The problems facing models have become more and more focused on getting details right, in a context where regional details must be correct in a global model. Increasingly, evidence is accumulating that detailed boundary layer processes can affect the climate state on all scales. There appears to be a strong interaction between boundary layer parameterization in the equatorial ocean and the equatorial surface divergence, undercurrent transport and the mean thermocline. Additional effects of temporally and spatially varying turbidity further complicate the problems facing model development. Boundary layer behavior at the eastern end of the equator is far different than that experienced in the warm pool, due to the different roles played by strong shears, upwelling, salinity and radiation.

In the atmosphere, recent measurements of the surface stress from satellite provide strong clues that the atmospheric boundary strongly interacts with the ocean on much smaller spatial scales than typically resolved in AGCMs (Chelton et al, 2000). In the western equatorial Pacific, cloud-resolving models have indicated that a significant feedback exists between the boundary layer and cloud-scale features in the atmosphere.

Problems also remain at higher latitudes, where the boundary layer plays the crucial role in oceanic subduction. The existing theories for how sub-tropical oceans may influence El Niño involve anomalous subduction in the sub-tropics. Accurate simulation of this process requires that the boundary layer models simulate not only the mean behavior of the upper ocean, but have proper sensitivity to atmospheric changes. A key issue for CLIVAR Pacific is determining the sensitivity of the mid-latitude atmosphere to mid-latitude SST variations. This is also true for the Atlantic, but the issues and mechanisms may well differ.

Earlier theories for the ocean surface mixed layers tended to imply that mixing of heat, salt, momentum and other tracers was largely similar within the ocean mixed layer, with the possible extension to account for

the effects of penetrating short-wave radiation. More recent evidence suggests that these quantities are not mixed by the same mechanism, and that models will need to distinguish the differences. An example is the barrier layer structure in the western and central Pacific Ocean, which has been shown to be tightly linked to ocean-atmosphere dynamics in the Warm Pool area.

#### *Ocean Western Boundary Currents*

The importance of the western boundary currents, including the Indonesian Throughflow was identified in the STC Workshop Report.

The connection of the subtropical ocean to the equator is believed to occur either through advection of density compensated anomalies of temperature along mean streamlines consistent with the general theory of the ventilated thermocline or through circulation anomalies associated with low frequency planetary wave behavior. In the first case, the circulation regime shows a narrow "window" of connection between the northern sub-tropics and the equator for water in the mid-thermocline. Many of the streamlines reaching the equator do not take a direct route, but instead reach the western boundary, forming a western boundary current that carries the mass to the equator. In the southern hemisphere, a more direct route is found, but many streamlines also reach the western boundary before reaching the equator. All of the wave-carried anomalies reach the western boundary, where the simplest theory indicates that a coastal Kelvin wave is induced which carries the mass anomalies to the equator. This aspect is often been studied with insufficient Indonesian Throughflow and especially static circulation. With realistic variability the pathway between low latitudes of both hemispheres and the tropical Pacific becomes very complex and is less well known.

The dynamics of western boundary currents remain one of the least well understood problems in ocean dynamics. The scales of motion and the dissipation and potential vorticity balances make accurate simulation of the details difficult. To the extent that the connection between the sub-tropics and equator involves interaction with the western boundary, it depends on simulations that are subject to these same difficulties.

The problem is compounded by the Indonesian Throughflow, which we consider here to be a special case of a western boundary current. With a transport on the order of 10Sv of upper thermocline water, the throughflow significantly influences the mass balance of the thermocline, and the implied cross-equatorial transport that likely occurs in a western boundary flow.

In the mid-latitudes, the Kuroshio and Oyashio system has been identified as likely exhibiting low frequency variability, and theories for decadal variations in the North Pacific (Latif and Barnett, 1996) note the importance of positive feedbacks in the air-sea interaction in the Kuroshio and Oyashio extension region. Several mechanisms can be posited for such interaction, but variations in the position of the Kuroshio would have a significant impact on the local SST. Models do not routinely position the Kuroshio front correctly without data assimilation, and if we are going to have improved confidence in understanding mechanisms for such variability, the models will need to establish better performance in simulating the mean position and its sensitivity to climate variations. Models with data assimilation may constrain the simulation to keep the Kuroshio positioned correctly while not shedding any light on the possibility for variability.

A similar concern exists with the East Australia Current. Here models are confronted with far more complex topography, and the accurate simulation of changes in this flow depend on their ability to treat such features.

#### *Ocean Bottom Boundary Flow*

The role of sill flows and bottom boundary currents is perhaps less important to CLIVAR Pacific than similar flows in the Atlantic. The absence of a strong overturning cell means that abyssal flows in the North Pacific are likely less energetic and less variable. The interaction of the models with the bottom topography does arise in two important cases: the Indonesian Throughflow and the connection of the Oyashio and the Sea of Okhotsk.

As discussed above, the Indonesian Throughflow has important consequences for the thermocline mass balance in the Pacific. The flow occurs through several narrow passages which are subject to extreme tidal mixing and interaction with the topography in ways that are not well modeled in global scale OGCMs, and not completely studied in high resolution simulations.

The outflow of very cold fresh water from the Sea of Okhotsk has recently been found to have significant impact on the position of the Kuroshio/Oyashio system in a high resolution ocean model. The connection occurs through narrow, shallow passages that are similarly not well resolved in global scale OGCMs.

#### *Ocean Eastern Boundary Currents*

The eastern boundary of the ocean plays a significant role in determining both local and interior structure of the thermocline. The STC Workshop identified the problem of eastern boundary termination of the major zonal currents such as the equatorial undercurrent (EUC) and the Tsuchiya Jets as an important uncertainty in our understanding of the upper thermocline dynamics. While ocean models have had relative success simulating the equatorial thermocline and the vertical structure of the equatorial current systems in the central Pacific, the problem of accurately simulating the termination of the EUC remains a significant problem. Related to this problem is the existence of a relatively strong thermocline beneath the equatorial undercurrent in the east, which is believed related to the ability to simulate Tsuchiya Jets.

In coupled models, problems arise with eastern boundary currents due partially to an uncertainty in the local coastal wind field (see next section) and partially due to the small scale and complex nature of the currents themselves and their interaction with topography. The detailed interaction of flow with topography remains one of the most difficult and uncertain parts of ocean model dynamics.

### Orography

The interaction of AGCMs with orography is a continuing problem for coupled modeling. Spectral GCMs exhibit Gibbs' phenomenon, leading to problems with interpreting fluxes at the sea surface. While grid-point models are free from this specific problem, they must deal with numerical problems associated with the interaction of vertical coordinate systems with the topography. Specific issues relate to the Pacific locale or, rather, regions that bound the Pacific and cannot be truly isolated from it. For example, convection over the Andes is thought to affect the extensive stratocumulus decks over the eastern Pacific but the mechanisms are not understood, and have not been systematically examined. Convection over the islands in the Indonesian 'Maritime Continent', which has high, steep orography, provides an extensive atmospheric heat source and has a marked diurnal cycle. These aspects need to be quantified, especially if their impacts turn out to be systematic.

### Diapycnal Mixing

Perhaps the most uncertain aspect of ocean models is their treatment of diapycnal mixing. While most diapycnal mixing occurs within the surface and bottom boundary layers discussed above, there is evidence of significant diapycnal mixing below the core of the equatorial undercurrent, and its accurate treatment appears to be important in simulating the flow.

In the thermocline, away from the surface boundary layer, theories based on negligible diapycnal mixing and conservation of potential vorticity appear to give a good description of the mean flow fields. However, neither numerical models nor observations support a view in which potential vorticity is exactly conserved, and diapycnal mixing of heat, salt and momentum, together with horizontal mixing are likely players in setting the thermocline's mean potential vorticity distribution. For modeling studies, which attempt to reproduce the evolution of slow variations of potential vorticity anomalies, dissipation through diapycnal mixing may play an important role in determining whether anomalies can be efficiently transported from sub-tropics to the equator.

In numerical models, diapycnal mixing occurs through explicit parameterization of vertical mixing, through inaccuracies in explicit horizontal mixing operators, and through numerical diffusion. Models which have vertical coordinates based on depth or pressure (both "Z" and "σ"-coordinate models) have made significant advances in reducing the second source of diapycnal mixing by rotating the mixing tensor. More sophisticated treatments are under construction which can be expected to substantially remove this problem. A recent study has demonstrated, however, that diapycnal mixing by numerical diffusion can not be so easily eliminated, and that such models will be susceptible to such mixing even as resolution becomes finer and finer.

Isopycnal ocean models naturally tend to eliminate the last two sources of diapycnal mixing, and can be run with very low values of explicit diapycnal diffusivity. In practice, the horizontal mixing along isopycnals is not exact, and some concern is being directed to refinements in horizontal mixing operators in such models. Spurious diapycnal mixing due to numerics does occur in isopycnal models, but this is through difficulties in connecting surface mixed layers with the discrete isopycnal layers beneath.

It is not clear, however, the extent to which spurious diapycnal mixing is important on timescales of interest to CLIVAR Pacific, particularly since the Pacific does not seem to have active variations in the mean overturning circulation. This is a question which is likely to be addressed by the larger ocean modeling community through such efforts as the working group on ocean circulation modeling for climate studies.

### Stochastic Processes

A key feature of the coupled climate system is the chaotic nature of the atmosphere and ocean. The underlying basis for climate prediction is a belief that there exist modes of variability that evolve slowly and deterministically in the face of stochastic forcing. Recent numerical experiments indicate that high frequency, unpredictable weather variations in the tropics can perturb ENSO in some models, leading to long term drift of the background state of the equatorial thermocline and apparent decadal variation in ENSO itself. This implicates features such as the MJO and westerly wind bursts in a possible route to decadal variation. Through atmospheric and oceanic pathways, such equatorially generated decadal changes may be relayed to mid-latitudes. A similar role for chaotic atmospheric behavior may play a role in mid-latitude air-sea coupling. One of the hypothesized mechanisms for coupled ocean-atmosphere interaction in the mid-latitudes is a shift in "storm tracks". The concept of a storm track is itself an expression of non-stationary and non-uniform statistical behavior of the atmosphere. A more recent development has been an attempt to model the relationships between shifts in the statistical behavior of the system and the larger scale system itself.

Modeling studies are therefore faced with the need to simulate and understand the role of "noise" in the climate system. This has typically been addressed through the use of ensemble forecasts or very long term integrations, and it is likely that such techniques will continue to play a role in CLIVAR Pacific modeling. The implication is simply that computing resources that might otherwise be utilized for increased resolution may need to be used for multiple realizations. It is further complicated by the possibility that the statistics of such chaotic behavior as westerly wind bursts may not be entirely random but related to the larger scale state of the system.

#### Clouds and Radiation

Clouds remain a major challenge to models of climate and to understanding the climate system and its variability. Of particular interest in the Pacific region are deep convection and stratocumulus as well as the coupling between these two cloud systems.

The cloud radiative forcing associated with these two cloud system types is quite different -- stratocumulus cool through reflecting shortwave radiation while deep convection (especially convectively generated stratiform clouds and cirrus) warm by trapping longwave radiation. Because the cooling and warming occur at different in the atmosphere, important dynamical feedbacks can occur. While shortwave and longwave radiative forcing tend to cancel in the western Pacific, this may not be generally true (e.g., eastern Pacific and Indian Ocean locale). An aspect needing quantification is the vertical and horizontal distribution of cloudiness (wrapped up in the 'cloud-overlap' problem of radiative transfer). The radiative effects of convectively generated cirrus and optically thin cirrus are primary source of uncertainty. The fact that climate models have difficulty in getting the energy budget simultaneously correct at top and bottom of the atmosphere underscores the cloud-radiation problem.

Precipitation is poorly predicted, especially in climate models. This causes much uncertainty in the water cycle, with strong climate repercussions. While the diurnal cycle of precipitation is primarily a problem over land, it affects in CLIVAR Pacific through the interaction with orography at ocean-continent boundaries. A poorly understood aspect is the effects of precipitating convection organized on scales ranging from order 10 km through thousands of kilometers, as in convectively coupled waves (e.g., MJO) and westerly wind bursts. The association of convective organization with up-scale transport (probably an issue in stochastic forcing) is a fundamental problem. The effect of precipitation on the ocean state remains an open question (input from oceanographers needed here).

Despite much research, major uncertainty remains concerning marine stratocumulus (see PBECS for details). Comparatively little work has been done on trade-wind cumulus, which may be need a focused study considering that CLIVAR Pacific has extensive fields of trade cumulus that play an active role in the Hadley circulation. Moisture is transported from the ocean in the trade cumulus regions and precipitated in the ITCZ. Occurring in a shear flow and being highly organized, trade cumulus may even affect the momentum balance of the boundary layer and the surface wind stress.

Polar outbreaks are associated with the largest air-sea heat exchange on Earth, especially in wintertime. While implications for atmosphere-ocean coupling are apparent, this problem has been little studied and little information is available regarding the degree of uncertainty. The diversity of convective regimes, and transitions among regimes along airflow trajectories, underscores the importance of this problem, and possibly has an effect on storm track statistics.

CLIVAR Pacific will need to maintain a strong link with the GEWEX efforts in this area (see below).

## Data Requirements

The interaction of numerical models and observational data occurs at many levels. Primary among them are (1) detailed measurements for improvement of model parameterizations of specific processes, such as measurements for evaluating CRMs and LES, (2) verification data for assessing model performance, (3) observations of model forcing, (4) state observations for initialization of prediction systems, and (5) long term state observations for inclusion in data assimilation products such as retrospective reanalyses. Among each of these categories, information is needed about the mean state, individual state estimators and statistical measures of variance and co-variances. Also, the increasing dynamic range of CRMs require a corresponding wider dynamic range of verifying observations.

The observing system for CLIVAR Pacific includes a meaningful and considered set of measurements that contribute to the overall needs of the modeling community. For some of the observations relating to the improvement of model parameterizations, it will be important to make highly specialized process measurements within a context of other background state observations that can relate to the large scale. An example would be diapycnal mixing within the equatorial ocean, which can interact with the mesoscale and large scale flow simulated in the model. Another example is cloud-scale behavior in the atmosphere and its interaction with the planetary boundary layer, which is influenced by the large scale atmosphere.

Unlike process studies, observations for long term state estimation need to be well distributed in space and time.

High quality observations are required for forcing model simulations. Depending on the process being studied, the forcing can be quite varied. On shorter timescales, the SST may be considered forcing for AGCMs, as the fluxes of heat, momentum and fresh water are forcing for OGCMs. For coupled studies, such observations become verification data, and the forcing may be removed to such items as atmospheric aerosol loadings. One promising development has been the ability of inverse models to combine state estimation and observations to refine estimators for the forcing fields themselves. During the course of CLIVAR Pacific, this methodology can be expected to improve with the increased availability of data, the improved resolution of the numerical models, and the improvement in physics included in the ocean models. The WGCM has organized the GCM Standardized Forcing Project.

The importance of sustained and enhanced high quality satellite measurements is noted in the STC Workshop Report.

## Model Development

Model development is by nature an evolutionary, not revolutionary process, and requires close co-operation between model developers, diagnosticians and observationalists. The large amount of time that must be invested in order to test thoroughly any new parameterization scheme often creates long delays before new insights from process studies are incorporated into models. Because of the myriad of complex interactions that occur within a climate model, there is no *a priori* guarantee that a more physically correct parameterization will lead necessarily to improvement in model simulation capability. Testing across a range of climate models is needed to improve the robustness of findings.

Progressively increasing computer power will impact model development in many ways. Because of the dynamic range explicitly simulated by them, cloud-resolving numerical models (CRM) and large eddy simulation (LES) are powerful tools with which to address the large-scale effects of cloud systems and boundary layer processes. CRM and LES studies conducted either along with field experiments or in idealized settings are therefore a utility to be exploited by CLIVAR Pacific. Similarly, increasing computing power has allowed for long (perhaps 1000 years) coupled GCM runs at resolutions used previously for predicting and simulating ENSO. This is bringing the climate change and paleo communities closer to the seasonal-to-centennial timescales of interest to CLIVAR Pacific.

GCM resolutions will likewise improve. The Japanese Earth Simulator will be capable of a 10-km global resolution on an experimental basis. By 2015 climate models should will have horizontal resolution of <100 km, operational medium-range (possibly seasonal) weather prediction model resolution will be about 10 km. Note that, in principle, at this resolution convective parameterization faces fundamental problems. Note that a 1-km (or even higher) resolution is needed to resolve convection. At 10-km resolution mesoscale organization is (crudely) resolved but convective parameterization is still required. While some short-term weather forecast models run at this resolution, their duration is arguably too short to manifest significant bias. At any rate, the advent of 10-km resolution points to the need for a better understanding of the boundary layer, air-sea interaction and their interaction with convection.



In the ocean, high resolution in the western boundary layers should permit a better analysis of the dynamics operating to transmit thermocline signals from the sub-tropics to tropics. Whether climate runs will be undertaken with eddy-resolving, convergent models in the next 10 years remains an open question.

Some pertinent questions are:

- How does sub-grid scale variability influence large-scale variability and mean error to a significant degree, requiring nonlocal and stochastic parameterizations?
- Is sensitivity at high frequency indicative of non-physical behavior in long simulations?
- Why do parameterizations tend to be model dependent?
- To what degree are regional climate models compromised by systematic errors in the global models that drive them?
- Do AGCMs and OGCMs and their different numerical realizations converge with increasing resolution and, if not, why not?
- Must the dynamic cores of GCMs represent nonhydrostatic equations at 10-km resolution?
- What are the implications of impending 10-km resolution for: (a) numerical weather prediction, (b) climate modeling? Are new approaches to parameterization needed and what are the implications for boundary layer parameterization and cloud-microphysics parameterization?
- What are the implications for data assimilation at 1-10 km resolution, (e.g., data from profiling satellites such as in the future CloudSat)?
- Will new process experiments be needed to address the above questions?

Further details on ocean model developments in the recent past can be found in the report: *Developments in Ocean Climate Modeling* WCRP Ocean Model Development Working Group (OMDWG).

#### Model Intercomparison Projects:

CLIVAR Pacific does not anticipate any specific model intercomparison projects. Instead, CLIVAR Pacific should work with the other CLIVAR modeling working groups to ensure that model intercomparisons that are organized by them are well known to the CLIVAR Pacific community.

The following intercomparisons and coordinated experiments are noted and of relevance to CLIVAR Pacific:

DYNAMO Dynamics of North Atlantic Models Simulation and assimilation with high resolution models, with the web site address:

<[http://www.ifm.unikiel.de/to/dynamo/dyn\\_m.html](http://www.ifm.unikiel.de/to/dynamo/dyn_m.html)>[http://www.ifm.unikiel.de/to/dynamo/dyn\\_m.html](http://www.ifm.unikiel.de/to/dynamo/dyn_m.html)

DAMEE-NAB Data Assimilation and Model Evaluation Experiments – North Atlantic Basin(DAMÉE-NAB) <<http://www.coam.usm.edu/damee/>><http://www.coam.usm.edu/damee/>

DOE Dynamics of Overflow Mixing and Entrainment

<<http://www.gfdl.gov/~rwh/DOE/dome.html>><http://www.gfdl.gov/~rwh/DOE/dome.html>

CMIP Coupled Model Intercomparison Project

<<http://www-pcmdi.llnl.gov/covey/cmip/cmiphome.html>><http://www-pcmdi.llnl.gov/covey/cmip/cmiphome.html>

OCMIP Ocean Carbon-Cycle Model Intercomparison Project

<<http://www.ipsl.jussieu.fr/OCMIP/>><http://www.ipsl.jussieu.fr/OCMIP/>

Subpolar Gyre Process, Simulation and Data Assimilation Experiments

<<http://seip.gso.uri.edu/nac/subpolar.html>><http://seip.gso.uri.edu/nac/subpolar.html>

AMIP: Atmospheric Model Intercomparison project (operated by WGNE)

PMIP: Palaeoclimate Modeling Intercomparison Project (a combined WCRP/WGCM and IGBP/PAGES project)

#### Numerical Experimentation and Theoretical Studies

CLIVAR Pacific aims to study climate variability on a wide range of timescales. On the longer scales, a sufficient quantity of direct observational evidence will not be available for making precise conclusions

about the dynamics of the climate system, nor to provide timely answers to many societal questions. Much of the science will hinge on the ability to build models based on theory, which can reproduce observations.

The present state of theory related to longer period climate variations is incomplete. Within the ocean, the past two decades have seen the development of theory for the mean state of the thermocline and upper ocean, along with a theoretical basis for understanding transients on the scale of ENSO. These processes are apparently non-linear, and can become complex when coupled to feedback processes with the overlying atmosphere. Many of the theoretical hypotheses behind decadal scale variations are necessarily incomplete and depend on conjectures.

To extend the theory beyond the limits of analytic tools, numerical models play an important role in developing a clear and consistent view of climate processes. A particular key feature of numerical models is the ability to withhold or alter certain key processes and thereby identify those parts of the system that are critical to the dynamics. For instance, the ability of density-compensated thermal anomalies to be advected from the sub-tropics to the equator through western boundary currents will depend importantly on the dynamics and thermodynamics within the western boundary.

A set of theoretical and modeling issues for the Pacific Ocean are set forth in the report *CLIVAR Workshop on Shallow Tropical/SubTropical Overturning Cells and their Interaction with the Atmosphere*, Venice, October, 2000.

#### Linkages

The modeling work of CLIVAR Pacific will not proceed in a vacuum. As discussed above, many of the modeling issues are common to global circulation models, and a substantial effort is underway in through many CLIVAR working groups, other international programs and several more ad-hoc model development efforts. Many of the goals and requirements of CLIVAR Pacific will be addressed by such activity, and many of the developments arising from CLIVAR Pacific modeling will be of benefit to the larger community.

#### GEWEX

The task of the <<http://www.gewex.com/gcss.html>>GEWEX Cloud System Study (GCSS) is to develop physically based parameterizations of sub-grid scale processes for climate models and numerical weather prediction models. The approach of choice is cloud-resolving models and large eddy simulation (LES) models. Of particular interest to CLIVAR Pacific are boundary layer processes, and precipitating convection. The approach will involve process studies in field campaigns as well as idealized studies to quantify basic aspects.

We need to ensure that modeling efforts between CLIVAR Pacific, VAMOS, and GEWEX evolve to assist the needs for regional climate studies and prediction. The G1 Research Area (ENSO, Extending and Improving Predictions) includes of improvements in prediction via an increased understanding of regional and smaller scale effects. CLIVAR Pacific will contribute to these efforts by bringing improved monitoring and observations of the eastern Pacific.

#### CLIVAR ACC and JSC/CLIVAR WGCM

The goals of the CLIVAR Climate Change Detection and Attribution (A2) research area include the need to determine natural climate variability, and the WGCM has initiated several modeling studies of natural and anthropogenic climate change. The coupled models used to make such studies are rapidly evolving to be capable of simulations of the most energetic interannual to century scale variability, and the CLIVAR Pacific modeling effort will share a strong common interest with the ACC modeling community. The effort to conduct model intercomparisons of coupled model simulations of the climate of the 20th Century (C20C) will by necessity examine interdecadal variability.

#### CLIVAR WGSIP

The CLIVAR Working Group on Seasonal-to-Interannual Prediction is concerned with advancing the state of forecasting.

#### PAGES/CLIVAR Working Group

<<http://www.clivar.org/organization/pages/index.htm>>PAGES/CLIVAR seeks to improve understanding of decadal to century scale climate variability by extending the instrumental record of climatic variables using high resolution paleoclimatic data. Much of the paleoclimatic record involves indicators appropriate for monitoring ENSO, and as such has a direct connection to CLIVAR Pacific. Workshops on

"ENSO, Past and Future " have been held in the US, with international workshops planned in the near future. The continuing dialog between the paleoclimate community, and the CLIVAR Pacific modeling community provide a strong mechanism for advancing our understanding of natural climate variability. There is also an interest within PMIP for a "climate of the past 1000 years" experiment.

#### Other Coordinated Modeling Efforts

Dynamics of Overflow Mixing and Entrainment (DOME). The DOME modeling group is an ad hoc consortium of ocean modeling groups concentrating on the problem of accurately simulating dense flows over topography, such as deep flow in the Denmark Strait, the Gibraltar outflow, and Antarctic bottom water formation. As discussed above, such flows are perhaps less important in the Pacific with the exception of the Sea of Okhotsk outflow. One of the important outcomes of DOME experimentation, however, will be an improved understanding of flow interaction with steep topography, and the numerical problems associated with their treatment.

Common Modeling Infrastructure. The proliferation of novel parallel computing architectures has complicated the process of coordinated model development and sharing. Efforts are underway at several centers to a common modeling infrastructure, wherein the particular needs of climate circulation models can be facilitated, hopefully avoiding the need for each center to individually invent solutions to new computing paradigms. CLIVAR should encourage and assist with such efforts. While many centers have made significant strides in adjusting to the most recent computing paradigms, it is unlikely that the most radical changes are behind us, as evidenced by the emergence of technologies such as GLOBUS and other efforts at "grid computing".

#### Recommendations

- CLIVAR Pacific encourages numerical experimentation and theoretical studies of interest for a wide range of problems of interest to CLIVAR Pacific. Examples include long period modulation of ENSO, examination of mid-latitude atmospheric response to mid-latitude SST anomalies.
- CLIVAR Pacific should host workshops every year or two, bringing together theoreticians and modelers. Look for a wide-range of topics.
- Support CLIVAR Pacific participation in PAGES/CLIVAR workshops
- Encourage coupled modeling that attempts to re-create decadal mechanisms found by others and explore predictability on decadal time scales. It is difficult to get such efforts funded, with individual PIs finding greater benefit in discovering new mechanisms for variability. Thus we are left with each mechanism unique to a single model and configuration.
- Continue to use atmospheric and oceanic GCMS in stand-alone mode to understand the sensitivity of the climate system (atmospheric and oceanic) in the Pacific Ocean to specified boundary conditions. Particular emphasis could be placed on understanding the freshwater budgets of the atmosphere and the ocean, and, especially, the role of precipitation in modulating the upper ocean barrier layer and ultimately ENSO.
- Coordinate model parameterization improvements with field programs when possible.
- Do Not form a separate CLIVAR Pacific Modeling Working Group.
- CLIVAR Pacific needs a direct connection to the WGSIP and WGCM and the Working Group on Ocean Model Development.
- Implement the recommendations of the Venice Workshop on Shallow Tropical/Sub Tropical Cells for the Pacific.

#### ***4.5 Process studies chaired by Steve Esbensen and Charlie Eriksen, summary contributed by Steve Esbensen***

##### Nature of proposed activities

The initial CLIVAR implementation plan for the Pacific region anticipates two types of intensive observational activities: (1) process studies of short duration, and (2) regionally enhanced monitoring over an extended period of time. The distinction between short duration process studies and regionally enhanced monitoring is not sharply defined. Both depend on the full implementation of the sustained basin-wide climate observing network. In general, the Pacific CLIVAR process studies will involve high resolution observations of the ocean or atmosphere over a time period of a season or less. The process studies will be designed to elucidate key physical processes or phenomena that must be better understood to improve climate analysis and prediction. Regionally enhanced monitoring involves spatially dense observations taken

over seasons to years that are needed to validate the quality of climate analyses and coupled model simulations in key climatic regimes at a resolution much greater than the basin-wide observation network. Enhanced monitoring observations may also provide context for the short duration process studies.

#### Proposed observational activities

The intensive observational activities discussed at the Workshop fall naturally into three categories: major coordinated process and enhanced monitoring activities involving both the ocean and atmosphere; regionally enhanced monitoring and targeted field activities of a more limited nature, involving either the ocean or the atmosphere; and other climate process research strongly linked to Pacific CLIVAR activities.

#### *Ocean-Atmosphere studies with international partners*

##### SUBTROPICAL OVERTURNING CIRCULATION

Objective: Observational and diagnostic studies are needed to better understand the processes that determine the decadal variability of the oceanic subtropical overturning circulation. The subtropical overturning circulation and its interaction with the atmosphere are central to a number of theories for decadal modulation of ENSO and other decadal variability involving the oceanic connections between the subtropics, where atmospheric forcing of the ocean is strong, and in the tropics where the ocean can efficiently affect atmospheric circulation. Of particular interest are: (1) the processes that control rates and spatial structure of the upwelling along the equator which modulate SST, (2) the pathways for returned upwelled water to the subtropics, (3) the atmospheric boundary layer processes, especially those involving the interaction of clouds and radiation, which modify the near surface water in the region of poleward Ekman transport, (4) the processes that control the water sources and rates at which subtropical water is subducted into the subtropical cells, and (5) the processes that control the pathways and time scales of water movement in the lower branch of the circulation as it makes its way back to the equator through a combination of interior Sverdrup advection and concentrated currents.

#### Implementation issues:

7.0 Would it be beneficial to conduct some or all of the observational activities simultaneously, or would a sequential approach within an overall framework be sufficient?

8.0 What can we learn from high resolution ocean observations that will not be adequately observed or diagnosed from the sustained ocean observing array?

**Timing: Depends on implementation strategy. The observational activities are in the planning stage.**

Contacts: Bretherton, Gregg, Ioualalen, G. Johnson, Kessler, Lukas, Niiler, Richards

#### Recommendation:

- It is recommended that the next stage of planning be built around a workshop to develop more detailed plans for a process study that addresses the most important scientific issue(s) within the context of Pacific CLIVAR science objectives, and knits that process study together with the modeling and broadscale sampling programs of Pacific CLIVAR.

##### EASTERN PACIFIC INVESTIGATION OF CLIMATE (EPIC/VEPIC)

**Objectives:** Observational studies in the eastern Pacific region are needed to address several major deficiencies in our understanding and ability to simulate upper ocean thermal structure and the associated patterns of atmospheric heating and cloudiness over the eastern Pacific Ocean. These deficiencies are believed to arise not just from the interaction of the ocean with the atmosphere, but also on the processes that couple the climate over the eastern Pacific with that over the adjacent land masses of South America, Central America and Mexico. The specific scientific objectives of EPIC/VEPIC are: (1) to observe and understand ocean-atmosphere processes responsible for the structure and evolution of the large-scale atmospheric heating gradients in the equatorial and northeastern Pacific portions of the cold-tongue/ITCZ complex; (2) to observe and understand the dynamical, radiative and microphysical properties of the extensive boundary layer cloud decks in the southeasterly tradewind and cross-equatorial flow regime, their interactions with the ocean below, and the evolution of the upper ocean under the stratus decks; and (3) to observe and understand the coupling between land and ocean climate variability in the southeast Pacific region, especially through the orographic effects of the Andes on atmospheric circulation and the effects of variability of atmospheric heat sources over South America on the divergent circulation over the eastern Pacific Ocean.

#### Implementation issues:

- **EPIC studies of the stratus decks envisions a pilot study phase (Phase 1), followed by a larger field study (Phase 2). A number of studies of boundary layer cloud decks, including FIRE and AZTEX, have resulted in major advances in our understanding and ability to simulate oceanic boundary layer cloud decks. Phase 1 is designed to determine whether there are significant differences between the extensive cloud decks in the southeastern Pacific and other stratus cloud regions. Phase 2 would seek to understand and simulate such differences.**
- VEPIC (VAMOS EPIC) is a program of data analysis, monitoring, and modeling activities together with pilot observational studies on the climate variability in the Eastern Pacific. Of particular interest is the coupling between ocean and land. Coordination between CLIVAR Pacific and CLIVAR VAMOS is needed.
- **GEF proposals are being developed for a moored air-sea interaction buoy array along the west coast of South America during the CLIVAR time period.**
- **Phase 2 of EPIC would benefit from the full implementation of ARGO in the southeastern Pacific.**

#### **Timing:**

- **2000-onward 2 air-sea interaction moorings have been deployed off Peru deployed**
- 2003-onward 2 air-sea interaction moorings are proposed to be deployed off Ecuador
- 2003-onward 15 air-sea interaction moorings are proposed to be deployed off Chile
- 2000-2004 NOAA and NASA is funding U.S. enhanced monitoring activities addressing all EPIC objectives.
- 2001-2004 NSF is funding EPIC2001, an intensive observing period during September and October 2001 focused on the cold-tongue ITCZ complex along 95W and a stratocumulus pilot cruise from the Galapagos to northern Chile.
- 2001-2004 VEPIC pilot studies primarily in the coastal region of South America
- 2005-2008 Possible Phase 2 of EPIC in the southeastern Pacific.

#### **Recommendations:**

- 1 The next stage of planning for VEPIC and Phase 2 of EPIC should be built around a workshop to evaluate the results of EPIC pilot studies and to decide whether a larger process study that addresses the most important scientific issue(s) within the context of Pacific CLIVAR science objectives is required.
- 2 Collaboration between the Pacific and VAMOS Panels on VEPIC has started well and should be further developed.

Contacts: Cornejo, Esbensen, Mechoso, Ruttlant

#### **KUROSHIO EXTENSION SYSTEM STUDY (KESS)**

Objective: The Kuroshio Extension System Study (KESS) provides an excellent opportunity to determine how SST anomalies in the Kuroshio-Oyashio outflow region are formed and what determines their spatial and temporal evolution and to investigate and better understand the impact on the atmosphere of the poleward transport and release at mid-latitude of heat by this strong western boundary current. This involves estimating air-sea fluxes, understanding the evolution of the coupled ocean-atmosphere mixed layers and determining the upper-ocean heat and freshwater budgets, focusing on cross-frontal exchange of subarctic (subpolar) and subtropical waters. It also involves the validation and improvement of ocean models, especially the simulation of physical processes associated with inter-gyre exchange of heat and potential vorticity.

#### **Implementation issues:**

- **The oceanic component of KESS is already underway with major Japanese contributions. Although planned as a joint Japan-US effort, US funding has not materialized to date.**
- **Present KESS plans do not appear to adequately address atmospheric processes. KESS has developed as an ocean process study, but clearly there are important atmospheric processes that are involved in the evolution of the SST anomalies that are either not well understood or well simulated. The effects of stratus clouds that form in the poleward moving warm, moist boundary layer air during summer are not well understood, either in terms of their effects on the atmospheric heat and moisture budgets or on the surface air-sea heat exchange. Wintertime air-sea heat fluxes are also not adequately simulated by coupled climate models over the region.**

#### **Timing:**

- IOP1: May –September 2001

- IOP2: 2003-2005

Contacts: Mitsundera, Norris, Qiu, Shapiro, Watts

Recommendation:

- Investigators planning KESS should more fully develop studies of air-sea interaction and atmospheric dynamics. Possible enhancements would include a winter study looking at the outbreak of cold air over the Kuroshio extension and a summer study of cloud processes over the Kuroshio extension.
- The next stage of KESS planning should include a workshop charged with developing more detailed plans for the atmospheric component of KESS, and knitting the study together with the modeling and broadscale sampling programs of Pacific CLIVAR.

*Regionally enhanced monitoring and targeted process research*

#### EASTERN BOUNDARY CURRENTS

Objectives: The objectives of eastern boundary current studies are: (1) understand the variability of upwelling intensity during ENSO cycle (all phases), and to estimate the coastal guided waves and their influence on coastal upwelling, and (2) to understand the processes that determine SST in the northeast Pacific warm pool region.

**Timing:**

- **2000-onward 2 air-sea interaction moorings deployed off Peru**
- **2003-onward 15 moorings are proposed to be deployed off Chile**

Contacts: Cornejo, Davis, Eriksen, Freeland, Schneider, Transviña, Tulley, Rutland

#### TROPICAL WESTERN BOUNDARY CURRENTS AND INDONESIA THROUGHFLOW

Objective: The objectives of these process studies would be: (1) to elucidate the role of the NGCC, NGCUC and MC in the maintenance of the warm pool; (2) to determine the extent to which variability in the NEC bifurcation and the MC can exert a control the basin wide decadal climate variability; and (3) to address whether the phase difference between Makassar inflow and outflow into Indian Ocean along with the implied local storage within the Indonesian seas, water mass variability in the internal basins, quantification of mass, heat and freshwater transport can play a role in longer term climate variability.

**Timing:**

1994-2004 Western Boundary Current: 8 moorings have been deployed

2002-2005 Indonesia Throughflow: 8 moorings are proposed

Contacts: Kuroda, Lukas, Susanto, Sprintall, Gordon

#### RECOMMENDATIONS FOR BOUNDARY CURRENT RESEARCH:

- **Observations in the western and eastern boundary currents and their bifurcations and recirculations are identified as key elements of the effort to quantify tropical-extratropical exchanges. Two actions need to be taken on boundary currents. First, small workshops should be held to develop detailed plans approaches to sampling the boundary currents. It is anticipated that these workshops may recommend pilot studies to test the recommendations in addition to providing the more comprehensive plans needed in advance of ongoing measurement campaigns to be done as part of Pacific CLIVAR. Second, work toward addressing the practical challenges of doing these field measurements, such as identifying national contacts, initiating clearance requests, and finding vessels, should begin with support by the ICPO staff.**

#### RADIATION FORCING BY DEEP TROPICAL CONVECTION

Objective: Observational studies are needed to determine the vertical profile of cloud radiative forcing in tropical deep convection and to explain the observed correlation of shortwave and longwave forcing. Understanding the role of the cloud population and cloud microphysics in cloud-radiation interaction is crucial.

Timing: 2004-2006 Earliest dates for a major field effort.

Contacts: Bretherton, R. Johnson, M. Moncrieff

**Recommendation:**

**It is recommended that following the field phase of EPIC2001, a small workshop be convened to evaluate current understanding of cloud-radiation interaction in regions of deep tropical convection**

**and to develop the concept of a focussed process study to address this issue. The workshop would be attended also by several of the Pacific CLIVAR oceanographers and would continue the integration of modelers and observationalists established at the Hawaii meeting. A goal of the workshop would be to increase international participation and the breadth and completeness of the atmospheric science community engaged in Pacific CLIVAR.**

*Closely related process research*

NORTH AMERICAN MONSOON EXPERIMENT/NAME (2002-2005)(contact: Higgins)

Recommendation:

NAME is a major component of VAMOS and US Pan American implementation plans. As NAME develops, joint interests in the eastern Pacific west of Central America and in the Gulf of California should be identified and pursued.

SOUTH CHINA SEA MONSOON EXPERIMENT (May-August 2003) (contact: Ding): 2001-2005 IOP.

Recommendation:

The western maritime continent plays a prominent role in Pacific as well as Austral-Asian climate variability. Coordination with the Austral-Asian Panel is recommended to maintain a focus on this region and its role in climate variability.

GEWEX CLOUD SYSTEM STUDIES (GCSS; ongoing) (contact: Moncrieff)

Recommendation:

Cloud-radiation interactions are crucial for understanding climate and there exist opportunities for collaboration between Pacific CLIVAR and GCSS groups on understanding and improving the representation of both deep and shallow convection in coupled climate models. These opportunities should be pursued.

GEWEX CEOP IN ASIA (contact: Yasunari)

## **5. Action items**

At the final phase of the workshop, a plenary discussion was held to identify and form consensus on the next steps. This discussion and subsequent e-mail dialog generated the following list of action items, which have the party(ies) to take action in parentheses:

1) The workshop recommended the formation of an international Pacific sector panel (hereafter Pacific Panel) with the following terms of reference

- \* To oversee and facilitate the implementation of CLIVAR in the Pacific sector in order to meet the objectives outlined in the Science and Initial Implementation Plans particularly with respect to  
Expanding and Improving ENSO predictions  
Variability and predictability of the Asian Australian Monsoon system  
Indo-Pacific Decadal Variability  
And also on Pacific impacts on:  
Variability and predictability of the American Monsoon system  
Southern Ocean Climate variability  
Climate change prediction/detection and attribution
- \* To collaborate with WCRP WG on Coupled Modeling, the CLIVAR WG on Seasonal-Interannual Prediction and the WG on Ocean model development in order to design appropriate numerical experiments. To be aware of the requirements of these groups for data sets needed to validate models.
- \* To liaise with the Ocean Observation Panel for Climate (OOPC), with the Joint Commission for Oceanography and Marine Meteorology (JCOMM) and other relevant groups to ensure that CLIVAR benefits from and contributes to observations in GOOS and GCOS
- \* To report to the CLIVAR SSG.

2) The ARGO Science Team to be informed that ARGO is essential for the implementation of Pacific CLIVAR and that, should the completion of basinwide ARGO in the Pacific be done in phases, that coordination of this phased deployment with regional foci within the Pacific would greatly assist Pacific CLIVAR.

(ICPO)

3) Broadscale sampling methods, strategies, and plans need to be more fully developed for the following elements:

- Surface fluxes
- Time series stations
- Boundary currents
- Remotely sensed (satellite) fields
- Surface drifters
- Atmospheric aerosols

a) Surface fluxes. The central issue is how to best develop accurate surface flux fields over the Pacific basin. CLIVAR Pacific plans outline the strategy of making high quality in-situ observations, using those observations to correct biases and errors in remotely-sensed and NWP-produced fields, and then using a combination of the best of the NWP and satellite fields in an assimilative model to produce surface flux fields. This strategy will require cooperation and collaboration among in-situ and satellite observationalists, the NWP centers, and modelers. It is recommended that a CLIVAR Surface Flux Working Group be established to bring together the different, requisite expertise, forge collaborations, and advance the process of producing the surface flux fields that CLIVAR requires.

(ICPO to put on agenda for CLIVAR SSG)

b) Time series stations. Time series stations are seen as a key element of Pacific CLIVAR, able to provide high vertical and temporal resolution, and offering platforms for multidisciplinary measurements. They have been proposed for boundary current and open ocean observations. It is recommended that the choice of sites and rationale for these time series stations in the Pacific be further developed in the context of the Pacific of the CLIVAR Pacific implementation plans advanced at this workshop.

(Pacific Panel)

c) Observations in the western and eastern boundary currents and their bifurcations and recirculations are identified as key elements of the effort to quantify tropical-extratropical exchanges. Two actions need to be taken on boundary currents. First, small workshops should be held to develop detailed plans approaches to sampling the boundary currents. It is anticipated that these workshops may recommend pilot studies to test the recommendations in addition to providing the more comprehensive plans needed in advance of ongoing measurement campaigns to be done as part of Pacific CLIVAR. Second, work toward addressing the practical challenges of doing these field measurements, such as identifying national contacts, initiating clearance requests, and finding vessels, should begin with support by the ICPO staff.

(Pacific Panel and ICPO)

d) The initial implementation workshop did not explicitly involve providers of the satellite data sets required by Pacific CLIVAR. It is recommended that the links to the satellite data providers and satellite remote sensing community be strengthened by entraining members of those communities into the process of implementing Pacific CLIVAR.

(Pacific Panel)

e) Surface drifters provide velocity at 15 m and a platform for observing SST, barometric pressure, and additional variables. A recommendation for the density of surface drifters needed in the Pacific to support CLIVAR should be developed, and that recommendation should explain the need for these drifters.

(Pacific Panel)

f) The atmospheric modelers requested that the broadscale atmospheric sampling plan under development include efforts to provide information about atmospheric aerosols.

(Pacific Panel)

4) Significant progress was made at the meeting to develop the atmospheric broadscale and process study elements of Pacific CLIVAR. To advance the state of maturity of the planning of these elements and to engage additional atmospheric scientists in Pacific CLIVAR, it is recommended that within the next 6 to 8 months, one or more small workshops on the atmospheric elements of Pacific CLIVAR be supported. These would be attended also by several of the Pacific CLIVAR oceanographers and would continue the



integration of modelers and observationalists established at the Hawaii meeting. A goal of these workshops will be to increase international participation and the breadth and completeness of the atmospheric science community engaged in Pacific CLIVAR.  
(Pacific Panel)

5) Process studies in several regions of the Pacific are planned to quantify mechanisms involved in the transport, exchange, and storage of heat, freshwater, and mass. The scientific needs and rationale for these process studies were identified at the workshop. Because developing more detailed plans for these process studies will greatly benefit from the inputs, exchanges, and deliberations of larger groups of investigators, it is recommended that the next stage of planning these process studies be built around a series of focused workshops, with each workshop charged with developing the plans for a specific process study, identifying how that process study addresses the Pacific CLIVAR science objectives, and knitting that process study together with the modeling and broadscale sampling programs of Pacific CLIVAR.  
(Pacific Panel)

6) The Kuroshio Extension System Study (KESS) provides an excellent opportunity to investigate and better understand the impact on the atmosphere of the poleward transport and release at mid-latitude of heat by this strong western boundary current. For this process study, the workshop made the specific recommendation that the investigators planning KESS more fully develop studies of air-sea interaction and atmospheric dynamics. The workshop suggested a winter study looking at the outbreak of cold air over the Kuroshio extension and a summer study of cloud processes over the Kuroshio extension.  
(ICPO to contact KESS )

7) The process of developing and maintaining the formal dialog with each of the Pacific nations that is required for international sampling within each of these nations and in their surrounding waters must be initiated and then carried forward. Staffing at the ICPO should be identified to do this. The recent effort by the ARGO Science Team to work with SOPAC and SPREP should be built upon; liaison with PICES should be pursued; and the past effort of the CCCO Pacific Panel should be taken into account. This effort is seen as critical for the implementation of the boundary current sampling recommended by Pacific CLIVAR.  
(ICPO)

8) The possibility that additional meteorological observations can be obtained using the surface buoys deployed in the Pacific by the various national weather services should be investigated.  
(Pacific Panel)

9) The western maritime continent plays a prominent role in Pacific as well as Austral-Asian climate variability. Coordination with the Austral-Asian Panel is recommended to maintain a focus on this region and its role in climate variability.  
(Pacific Panel and AA Monsoon Panel)

10) Coordination with plans for VAMOS activities in the eastern Pacific should be maintained. This has started well with EPIC and VEPIC. As NAME develops, joint interests in the eastern Pacific west of Central America and in the Gulf of California should be identified and pursued.  
(Carlos Ereno and VAMOS Panel)

11) To maintain an the International Pacific CLIVAR website established for the Workshop an use it to facilitate exchange of national and other plans, to coordinate implementation, to catalog data collected, being collected, or to be collected in the Pacific basin, to provide pointers to modeling and empirical studies, and to allow exchange of results and graphics relevant to Pacific CLIVAR science.  
(Pacific Panel and ICPO)

## 6. Annexes

### 6.1 Meeting agenda

#### *Pacific CLIVAR Implementation Workshop*

Agenda

February 5-8, 2001

East-West Center, Univ. of Hawaii

#### **February 5, 2001**

8:00 - 8:30 Registration, coffee

08:30 - 08:45	Welcome, Logistics - Jay McCreary
08:45 - 09:00	Charge to workshop - John Gould, Bob Weller
09:00 - 09:45	Pacific CLIVAR Science overview - A. Busalacchi (each talk to allow 10-15 minutes discussion)
09:45 - 10:30	Broadscale ocean sampling - Dean Roemmich
10:30 - 11:00	Coffee
11:00 - 11:45	Broadscale atmosphere sampling - George Kiladis
11:45 - 12:30	Regionally enhanced observations - Roger Lukas
12:30 - 1:30	Lunch
1:30 - 2:30	Charge to Working Groups #1
2:30 - 3:30	Working Groups #1 Broadscale sampling, ocean (Yoshi Kuroda - org. com. liaison) (John Gould, Greg Johnson - co-chairs) Broadscale sampling, atmosphere (Rit Carbone - org. com liaison) (Dick Johnson, Jose Rutllant - co-chairs) Regionally enhanced observations (Roger Lukas - org. com. liaison) (Billy Kessler, Yihui Ding - co-chairs)
3:30 - 4:00	Coffee
4:00 - 4:30	Working Groups #1 - wrap up group activities
4:30 - 5:30	Plenary - presentation of WG summaries and discussion
5:30 - 7:30	Reception hosted by IPRC

#### **February 6, 2001**

8:00 - 8:45	Atmospheric data assimilation - Michael Ghil
8:45 - 9:30	Ocean model development - Andreas Schiller
9:30 - 10:15	Atmospheric model development - Mitch Moncrieff
10:15 - 10:45	Coffee
10:45 - 11:30	Coupled model development - Bryan MacAvaney
11:30 - 12:15	Ocean process studies - Russ Davis
12:15 - 1:15	Lunch
1:15 - 2:00	Atmospheric process studies - Chris Bretherton
2:00 - 2:15	Working groups # 2 charge
1:30 - 3:30	Working groups #2 Model requirements (Phil Sutton - org. com liaison) (Pablo Lagos, Magdalena Balmaseda-cochairs) Process studies (Dick Johnson, Bob Weller - o.c. liaisons) (Charlie Eriksen, Steve Esbensen-cochairs)
3:30 - 4:00	Coffee
4:00 - 5:30	Working groups #2 continue

**February 7, 2001**

8:00 –8:45	Data assimilation - ocean - Detlef Stammer
8:45 - 9:45	Plenary discussion of data assimilation
9:45 -10:30	Coffee
10:30 -12:00	Working groups #2 report
12:00 -1:30	Lunch
1:30-2:00	Discussion of Terms of Reference for Pacific Panel
2:00 - 3:30	Working groups writing and developing plans
3:30-4:00	Coffee
4:00 - 5:00	Working group meetings and writing
5:00 - 5:30	Plenary
	Identification of action items
	Identification of gaps in discussion of
	Pacific implementation plans
5:30	Adjourn formal workshop

**February 8, 2001**

8:00 -2:00	Preparation of workshop report
2:00 - 5:00	Working groups finish reports as needed
2:00 - 5:00	Organizing committee meets
	Review workshop
	Develop recommendations for Pacific Sector Panel
	Identify action items, key dates
	Discuss future meetings

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