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Call for Contributions

In the next issue of Exchanges, which will be published in December, we would like to highlight the accomplishments and future challenges in climate modelling. If you would like to contribute, please send your manuscripts which should not exceed 4 pages of text (single spaced) plus 2 figures electronically (text either in Word, RTF or ASCII, figures in postscript, eps or high resolution tiff format) to the editor of CLIVAR Exchanges: andreas.villwock@clivar.dkrz.de.

Please note, that your contribution has to be submitted by November 12th, 1999.

News from the ICPO

Dr. John Gould, Director, International CLIVAR Project Office, Southampton, UK

This issue of Exchanges has been timed to coincide with the conference on "The Ocean Observing System for Climate" (known in short as "OceanObs'99"). The Conference will focus on the design of the optimum mix of measurements needed to meet the goals of the Global Climate and Ocean Observing Systems (GCOS and GOOS) and of research programmes of which CLIVAR is the main one. CLIVAR through its Upper Ocean Panel (UOP) is one of the co-sponsors of the meeting and many members of CLIVAR panels and WGs will be attending. The CLIVAR UOP and the Data Task Team will meet at OceanObs.

We have selected a number of the articles for this issue of Exchanges that are based on papers to be presented at Oceanobs'99. They cover topics as diverse as sea surface height from satellites and tide gauges, buoy measurements and their assimilation, sea surface salinity and regional implementation issues for the Southern Ocean and South Atlantic. There is also, of course, a paper on the global ARGO array of profiling floats that will be a central plank of CLIVAR's observational strategy.

CLIVAR will use almost all the ocean observing systems to be described at OceanObs. Each presents scientific, technological and logistical challenges that will have to be faced as CLIVAR proceeds with implementation and melds these with atmospheric observations and modelling activities to form a coherent whole.

ICPO involvement in recent meetings

At the end of June I made a presentation to the General Assembly of the Intergovernmental Oceanographic Commission (IOC) on the theme of the influence of the ocean on the earth's climate and ultimately on peoples lives. The presentation is available under: http://www.dkrz.de/clivar/ioc_talk.html. Many of the earth's natural disasters are weather/climate induced and while there is a limit to the extent to which we can mitigate such impacts, certainly mitigation depends on understanding and predicting the climate systems and here CLIVAR together with the other component programmes of WCRP has a key role to play.

Fred Semazzi attended the IPCC Third Assessment Report (TAR) Working Group II for the preparation of Chapter 10 on Africa. The IPCC TAR is the first time a regional climate change projection assessment has being specifically prepared for IPCC for the whole of Africa based on global climate change prediction models. Discussion addressed many CLIVAR-related topics which could benefit from the CLIVAR Africa initiatives (See below).

In June Fred also took part in the international workshop on West African Monsoon Variability and Predictability (WAMAP), in Dakar, Senegal. The workshop was co-sponsored by CLIVAR to foster international communication and co-operation in advancing the understanding of the West African monsoons and its variability.

The workshop featured a special session on the status of the CLIVAR strategy for Africa. There was extensive discussion of the prospects for maintaining the momentum of the workshop's accomplishments through the CLIVAR Africa initiative. Several research projects on the West African Monsoons were represented, but they clearly exhibited need for international co-ordination in the area of climate variability and predictability. A panel discussion concluded that a dedicated CLIVAR Africa panel could play a critical role in providing the necessary scientific co-ordination and also minimise the current duplication of research efforts.

Finally both Fred and I attended the second week of the IUGG meeting in Birmingham which is reported on by Neville Nicholls (Page 39). The ICPO had a display of its PRA posters and many copies of the "Can we Predict Climate for the 21st Century" posters were distributed. Overall there were many papers of direct relevance to CLIVAR science but few were identified specifically as contributions to CLIVAR. Our aim should be that as CLIVAR moves towards implementation such papers will be acknowledged as contributions to CLIVAR.

Implementation issues

Countries are, I know, moving forward with formulating their national strategies for participation in CLIVAR and the co-ordination of these activities will in large part be a task for the CLIVAR Implementation Panels that we are starting to establish. (See Kevin Trenberth's article in Exchanges June 1999). The first of these Panels covers the Atlantic sector and I am pleased to say that Allyn Clarke our immediate past CLIVAR SSG co-chair has agreed to chair this group.

The CLIVAR Africa Study Group has produced its report which is a summary of their view of the important climate variability issues for the African continent. Following a decision by the SSG the Study Group will be superseded by a smaller Task team to be chaired by Chris Thorncroft and will be asked to

(a) develop an implementation plan for an international project to investigate the variability and predictability of the African climate. An important goal of the CLIVAR Africa research agenda would be to advance our understanding of the variability and predictability of the African climate and to promote relevant experimental prediction activities.

(b) build on the science report prepared by the CLIVAR Africa Study Group and to advise the SSG on the next steps for the development of an implementation plan. The study group is tasked to identify a manageable set of phenomena for which the respective states of readiness, from both scientific and resource points of view are sufficient for them to be the initial foci of the CLIVAR-Africa research agenda.

Other ICPO activities

On the staffing front we now have a new member of the ICPO, Dr. Katherine Bouton, who started in early July to work 50% of her time for the next 2 years in the ICPO primarily on data issues The Data Task Team, with Katherine's assistance, will be assessing the capabilities of the existing data and information delivery systems that cover the areas of CLIVAR science and assessing the extent to which these meet CLIVAR's needs. The Data Task Team will hold its first meeting under its chairman Ferris Webster in St. Raphael on October 23rd. In her first spell in the ICPO Katherine has started compiling a spreadsheet showing the CLIVAR data streams, identifying the data sources and also assessing the existing timescale for data delivery and the means of quality assurance. This will be a useful aide-memoire for the DTT.

With Katherine's help we have also made a start on producing a searchable bibliography of publications covering the broad scope of CLIVAR science. We are planning to use the monthly accession lists published by the UK Meteorological Office, to add key words reflecting the association of a publication with the CLIVAR PRAs, modelling activities, climate processes, observation techniques and regions. A trial version based on only 1-2 months' accessions will be trailed on the SSG before we decide to develop this further and to make it available on the WWW.

In parallel with this activity Christine Haas who is based in WMO in Geneva and who has been assisting Valery Detemmerman is constructing a searchable data base of the CLIVAR project that will enable an enquirer to find the status of development of research in the various PRAs and component project elements of CLIVAR. Christine and Katherine have been working together on this and aim to have an initial version ready for evaluation by December this year. It will be based on information held in the ICPO but clearly will provide a means of the ICPO being alerted to errors and omissions that can later be corrected.

This and future issues of Exchanges

We are introducing a new format for Exchanges in an attempt to reduce production costs. This time we have no colour figure but in future these will be grouped in 4 or 8 page spreads. We have for the first time printed Exchanges on recycled paper so as to save some trees.

These changes are the first of a number that we plan to make in the coming months to change CLIVAR's image. The changes will include a new logo. The original one has served us well but it uses red and green colours that designers say should never be used together (perhaps to help people who are colour blind) so we expect to enter the new millennium with a new image.

In Valery Detemmerman's article about the May SSG meeting (in Exchanges No 12) there she reported a decision made about the content of Exchanges. The SSG wished to see Exchanges contain more reports of CLIVAR science. I think with this bumper issue we are off to a good start and I ask you to please send us short articles on science topics relating to CLIVAR that you would like to share quickly with the over 2000 readers of Exchanges worldwide. It will be an immediate way of connecting the CLIVAR name with the science topics that the project addresses.

ARGO: The Global Array of Profiling Floats

The ARGO Science Team:
Dean Roemmich (chair) Scripps Institution of Oceanography, Ja Jolla, USA;
Olaf Boebel, Yves Desaubies, Howard Freeland, Brian King, Pierre-Yves LeTraon, Robert Molinari, Brechner Owens, Stephen Riser, Uwe Send, Kensuke Takeuchi, Susan Wijffels.

This contribution is an abstract of a paper which will be presented on the Ocean Obs99 Conference in St. Raphael, France in October and be published in the proceedings of this conference.

A broad-scale global array of temperature/salinity profiling floats, known as Argo, is planned as a major component of the ocean observing system, with deployment scheduled to begin in 2000. Conceptually, Argo builds on the existing upper-ocean thermal networks, extending their spatial and temporal coverage, depth range and accuracy, and enhancing them through addition of salinity and velocity measurements. The name Argo is chosen to emphasise the strong complementary relationship of the global float array with the Jason altimeter mission. For the first time, the physical state of the upper ocean will be systematically measured and assimilated in near real-time.

Objectives of Argo fall into several categories. Argo will provide a quantitative description of the evolving state of the upper ocean and the patterns of ocean climate variability, including heat and freshwater storage and transport. The data will enhance the value of the Jason altimeter through measurement of subsurface vertical structure (T(z), S(z)) and reference velocity, with sufficient coverage and resolution for interpretation of altimetric sea surface height variability. Argo data will be used for initialisation of ocean and coupled forecast models, data assimilation and dynamical model testing. A primary focus of Argo is seasonal to decadal climate variability and predictability, but a wide range of applications for high-quality global ocean analyses is anticipated.

The initial design of the Argo network is based on experience from the present observing system, on newly gained knowledge of variability from the TOPEX/Poseidon altimeter, and on estimated requirements for climate and high-resolution ocean models. Argo will provide 100,000 T/S profiles and reference velocity measurements per year from about 3000 floats distributed over the global oceans at 3-degree spacing Fig. 1). Floats will cycle to 2000 m depth every 10 days, with a 4-5 year lifetime for individual instruments (Fig.2). All Argo data will be publicly available in near real-time via the GTS, and in scientifically quality-controlled form with a few months delay. Global coverage should be achieved during the Global Ocean Data Assimilation Experiment, which together with CLIVAR and GCOS/

Drifting buoy positions after 3 years at a nominal depth of 1250 m
simulated by the 1/16° NRL global ocean model forced by 12 hourly ECMWF winds

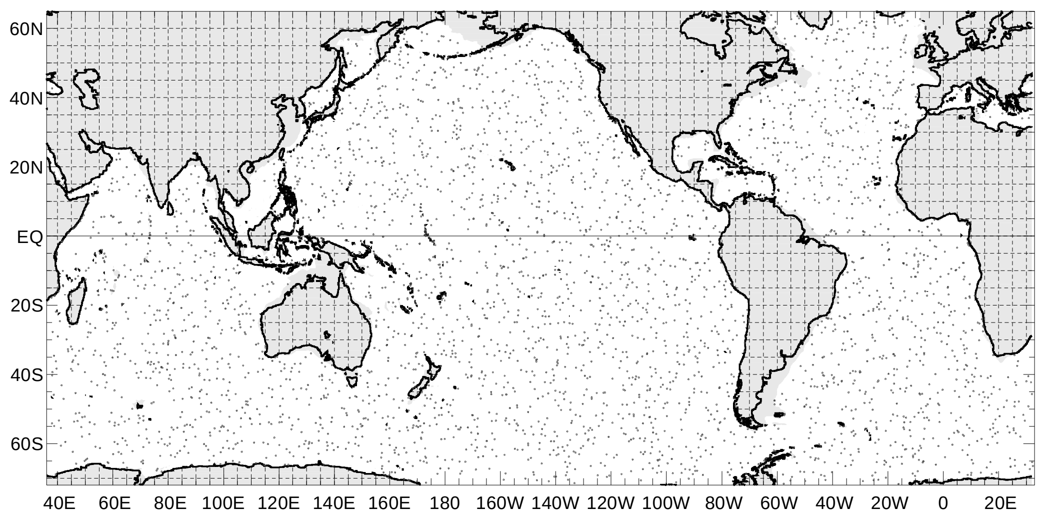

Figure 1: An example of the projected global distribution of ARGO floats

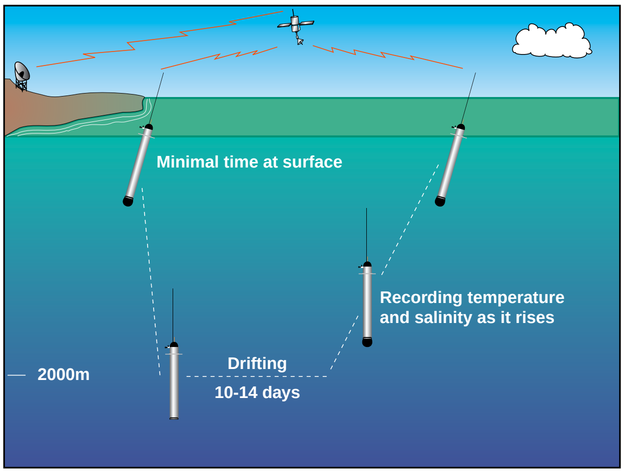

Figure 2: Schematic diagram of a ARGO float cycle

GOOS, provide the major scientific and operational impetus for Argo. The design emphasises the need to integrate Argo within the overall framework of the global ocean observing system.

International planning for Argo, including sampling and technical issues, is co-ordinated by the Argo Science Team. Nations presently having Argo plans that include float procurement or production include Australia, Canada, France, Germany, Japan, the U.K., and the U.S.A., plus a European Union proposal. Combined deployments from these nations may exceed 700 floats per year as early as 2001. Broad participation in Argo by many nations is anticipated and encouraged either through float procurement, logistical support for float deployment, or through analysis and assimilation of Argo data.

Sea Surface Salinity Observations for the Tropical Pacific

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The Tropical Pacific Ocean (TPO), in particular the western warm pool, is a region where salinity variations have an important influence on upper layer dynamics and thermodynamics, with implications on ENSO modelling and prediction (Lukas and Lindstrom, 1991; Webster, 1994; Anderson et al., 1996; Ji et al., 1999). Salinity corrections are needed to initialise heat storage in an ocean model properly with altimeter height data, considering that otherwise height errors can be as large as 5-10 cm, as shown in Fig. 1 (from Maes and Behringer, 1999. Upper layer salinity profiles can be estimated quire accurately with sea surface salinity (SSS) data combined with vertical EOF basis functions of T and S and surface height (altimeter) data (e.g. Maes, 1999). It is therefore evident that measuring SSS in the warm pool region offers important data for climate monitoring and prediction.

The climatic variations of SSS in the western TPO are quite substantial. This is evident from a monthly gridded TPO SSS field for the period 1979-92 which has been assembled and analysed from a combination of bucket, ship thermosalinograph (TSG) and CTD data (Delcroix, 1998). On average, low-salinity waters are observed near the Inter Tropical Convergence Zone (ITCZ), near the South Pacific Convergence Zone (SPCZ), and in the western Pacific warm pool. The maximum variability is located in both convergence zones, and near the eastern edge of the warm pool at the equator (between 150°E-160°W). An EOF analysis (not shown here) reveals that the variability in the convergence zones occurs chiefly at seasonal time scale, in relation to seasonal changes in precipitation and zonal advection of the North and South Equatorial Counter Currents, and to a lesser extent at the ENSO time scale, in relation with the equatorward (poleward) shift of the ITCZ and SPCZ during El Niño (La Niña). An EOF analysis of low-passed data (1 cycle per year and higher frequencies removed to study interannual signals) yields a temporal function (not shown) that is in phase with the Southern Oscillation Index (SOI). The spatial pattern (Fig. 2) clearly reveals predominant variability in the equatorial band near the dateline with decrease (increase) of SSS during El Niño (La Niña) events.

Given both the magnitude and the relevance of SSS variability, considerations for a TPO SSS observing system are presented by Lagerloef and Delcroix (1999) with the intent that it may also serve as an example for other regions where measuring SSS variability is important to CLIVAR science objectives. The network would ideally be comprised of *in situ* and satellite SSS measurements. The necessary time and space scales to resolve will vary depending on the scientific questions and the relevant physical processes. Nevertheless, some indicators to guide the choice of resolution scales are the natural decorrelation scales of SSS variability in the tropics. Using an SSS time series for the TAO mooring

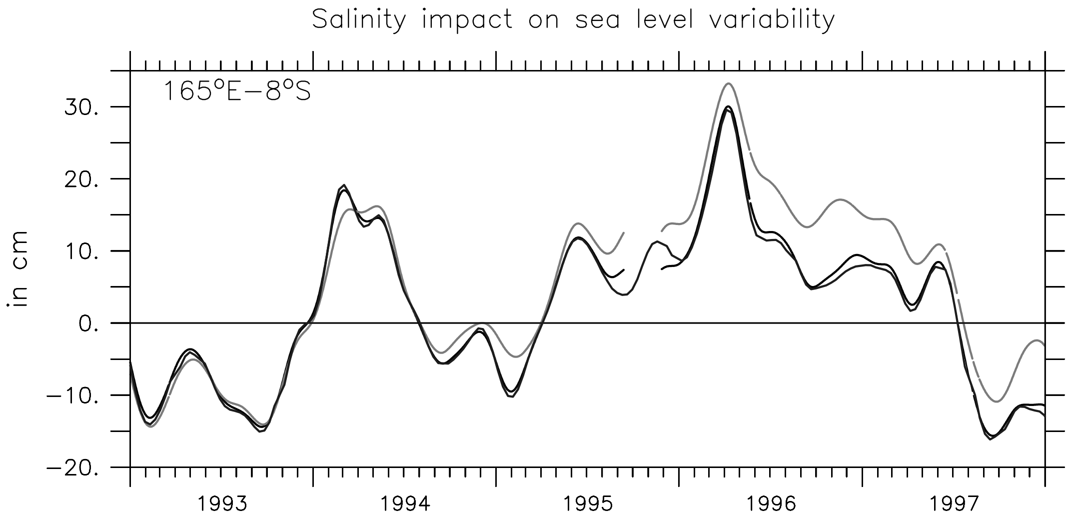


Figure 1: Time series of dynamic height with (dark curve) and without (upper light curve) salinity variability, compared with TOPEX/Poseidon (lower light curve) (from Maes and Behringer, 1999).

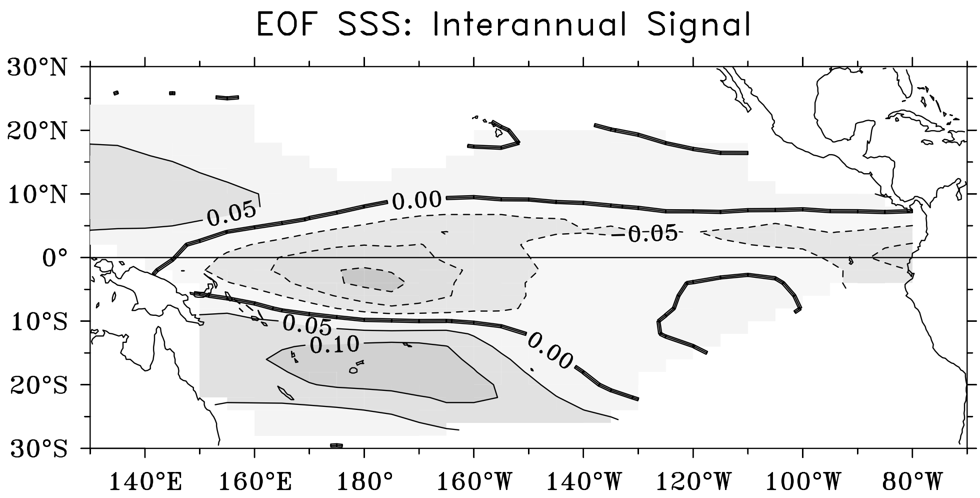


Figure 2: Spatial pattern of the interannual EOF in SSS. The time function (not shown) is in phase with the SOI. (Adapted from Delcroix, 1998).

at 0°-156°E, and several ship TSG transects in the Pacific warm pool, decorrelation scales are estimated to be ~70-90 days temporal and 2-4° spatial (Fig. 3), based on the zero crossing of the autocorrelation function. Sampling would well balanced between space and time decorrelation scales (~300 km and 90 days, respectively) with approximately 100 km and 30 day resolution.

Signal strengths as indicated by the standard deviations range from 0.4 to 0.6 psu, and the dynamic range is 1.5-2 psu. Errors on the order of 0.1 psu appear adequate to resolve the important seasonal to interannual patterns. A relative assessment of errors associated with *in situ* versus satellite can be made considering both measurement and sampling error. Measurement error implies the difference between a value measured from a sensor and the true value. For *in situ* observations, this is negligible (~.01 psu or less) as long as calibration procedures are adopted. On the other hand, measurement error with satellite SSS sensors may range from ~0.1->1 psu, depending on averaging scales and other factors. Sampling error implies the uncertainty of a single measurement within a particular space-time interval as representing the mean over that interval, given the space-time variability. This is estimated here by calculating the standard deviation over 10 day blocks in the TAO time series and 2 degree blocks in the ship transects described above (Fig. 3). The sampling errors sometimes approach .3 psu, while the root sum square (rss) of all the blocks within the respective time or space dimensions are consistently about 0.1 psu. An rss of all three dimensions (time, lat and lon) combined implies a sampling error of sqrt(3*(0.1)^2), or about 0.17 psu for one observation in a 2°x2° square every 10 days. This potential sampling error can be considered as the only important *in situ* error source in designing the observing system. Measurement errors from satellite (optimally designed for salinity measurements) are projected to be as

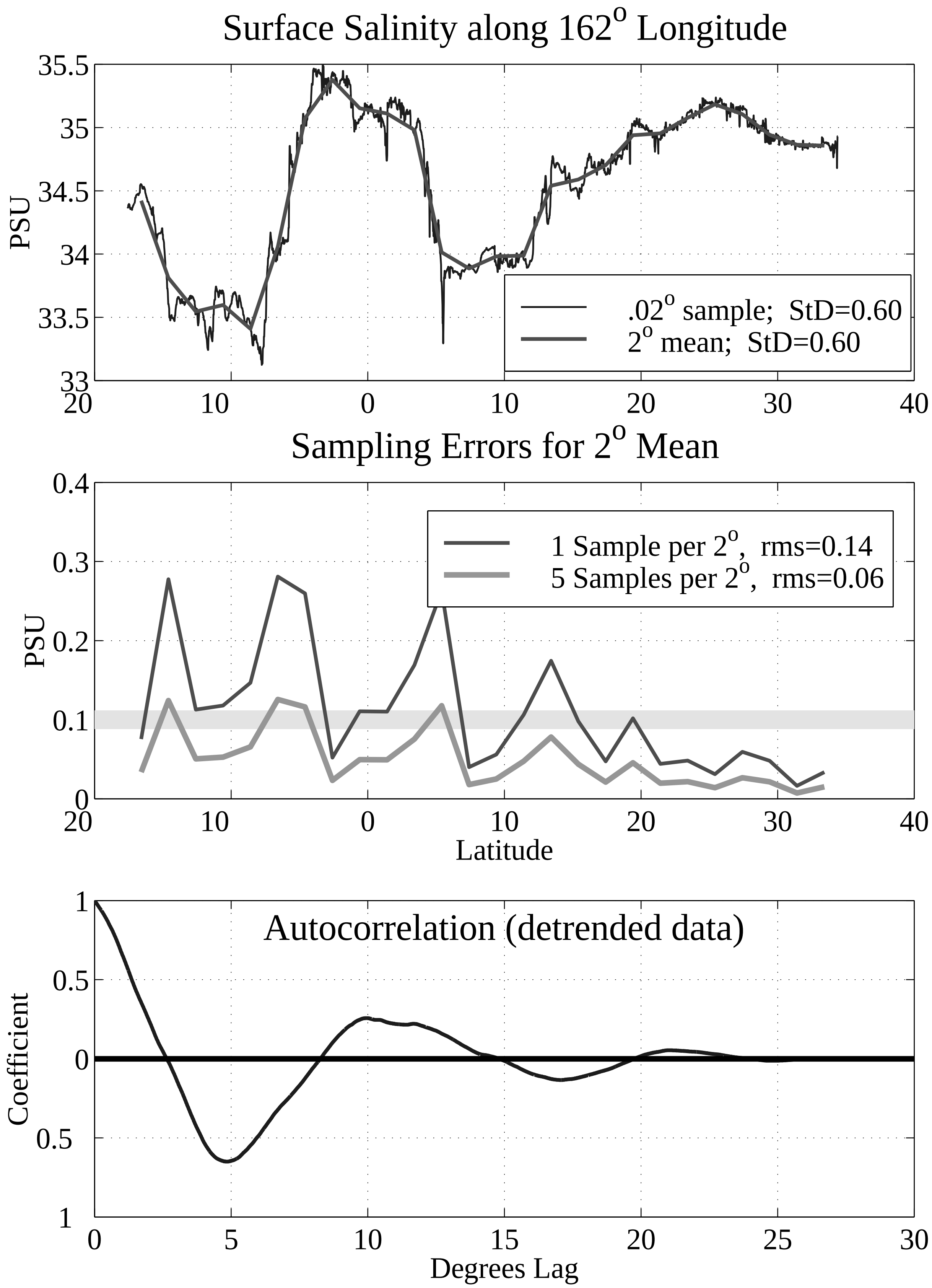


Fig. 3a: *Top: meridional SSS section along 162°E; middle: sample errors; bottom: auto-correlation function.*

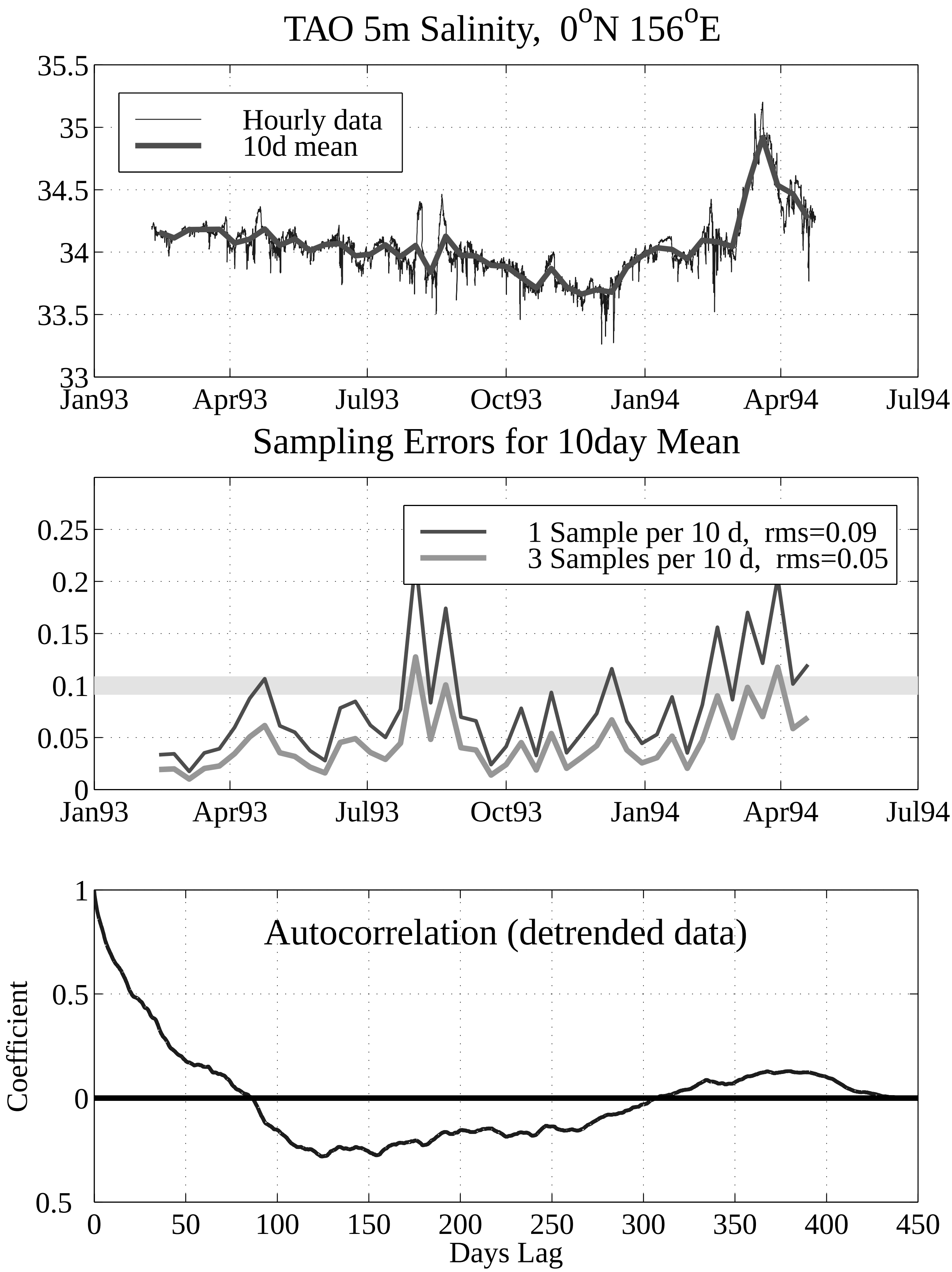


Fig. 3b: *Same as Fig. 3a except for a time series at 0, 156°E (Data courtesy of NOAA/PMEL).*

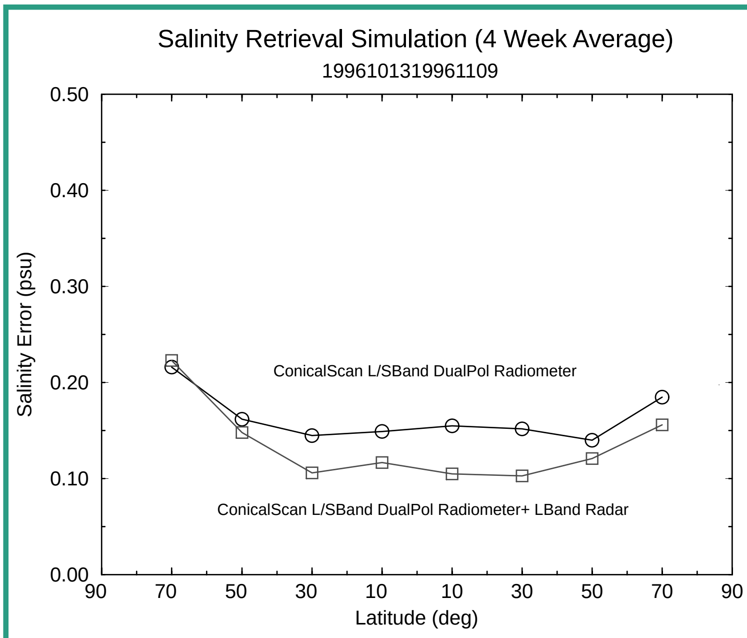
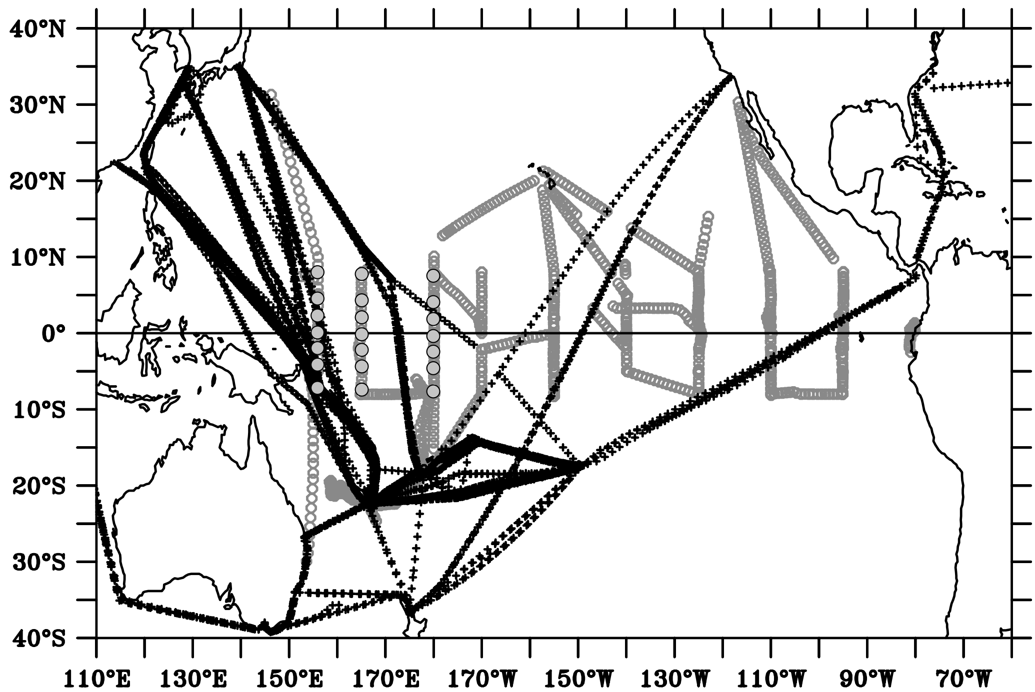


Figure 4 (left): *Simulated global OSIRIS satellite SSS measurement error versus latitude for 100 km and 30 day averages. Lower curve includes active radar for surface roughness corrections. (Courtesy S. Yueh, NASA/JPL).*

Figure 5 (below): *Typical yearly distribution of shipborne thermosalinograph lines and TAO moorings with SSS during 1997-1999.*



small as ~0.1-0.2 psu in the tropics (Fig. 4). Satellites have the advantage of uniform, systematic sampling and high resolution, but space-time filtering will be required to reduce measurement error to these acceptable levels. *In situ* systems provide long time series monitoring, characterization of subgrid space and time scale variations along available ship tracks and at available moored time series respectively, and an essential resource for satellite calibration.

A multi-platform *in situ* system (ship tracks, moorings and drifters) is clearly preferable over any stand-alone platform. Ship tracks and moorings provide the essential information on space and time scales as shown above, as well as extended time series, while a drifting array (surface drifters and ARGO) will be needed to fill in the gaps between fixed ship tracks and mooring sites. The TPO SSS observing system presently has some essential *in situ* elements in place; namely the TSG tracklines, and a number of TAO moorings with salinity sensors (Fig. 5). However, the sampling remains very sparse and certainly inadequate to resolve the space-time decorrelation scales.

The advent of ARGO will improve the sampling rate considerably in both space and time (ARGO Science Team, 1999). The component that has received less attention is the surface drifter programme. A large number of surface drifters are deployed in the tropical Pacific every year. Experimental salinity sensors were successfully used on some buoys in 1992-1993 and it is feasible to include specially designed salinity sensors on surface drifters in the future at a unit cost of about $2K. Technical approaches to maintaining calibration stability over ~1 year life of the drifter need to be considered.

Satellite SSS measurements (Lagerloef et al., 1995) will likely become available in the next half decade. Two satellite concepts are relatively advanced in their design. SMOS (Soil Moisture Ocean Salinity) is approved by the European Space Agency (ESA) (see http://www-sv.cict.fr/cesbio/smos). The sensor is a Y-shaped array, 2-D interferometric radiometer and the mission is planned for 3-5 year duration. SMOS is designed to address terrestrial hydrology and ocean science, as the name implies. Considering the technical challenges with its interferometric design, the ultimate SSS retrieval errors cannot be predicted reliably at present and will be addressed in the next two years. The anticipated launch year is 2004 or 2005. OSIRIS (Ocean salinity Soil moisture Integrated Radiometric Imaging System) is a large mesh antenna design under development at NASA/JPL (Njoku et al., 1999), but is not an approved mission. OSIRIS is designed with the primary objective of obtaining ocean salinity retrievals, as well as soil moisture, with the highest possible measurement accuracy using current technology. It includes a conical scanning ~6 m antenna and constant incidence angle viewing geometry that will allow forward and backward beams to be averaged with a spot resolution of ~40 km. An optional L-band radar for wind and sea state correction is also being evaluated. The relatively simple OSIRIS design allows retrieval simulation studies to predict that errors will be ~0.1 psu in the tropics when averaged to 100 km and 30 day scales as shown above. From this, it is concluded that, in principle, satellites will be able to resolve the important space and time scales with errors similar to or perhaps less than the sampling error of any foreseeable in situ network. However, they will not achieve this accuracy without perpetual calibration from in situ data. The satellite and in situ components together offer the optimal SSS observing system for climate studies in tropical Pacific, and this assessment is undoubtedly applicable to other regions as well.

References:

Anderson, S.P., R.A. Weller and R. Lukas, 1996: Surface buoyancy forcing and the mixed layer of the Western Pacific warm pool: Observations and 1-D model results, *J. Climate*, **9**, 3056-3085.

ARGO Science Team: On the design and implementation of Argo, 1999: an initial plan for a global array of profiling floats. *International CLIVAR Project Office Report No. 21*, 32pp.

Delcroix, T., 1998: Observed surface oceanic and atmospheric variability in the Tropical Pacific at seasonal and ENSO time scales: a tentative overview, *J. Geophys. Res*, **103**, 18611-18633.

Delcroix, T., L. Gourdeau and C. Hnin, 1998: Sea surface salinity changes along the Fiji-Japan shipping track during the 1996 La Niña and 1997 El Niño period, *Geophys. Res. Letts*, **25**, 3169-3172.

Ji, M., R.W. Reynolds, and D.W. Behringer, 1999: Use of TOPEX/POSEIDON sea level data of ocean analyses and ENSO prediction: some early results, *J. Climate*, in press.

Lagerloef, G., C. Swift and D. LeVine, 1995: Sea surface salinity: The next remote sensing challenge. *Oceanography*, **8**, 44-50, 1995.

Lagerloef, G. and T. Delcroix, 1999: Sea surface salinity, A regional case study for the tropical Pacific, *Proceedings: International Conference on the Ocean Observing System for Climate*, in press.

Lukas, R., and E. Lindstrom, 1991: The mixed layer of the western equatorial Pacific ocean. *J. Geophys. Res.*, **96**, 3343-3358.

Maes, C., 1999: A note on the vertical scales of temperature and salinity and their signature in dynamic height in the western Pacific Ocean. Implications for data assimilation. *J. Geophys. Res.*, **104**, 11037-11048.

Maes, C. and D. Behringer, 1999: Using satellite-derived sea level and temperature profiles for determining the salinity variability: a new approach. *J. Geophys. Res.*, submitted.

Njoku, E., W.J. Wilson, S.H. Yueh, and Y. Rahmat-Samii, 1999: A Large Antenna Microwave Radiometer-Scatterometer Concept for High-Resolution Surface Sensing, *IEEE Trans. Geosci. Remote Sensing*, submitted.

Webster, P., 1994: The role of hydrological processes in ocean-atmosphere interactions. *Rev. Geophys.*, **32**, 427-476.

Sea Surface Height Observations from Altimeters and Tide Gauges

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This report is largely based on a longer paper (Mitchum et al., 1999; hereinafter O99) that we have recently prepared for the OCEANOBS '99 conference to held in St. Raphael, France in October, 1999. We will give a summary of that more complete discussion of the future of the global sea surface height observations, which we define as height measurements by satellite altimeters and sea level measurements from tide gauges, and will identify the main issues that we see in creating and maintaining a long-term observing system capable of addressing the CLIVAR research questions. In the O99 paper we discussed several climate-related problems where the sea surface height observations have already proven to be useful, such as studies of the energetics of the global mesoscale field (e.g., McLean et al., 1997; Stammer and Wunsch, 1998) and the interactions of this field with the oceanic mean circulation, studies of El Niño - Southern Oscillation (ENSO) interannual variations (e.g., Cheney and Miller, 1988; Boulanger and Menkes, 1999), and some recent efforts, which we will briefly discuss below, to use combinations of sea level and altimetric measurements in an attempt to measure global volume change rates well enough to test the projections of the Intergovernmental Panel on Climate Change (IPCC, see Warrick et al., 1996). In this report we will focus on the volume change problem because of the importance of this effort for assessing possible anthropogenic impacts on the Earth's climate, and also because it is an excellent example of how the tide gauge and altimetric series are more useful together as part of an integrated system than

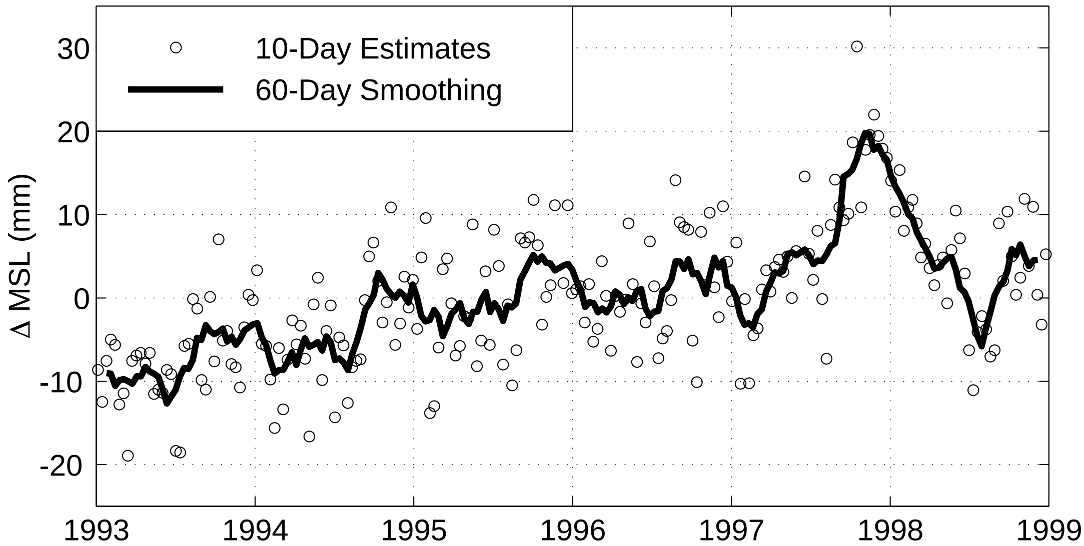

Figure 1: Time series of the global mean sea level computed from T/P (after Nerem and Mitchum, 1999). A mean sea level estimate is computed for each 10-day T/P cycle, and these points are shown by open circles. The solid curve is a 60-day running mean of the 10-day points that emphasises the low frequency variability in the curve.

Sea level records longer than 50 yrs in the PSMSL archive

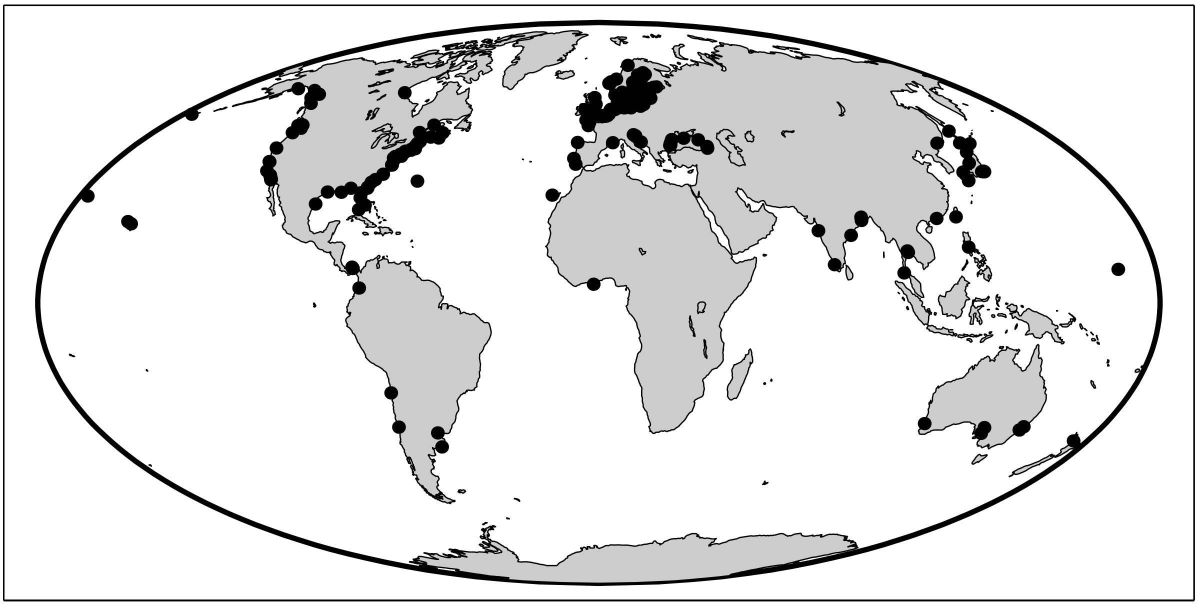

Figure 2: Sea level stations from the PSMSL dataset that have at least 50 years of monthly mean data available. Although the coastlines of Europe and North America are well represented, open ocean islands are not and the southern hemisphere is also under-represented. Despite these spatial coverage limitations these records represent a unique resource for studies of interannual to decadal variability in the ocean-atmosphere system.

when used alone. We will also summarise our conclusions concerning the future strategy for maintaining a sea surface height observing system, although space will not allow us to justify these conclusions in detail. Readers interested in further detail, however, can refer to the O99 paper.

As most readers will know, sea surface height (SSH) responds to a rich set of phenomena, and SSH data can therefore be used to study the processes giving rise to these phenomena. For example, SSH changes with variations in surface geostrophic velocities via the geostrophic balance, and with changes in the heat content of the upper ocean. An excellent discussion of the signals in tide gauge records, which of course also applies to altimetric heights, was given a number of years ago for sea level data by Chelton and Enfield (1986), and more recent reviews that focus more on SSH from altimetry have also been given (e.g., Wunsch and Stammer, 1998; Fu, 1999). SSH also responds to changes in the total ocean volume that might accompany increases or decreases of grounded ice mass, for example, and we will focus here on a brief review of this application. Although it may seem that altimetric time series must be too short to address this problem, and that the global tide gauge network determinations (e.g., Douglas, 1991, 1995; Warrick et al., 1996) of the rise rate cannot be improved upon, this is not necessarily the case. The reason is that the altimetric data can make a sensible estimate of the global average SSH at a point in time, thus allowing signals that correspond to simple redistributions of ocean mass to largely cancel out. Tide gauge estimates of volume change, on the other hand, must use long time series to temporally average out interannual and decadal variations in SSH. Averaging over the global network helps, but cannot remove mass redistribution signals at interannual to decadal time scales.

Estimates of the trend in global mean sea level from altimetry have been done by various groups (e.g., Nerem, 1995; Minster et al., 1995; Cazenave et al., 1998; Nerem et al., 1999), and a recent summary of these calculations has been given by Nerem and Mitchum (1999), who give the mean sea level change, or volume change, curve that we have reproduced here (Fig. 1). One reason for focusing on the volume change problem in this report is that in order for altimetric estimates of SSH to be useful in this context, the altimetric time series must be stable in time. That is, the bias, or drift, errors must be controlled very carefully. The necessity of monitoring errors such as these has led to the development of altimetric drift estimates from the global tide gauge network (Mitchum, 1998), which provides an excellent example of the synergistic use of the two components of the overall sea surface height observing system. For researchers interested in shorter time scales, it might be useful to note that if the altimetric series can be maintained to a standard that allows these ocean volume calculations to be done, then the SSH series will certainly be stable enough for studies of variability at interannual to decadal scales; that is, these data will be adequate for

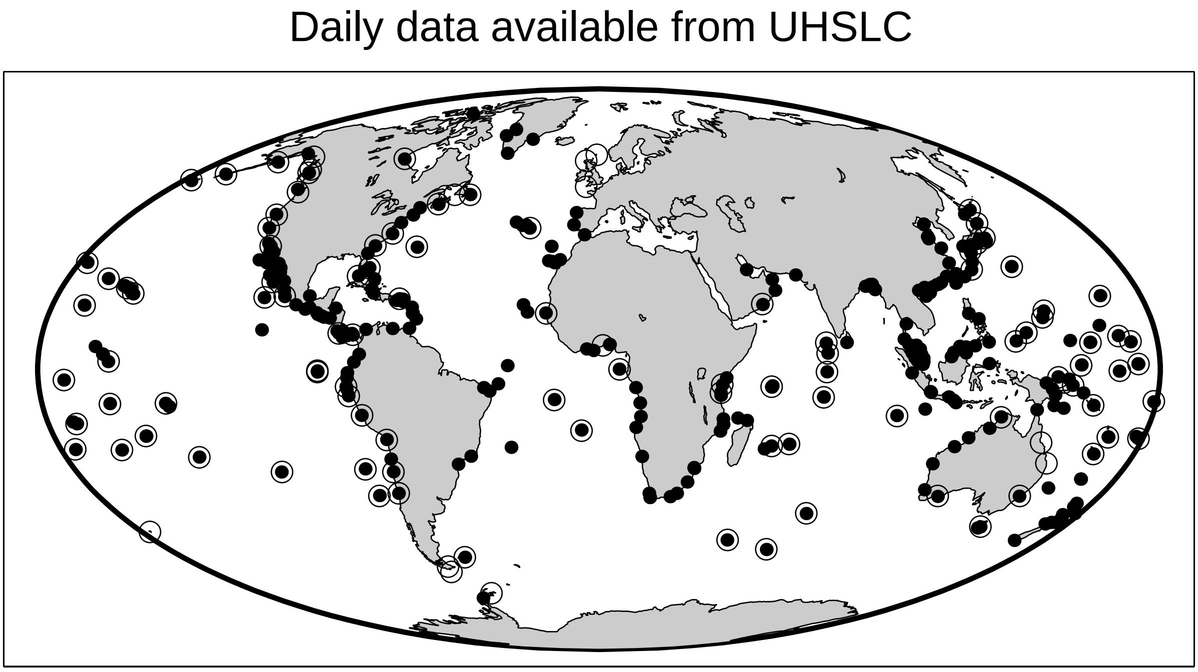

Figure 3: Sea level stations where daily data is available from the University of Hawaii Sea Level Center. Note that all stations are shown regardless of the record length available. Few of these records approach the 50-year lengths shown in the previous figure. The stations shown with open circles, however, report daily data in near real-time (i.e., after 1-2 months), which is a significant advantage for studies combining sea level and altimetric heights.

addressing the CLIVAR objectives.

Before discussing this problem further, we will digress briefly to review the assessment given in O99 of the present status of the observing system and the prospects for continuation and improvement in the future. The altimetric situation at present is that the TOPEX/Poseidon (T/P) mission, a joint mission of the U.S. NASA and the French CNES, continues to return high quality data and these time series are approaching 7 years in length at the time of this writing. ERS-2, the continuation of the ERS-1 satellite launched by the European Space Agency in 1992, is also continuing to produce data that is nearly of T/P quality. Having these two altimeters in orbit simultaneously has proven to be a unique advantage. The spatial- temporal sampling is improved using both datasets, and the quality of the T/P dataset has proven useful in improving the orbit estimates for ERS-2 (LeTraon and Ogor, 1998) and in evaluating the basic precision and accuracy of these data. In turn, the measurements from ERS-2 have been used to evaluate potential problems with the T/P instruments, making it clear that multiple altimetric instruments are complementary rather than redundant. In addition, multiple altimeters are absolutely necessary for properly observing the oceanic mesoscale variations (e.g., LeTraon et al., 1999 and Jacobs et al., 1999), although in the interest of space we will not discuss this important issue further.

Despite the success of the present missions, it is not certain that precision altimetry will continue into the future. The continuation of the T/P time series seems fairly certain, with the JASON-1 mission, again a French and U.S. collaboration, scheduled to launch in 2000 and to occupy the T/P groundtrack. There is also a proposed JASON-2 scheduled for 2004, although this mission is not yet formally approved. ENVISAT is scheduled to launch in late 2000 or early 2001 and will be in the same orbit as the ERS series. These missions, if all go forward, will carry the T/P and ERS time series until probably 2005 and possibly until 2010, although the latter is likely an overly optimistic estimate. Past that time, starting around 2010, there is a U.S. plan to include an altimeter in the NPOESS series, although these plans are not yet defined in detail. On the positive side, there are technological developments on the horizon that are potentially very exciting. First, as part of the NASA Instrument Incubator Program, a project has been funded at the Johns Hopkins University's Applied Physics Laboratory to develop a low-power altimeter that is light enough to enable multiple altimeters to be placed into orbit from a single launch vehicle (Raney, 1998). CNES in France is also investigating low cost altimeter missions on microsatellites as part of their ALTIKA project, which will similarly allow multiple altimeter coverage at low cost. Second, an alternative to multiple satellites may be the development at the JPL in the U.S. of a wide swath altimeter that obtains SSH measurements not only at nadir, which is the situation with all present altimeters, but along a swath of order 200 km total width, and it is possible that an experimental version of this swath altimeter might be flown as part of the JASON-2 mission.

A major advantage of the sea surface height observing system is that the satellite altimetry is complemented by one of the most comprehensive set of time series of comparable in situ data available for any physical parameter. These are, of course, the tide gauge sea levels. Instrumental sea level records from tide gauges exist back to the 19th century, and records exceeding 50 years in length are not uncommon (Fig. 2). Having these long in situ records in conjunction with the shorter altimetric records allows studies of the longer temporal context for any signals observed in the altimetric record of SSH. One example of this (Johnston and Merrifield, 1999) is the combination of the spatial information from altimetry and the temporal strength of the tide gauge series to describe interannual variability in the strong zonal circulation in the tropical Pacific. Historically, the sea level data used by most researchers have been the monthly mean sea level values collected at the Permanent Service for Mean Sea Level (PSMSL) of the International Council of Scientific Unions. These activities are complemented by a programme of the Intergovernmental Oceanographic Commission called the Global Sea Level Observing System (GLOSS; see IOC, 1997) that exists to monitor the development of the global sea level system and dataset. Major contributions to GLOSS have been made as part of the Tropical Ocean Global Atmosphere (TOGA) and World Ocean Circulation Experiment (WOCE) projects in the area of making daily data available in addition to the monthly means, which can be important for the joint use of the sea level data with the altimetric series. At present daily data from over 200 stations are available, over 100 of them in near real-time, from the University of Hawaii Sea Level Center (Fig. 3). The future plans for the tide gauge network are focused on maintaining and improving the quality of the GLOSS Core network, which is largely complete in the sense that most of the GLOSS gauges are presently operational, although modernisation and upgrades are required at many sites. An important part of the plan for the future is to provide better geodetic controls on the tide gauges in the GLOSS Core Network and in the wider GLOSS Long-Term Trends network (IOC, 1997; Neilan et al., 1998). This issue arises naturally as we now turn to a discussion of how the tide gauges are presently being used to estimate altimeter drift rates in order to allow an estimation of the very low frequency global sea

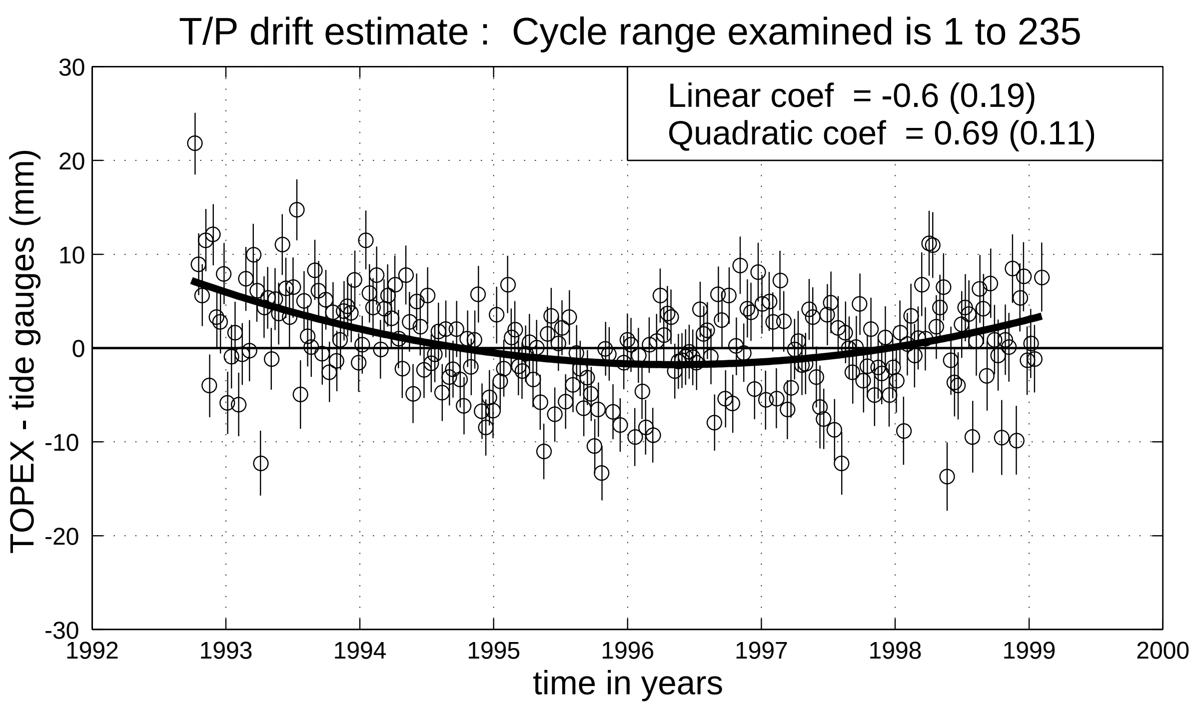

Figure 4: The present estimate of the estimate of the T/P drift error based on the global tide gauge network. All of the tide gauges shown as open circles in Figure 3 were used in this analysis, although some did not prove useful. Additional details on the method used to derive this estimate are given by Mitchum (1998) and in Nerem and Mitchum (1999). The solid curve is from a weighted least squares fit of a quadratic curve to the 10-day estimates given by the open circles.

level changes associated with ocean volume change, for example those shown in Figure 1.

Focusing on the altimetric drift rate estimates assumes that the altimetric data are already quite repeatable; i.e., that the precision of these data is very good. Fu et al. (1994) provide a summary of results from the initial T/P evaluation that indicated that T/P were repeatable to order several centimetres for the highest resolution data, which are taken at 1 Hz frequency, or at approximately 6-7 kilometre spacing along the groundtrack. Of course, spatially and temporally averaged data are even more precise. Since that time the errors have decreased further, largely due to improvements in the orbit determination (e.g., Tapley et al., 1996), but despite this admirable precision, we must still be concerned with identifying low frequency errors, or drifts, in the T/P data when using these data for estimating sea level change. Techniques to do this have been developed using the tide gauge measurements, and we will focus on a method that uses the global tide gauge network (Mitchum, 1998). This technique works by computing a difference of the T/P heights with the in situ estimates of sea level in order that the ocean signals that are common to both the T/P and in situ data will cancel, isolating the errors for further analysis. After this global tide gauge approach successfully identified an algorithm error in the early T/P data and also gave the first indication of a possible drift in the wet correction (Mitchum, 1998), confidence in these calculations increased and these drift estimates are now routinely considered in the ongoing T/P calibration and validation activity. These estimates of the altimeter drift (Fig. 4) are essential for properly interpreting the mean sea level curves (e.g., Fig. 1) as due to true ocean volume changes.

Using tide gauges to provide a ground truth for the T/P variations does have a serious limitation in that it is necessary to independently estimate the vertical land motion in the vicinity of each gauge used in the analysis. A striking demonstration of the effect of land motion has been given by Cazenave et al. (1999) at the island of Socorro off the west coast of Mexico, for example, using independent estimates of the land motion at the site from DORIS measurements. The ultimate solution to the land motion problem is to have space geodetic measurements, such as DORIS or GPS, at any tide gauge used in the drift estimation. Although at present relatively few gauges are so equipped, plans do exist for adding these measurements to the GLOSS gauges (Neilan et al., 1998), but for now alternative methods for estimating land motion and assessing the uncertainty due to land motion have been devised. Discussing these methods is beyond our scope of the present paper, but we simply note that a sensitivity analysis indicates that the uncertainty in the inferred drift rate due to the uncertainty in the land motion is of order 0.4 mm/yr. This is still the dominant error in the estimate of the drift rate, but it is a significant improvement over the 1 mm/yr. error estimate made by Mitchum (1998) in the earlier calculations.

To summarise, with the success of the T/P mission, as well as with the ERS series of altimeters, we now know how to maintain an effective altimetric observing system. Although we did not go into detail here, we conclude that ideally the future altimetric portion of the sea level observing system should consist of an altimeter of T/P class or better (such as JASON) in the T/P groundtrack. This altimeter would be supplemented with additional altimeters, possibly of somewhat lesser precision, in order to resolve the oceanic mesoscale variations. Potentially a swath altimeter in the T/P track could significantly improve the spatial resolution available from a single altimeter, and various plans exist to enable multiple, inexpensive altimeters as an alternative. In other words, the technology exists to make an effective altimetric observing system, and resources are the limiting factor at this point. In terms of the tide gauge component of the system, two considerations are most important. First, the GLOSS Core network and the larger GLOSS Long-Term Trends network (IOC, 1997) must be maintained and access to the high frequency data needs to be improved. Second, space geodetic techniques need to be used at as many gauges as feasible in order to remove the ambiguity associated with land motion when using the tide gauges to insure the stability of the altimetric heights. If this can be done, the combined sea surface height time series will be of adequate precision and accuracy to address a broad range of climate questions, including the IPCC projections of accelerated sea level rise rates and the decadal variability goals of CLIVAR.

References:

Boulanger, J.-P., and C. Menkes, 1999: Long equatorial wave reflection in the Pacific Ocean from TOPEX/POSEIDON data during the 1992-1998 period. *Climate Dynamics*, **15**, 205-225.

Cazenave, A., K. Dominh, M.C. Gennero, B. Ferret and C. Brossier, 1998: Global mean sea level changes from T/P and ERS-1. *Physics and Chemistry of the Earth*, **23**, 1069-1075.

Cazenave, A., K. Dominh, F. Ponchaut, L. Soudarin, J.-F. Cretaux, and C. Le Provost, 1999: Sea level changes from Topex-Poseidon altimetry and tide gauges, and vertical crustal motions from DORIS. *Geophys. Res. Lttrs*., **26**, 2077-2080.

Chelton, D., and D. Enfield, 1986: Ocean signals in tide gauge records. *J. Geophys. Res*., **91**, 9081-9098.

Cheney, R.E., and L. Miller, 1988: Mapping the 1986-87 El Niño with GEOSAT altimeter data. *EOS Trans. AGU*, **69 (31)**, 754-755.

Douglas, B., 1991: Global sea level rise. *J. Geophys. Res*., **96,** 6981-6992.

Douglas, B.C., 1995: Global sea level change: Determination and interpretation. *Revs. Geophys. (supp.)*, 1425-1432.

Fu, L.-L., 1999: Ocean Circulation and Variability from Satellite Altimetry, in Ocean Circulation and Climate, J. Church and G. Siedler (eds). *Academic Press,* in press.

Fu, L.-L., E. Christensen, C. Yamarone, M. Lefebvre, Y. Menard, M. Dorrer, and P. Escudier, 1994: TOPEX/POSEIDON Mission Overview, *J. Geophys. Res*., **99**, 24369-24381.

IOC, 1997: Global Sea Level Observing System (GLOSS) implementation plan-1997. *Intergovernmental Oceanographic Commission, Technical Series,* No. 50, 91 pp. and Annexes.

Jacobs, G., C. Barron, M. Carnes, D. Fox, H. Hurlburt, P. Pistek, R. Rhodes, W. Teague, J. Blaha, R. Crout, O. Smedstadt, K. Whitmer, 1999: Navy Altimeter Data Requirements. Technical Report, Naval Research Laboratory, Stennis Space Center, MS 39529-5004, USA.

Johnston, T.M.S, and M. Merrifield, 1999: Interannual Geostrophic Current Anomalies in the Near-Equatorial Western Pacific. *J. Geophys. Res.*, in press.

P.Y. Le Traon and F. Ogor, 1998: ERS1/2 orbit improvement using T/P: The 2 cm challenge. *J. Geophys. Res*., **95**, 8045-8057.

LeTraon, P., and G. Dibarboure, 1999: Mesoscale mapping capabilities of multiple-satellite altimeter missions. *J. Atmos. and Oceanic Tech*., in press.

McLean, J., A. Semtner, and V. Zlotnicki, 1997: Comparisons of mesoscale variability in the Semtner-Chervin 1/4° model, the Los Alamos 1/6° model, and TOPEX/POSEIDON data. *J. Geophys. Res.*, **11**, 25203-25226.

Minster J.F., C. Brossier, and P. Rogel, 1995: Variations of the mean sea level from T/P data. *J. Geophys. Res*., **100**, 25153-25162.

Mitchum. G., 1998: Monitoring the stability of satellite altimeters with tide gauges. *J. Atmos. and Oceanic Tech*., **15**, 721-730.

Mitchum, G., R. Cheney, L.-L. Fu, C. Le Provost, Y. Menard, and P. Woodworth, 1999: The Future of Sea Surface Height Observations. Proceedings of OCEANOBS '99, St. Raphael, France, October, 1999, in press.

Neilan, R., P.A. Van Scoy, and P.L. Woodworth (eds), 1998: Proceedings of the workshop on methods for monitoring sea level: GPS and tide gauge benchmark monitoring and GPS altimeter calibration. Workshop organised by the IGS and PSMSL, Jet Propulsion Laboratory, 17-18 March 1997, 202pp.

Nerem R., 1995: Measuring global mean sea level variations from TOPEX/POSEIDON altimeter data., *J. Geophys. Res*., **100**, 25135-25152.

Nerem. R., and G. Mitchum, 1999: Sea level changes, in Satellite Altimetry and Earth Sciences, L.-L. Fu and A. Cazenave (eds). *Academic Press*, in press.

Nerem, R., D. Chambers, E. Leuliette, G. Mitchum, and B. Giese, 1999: Variations in global mean sea level associated with the 1997-98 ENSO event. *Geophys. Res. Lttrs.*, in press.

Tapley, B. D., M. M. Watkins, J. C. Ries, G. W. Davis, R. J. Eanes, S. R. Poole, H. J. Rim, B. E. Schutz, C. K. Shum, R. S. Nerem, F. J. Lerch, J. A. Marshall, S. M. Klosko, N. K. Pavlis, and R. G. Williamson, 1996: The Joint Gravity Model 3. *J. Geophys. Res*., **101**, 28029-28049.

Raney, R.K., 1998: The delay/Doppler radar altimeter. IEEE Trans. Geosci. Rem. Sens., 36 (5), 1578-1588.

Stammer, D., and C. Wunsch, 1998: Temporal changes in eddy energy of the oceans. *Deep Sea Res. II*, **46**, 77-108.

Warrick, R.A., C. Le Provost, M.F. Meier, J. Oerlemans, and P.L. Woodworth, 1996: The science of climate change. Second assessment report of the Intergovernmental Panel on Climate Change, eds. J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell. Cambridge University Press, 572pp.

Wunsch, C., and D. Stammer, 1998: Satellite altimetry, the marine geoid, and the oceanic general circulation. *Ann. Rev. Earth Planet. Science*, **26**, 219-253.

PIRATA: Recent results and future perspectives

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PIRATA has initiated the installation and maintenance operations of an ocean observing system for climate studies in the Tropical Atlantic based on an initial array of 12 moored PMEL/NOAA Next Generation ATLAS moorings (which extends the capability of the previous ATLAS technology), meteorological and tide stations with satellite transmitting capability on two Brazilian oceanic islands, one coastal meteorological buoy near the Brazilian coast, one tide station in one island in the Gulf of Guinea, and one internally recording ADCP current meter mooring on the Equator (Figure 1). The principal objective is to monitor atmospheric-oceanic surface variables and upper ocean thermal structure at optimal locations in the Tropical Atlantic, where the most important regional large scale ocean-atmosphere interaction processes take place. The measurements are transmitted daily via satellite, and are available to all interested users in the research or operational communities. In addition, the original data are recorded internally every 10 minutes for most of sensors in the acquisition system, to be retrieved one year later during mooring substitution and refurbishment operations. Presently, PIRATA is concentrating on the operational side of the initiative and very broad themes related to the future expansion of the array, and the main scientific findings will be the subject of discussions next year.

The choice of the "optimal locations" was made based on past but recent knowledge of the areas where the most critical ocean-atmosphere interaction processes seem to take place. The two main processes which guided the design of the array geometry were: (1) the "equatorial mode of variability", of "El Niño type", which is known to be important in the description of the annual cycle, but also seem to play a role in Atlantic Warm Events at interannual scales; (2) a "dipole mode", which refers to the decadal variability of the interhermispheric sea surface temperature (SST) gradient, which correlates well with land climate variability at these scales.

Implementation started with the first deployment in September 1997. The initial scheduling anticipated an end of the "Pilot Phase" in March 2001, but extension of this phase up to 2006 is presently being agreed upon by the partners.

Three years of measurements will give a good start on the issues of seasonal to interannual variations in the tropical Atlantic, but will not be enough to relate directly to decadal scale variability. However, these observations will make it possible to understand a few key processes thought important for forcing variability on this long time scale. PIRATA also has the potential to establish the foundation for a longer term monitoring network that will address more completely some important scientific problems, under the auspices of CLIVAR, GOOS and GCOS.

Scientific questions of interest

Of the main "socio-economic" drivers for the establishment of PIRATA, two are noteworthy: (a) the strong long term correlation between seasonal precipitation anomalies in the semi-arid north-northeastern Brazil and the African Sahel, and off-equatorial Atlantic SST anomalies (correlation has an inter-hemispheric dipolar distribution), which reveal variability peaking on a decadal (12-13 years) scale, as compared to a smaller correlation with El Niño/ La Niña in the Pacific at this scale, and (b) an "Atlantic El Niño", the El Niño-like warm event in the Eastern Atlantic, which modulates and also disturbs fisheries ecosystems from the Gulf of Guinea down to Namibia, and equally influences the terrestrial climate, this process having a seasonal to decadal variability.

The scientific questions of interest in PIRATA may therefore be formulated thus:

- what processes are responsible for changes in the off-equatorial meridional SST gradient vs. those changes in SST along the equator, and the related problem of variability of the excursions of the Inter-tropical Convergence Zone (ITCZ)?
- to what degree does the tropical Atlantic upper ocean variability affect the coupled ocean-atmosphere-land system of the region and its predictability?

- to what extent is the predictability of the equatorial effects affected by the meridional off-equatorial variability?
- to what degree is the predictability of the coupled system within the tropical Atlantic basin determined by local interactions vs. external influences such as connections with the El Niño-Southern Oscillation (ENSO) and extra-tropical Atlantic processes (North Atlantic Oscillation - NAO, the South Atlantic Convergence Zone-SACZ, the northward propagation of cold fronts)?
- how do anomalous changes in the oceanic transports of mass, heat and freshwater in the region affect SST within the tropical Atlantic basin and via exchanges to higher latitudes?

Although the full explanation for the tropical Atlantic variability should involve the coupling of possibly unknown processes, the PIRATA proposal included, from the outset, the suggestion that one attribute, the so-called "dipole mode", referring to a model of a coherent inter-hemispheric tropical SST anomaly field (SSTa) of opposite signs in each hemisphere, should be important for predictability. Presently, there is a debate in the scientific community as to whether this interhemispheric gradient in SST may be related to a physical mode or it is just a statistical artifact explaining part of the variance. One of the possible hypotheses for such a process is now well stated in the literature, involving a wind-induced evaporation-SST positive feedback, such that the SST anomalies maintain the anomalous wind field, via surface latent heat flux, while low frequency ocean motions should set the restoring force for the oscillation with a period of 12-13 years to be sustained (see, e.g., Chang et al., 1997). Other processes may emerge from future studies based on new data, to explain why the net SSTa variance seem to involve a sort of "symmetry breaking" from the "dipole mode". Is has been shown by several authors that most of the variance of the tropical Atlantic SSTa interhemispheric gradient seem to be related to possibly independent oscillations of the north and the south portions of the "dipole" in the decadal scale (see, e.g., Mehta, 1998), but so far no alternative ocean-atmosphere processes have been proposed to explain the "symmetry braking" of the proposed "dipole process". That is to say that the final explanation for the SSTa variances should possibly include the coupling of the dipole mode with other still unknown processes yet to be proposed. The main issue in PIRATA is, however, the relationship of the ocean to the land climate, and presently the "SST dipole" is still quite appealing a process, as related to the observed correlations of SSTa and precipitation anomalies on land.

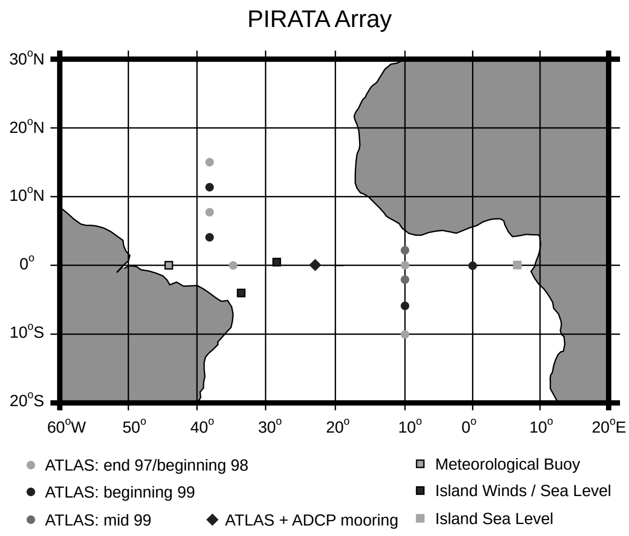

Figure 1: The PIRATA ocean observing system geometry in the tropical Atlantic.

Scientific and technical goals of PIRATA

These goals are multiple:

- to provide an improved description of the seasonal-to-interannual variability in the upper ocean and at the air-sea interface in the tropical Atlantic,
- to improve our understanding of the relative contributions of the different components of the surface heat and freshwater fluxes, and ocean dynamics, in the formation of the oceanic and atmospheric mixed layer, to be able to understand the seasonal and interannual variability of SST within the tropical Atlantic basin, via predictive models of the coupled Atlantic climate system
- to provide a data set that can be used to develop and improve this detailed understanding of how basic mass, momentum, heat and freshwater fluxes couple in the oceanic and atmospheric mixed layer,
- to design, deploy, operate and maintain a pilot array of moored buoys and island stations, similar to the ones used during the TOGA programme in the tropical Pacific,
- to collect high resolution (10 minute time steps) data, and transmit via satellite in real-time a set of quality controlled oceanic and atmospheric daily average data to observe and study the upper ocean and the ocean-atmosphere interface of the tropical Atlantic.

High resolution data from three Brazilian moorings and one French mooring are now available in the PIRATA web page. This data set is very important in support of flux and local air-sea interaction process studies.

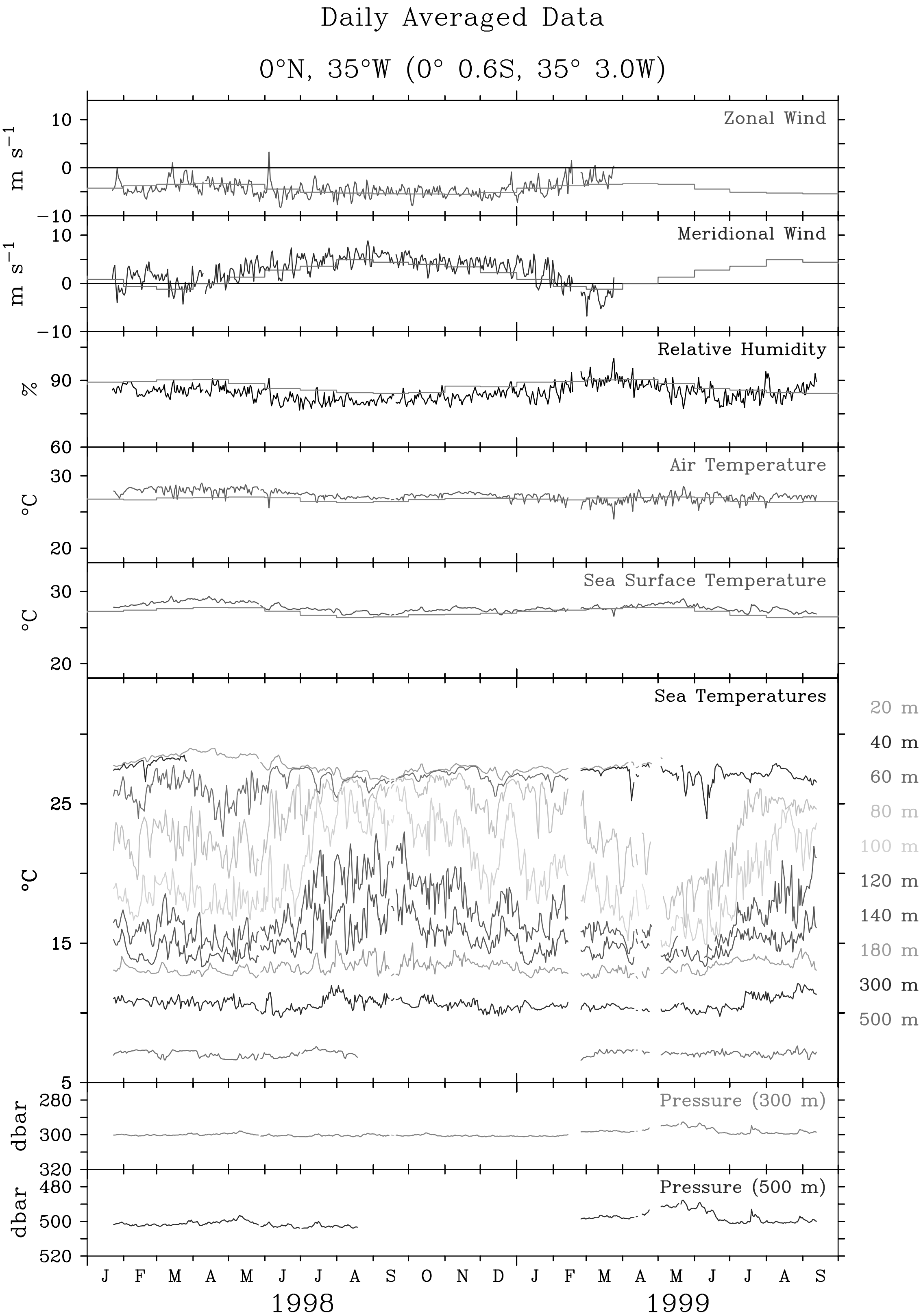

Figure 2a: Surface and subsurface measurements of a PIRATA buoy at the equator, 35°W

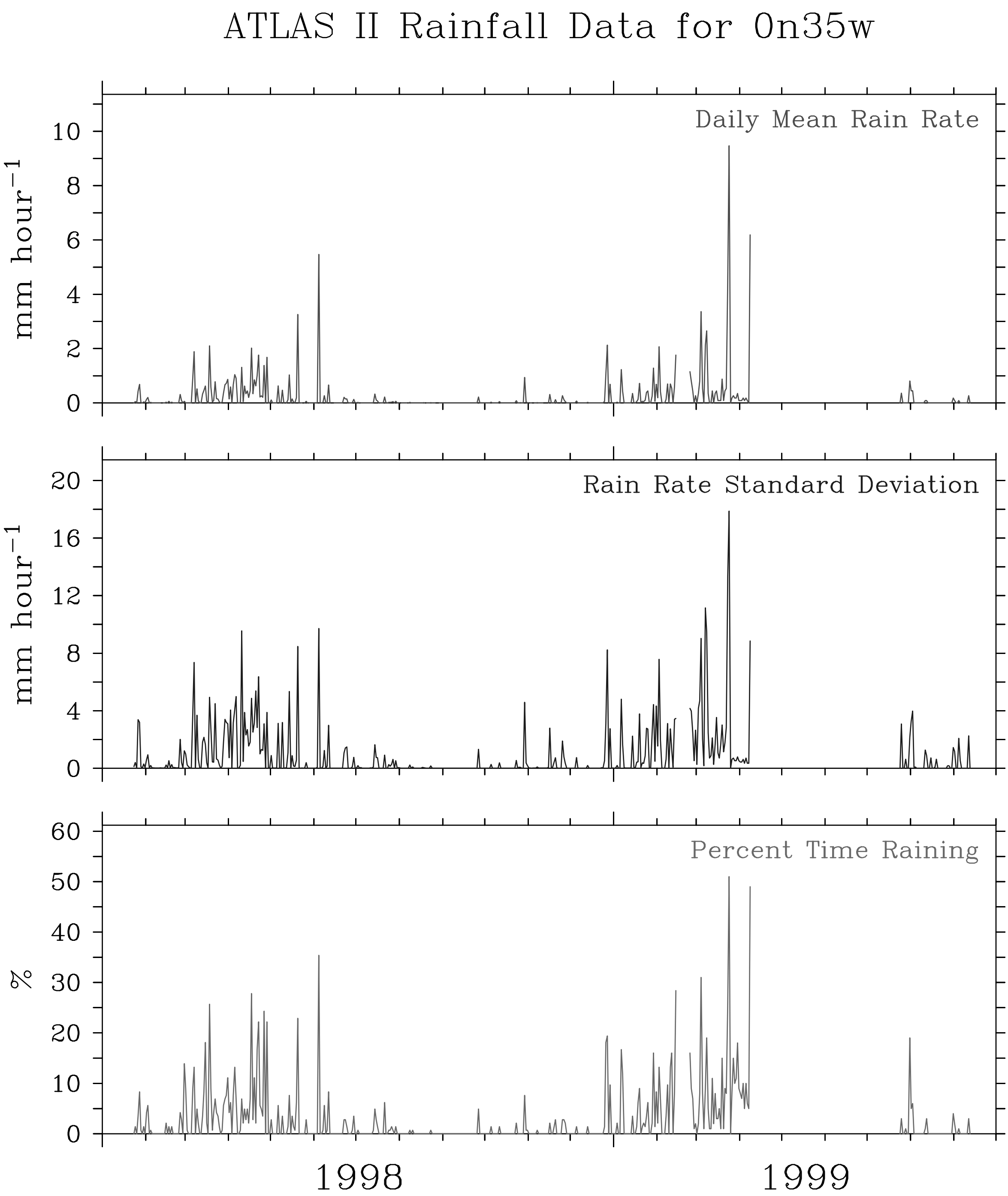

Figure 2b: Rainfall parameters for the PIRATA buoy at 0°, 35°W

The PIRATA Array

PIRATA consists of 12 ATLAS moorings, 4 spanning along the equator, and 8 spanning two meridional lines (Fig.1). This specific configuration has been chosen to provide coverage along the equator of regions of strong wind forcing in the western basin and significant seasonal-to-interannual variability in SST in the central and eastern basin. The meridional arrays cover the regions of high SST variability associated with the SSTa dipole mode, with the northwestern meridional line cutting across the ITCZ during most of the year. The variables measured are surface winds, SST, sea surface conductivity (salinity), air temperature, relative humidity, incoming short-wave radiation, rainfall, subsurface temperature (10 depths in the upper 500 m), subsurface conductivity (presently 3 depths in the upper 150 m, 4 depths in future moorings), and subsurface pressure (at 300 m and 500 m). Examples for some PIRATA measurements are given in Figs. 2-4. An acoustic Doppler current profiler mooring is proposed for 0°N-23°W to monitor the vertical current profile variations in the central Atlantic where high zonal current variability occurs, close to the ATLAS mooring sited at 0°N-23°W (the 20°W mooring position had to be displaced to the west due to difficulties with local bottom topography).

The present importance of obtaining good subsurface temperature and salinity data, especially in the upper 150m, is driven by the need to monitor the influence of shallow mixed layers (30m) occurring with waters of different temperature and salinity stratifications (causing what is known as a "Barrier Layer"), which have impacts on the vertical heat transfer in the ocean, affecting SST. Mixed layer parameterisations for predictive models should take into account such salinity effects, which will be even better monitored once the ATLAS moorings to be deployed in the year 2000 will carry conductivity sensors at five depths (1m, 20m, 40m, 80m and 120m). The demand for these five depths is the result of the observation of "barrier layers" in the vertical profiling with CTD's, which form a necessary part in the data collection made during the deployment cruises.

The initial ATLAS deployments were made during 1997-1999 (Fig.1). In addition to the ATLAS mooring observations, wind measurements and tide-gauge data are scheduled to be available in real-time from a few equatorial sites: Brazil will deploy systems at St. Peter and St. Paul Rocks Archipelago (0.7°N-29.2°W) and Atol das Rocas (3.9°S-33.5°W), while France will maintain the tide gauge at São Tomé island (0.5°N-6.5°E). Brazil must also deploy a coastal meteorological buoy at 0°N-44°W, offshore the State of Maranhão.

PIRATA Status (August 1999)

Since November 1998 nine deployments have been made, giving an initial data return statistics around 90%, up to last May. By the end of August some sensor problems, vandalism, and delays in the deployment schedule are showing up, a fact that is considered normal in this kind of "Pilot Project", as has been anticipated in the Implementation Plan. Details may be obtained directly from the PIRATA web page.

The final phase of the PIRATA experiment (spring 2000 - early 2001) will be hopefully dedicated to the yearly maintenance of the ATLAS sites and the other components of the in-situ observing system. Thus, an integrated ocean observing system (full PIRATA array + equatorial current measurements + equatorial sea level data + equatorial Met observations) is expected to be operational during (at least) one year.

Other nations are being stimulated to join in the maintenance and possible expansion of PIRATA (and other type of in-situ oceanic observations) to constitute a tropical Atlantic Ocean "fixed" in-situ observing system after 2001. A dedicated meeting to discuss all of the oceanographic projects and proposals within the Tropical Atlantic (Climate Observing System in the Tropical Atlantic, COSTA) was hosted by Dr. Sylvia Garzoli at AOML/NOAA in Miami (May 3-7 1999) where these discussions took place, at the same time of the sixth meeting of PIRATA (PIRATA-6, Miami, 2-3 1999) where practical and strategic questions about the final phases of the PIRATA project have been discussed. To facilitate the management of this increasingly complex implementation, a PIRATA Resources Committee (PRC) is being formed by the major sponsors of the Project, to establish a long-term strategy for funding, logistics, training, and national priorities and interests regarding the future of PIRATA (where the P will then stand for "Permanent").

One of the main issues facing PIRATA now is the feasibility of participation of other countries in PIRATA, as it will continue post- 2001, after the first "pilot phase" ends. Presently there are statements from both Brazil and France assuring ship time to the end of this first phase, but discussions will continue regarding the extension of the project up to 2006, including geographical extensions of the array. Some extensions are only possible with the entrainment of other countries, but some are also being proposed by the present partners. This issue is also dependent on capacity building in the region in the form of an efficient training and technology transfer programme needed to help alleviate the

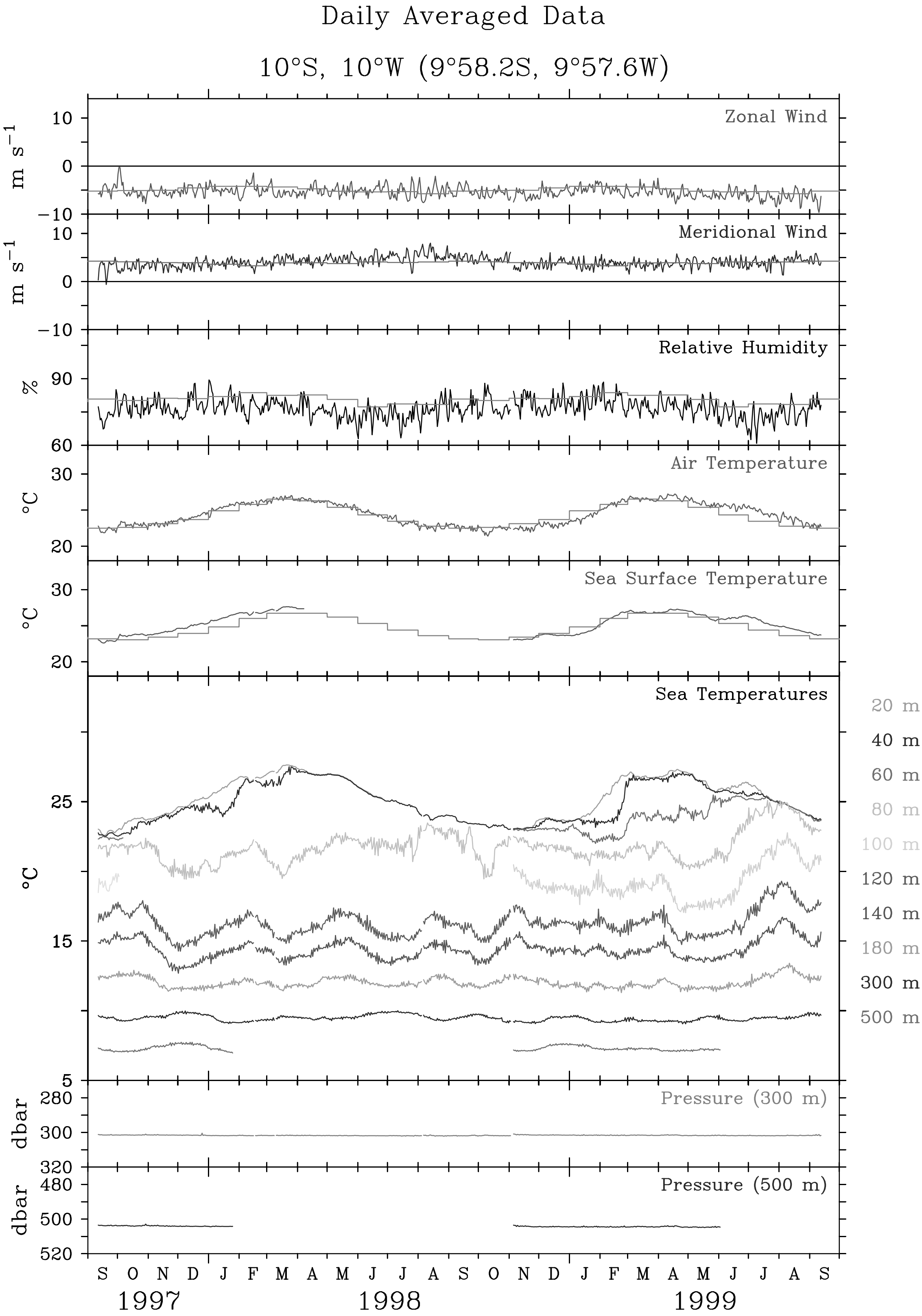

Fig. 3: as for Fig. 2, for the mooring at 10°S, 10°W

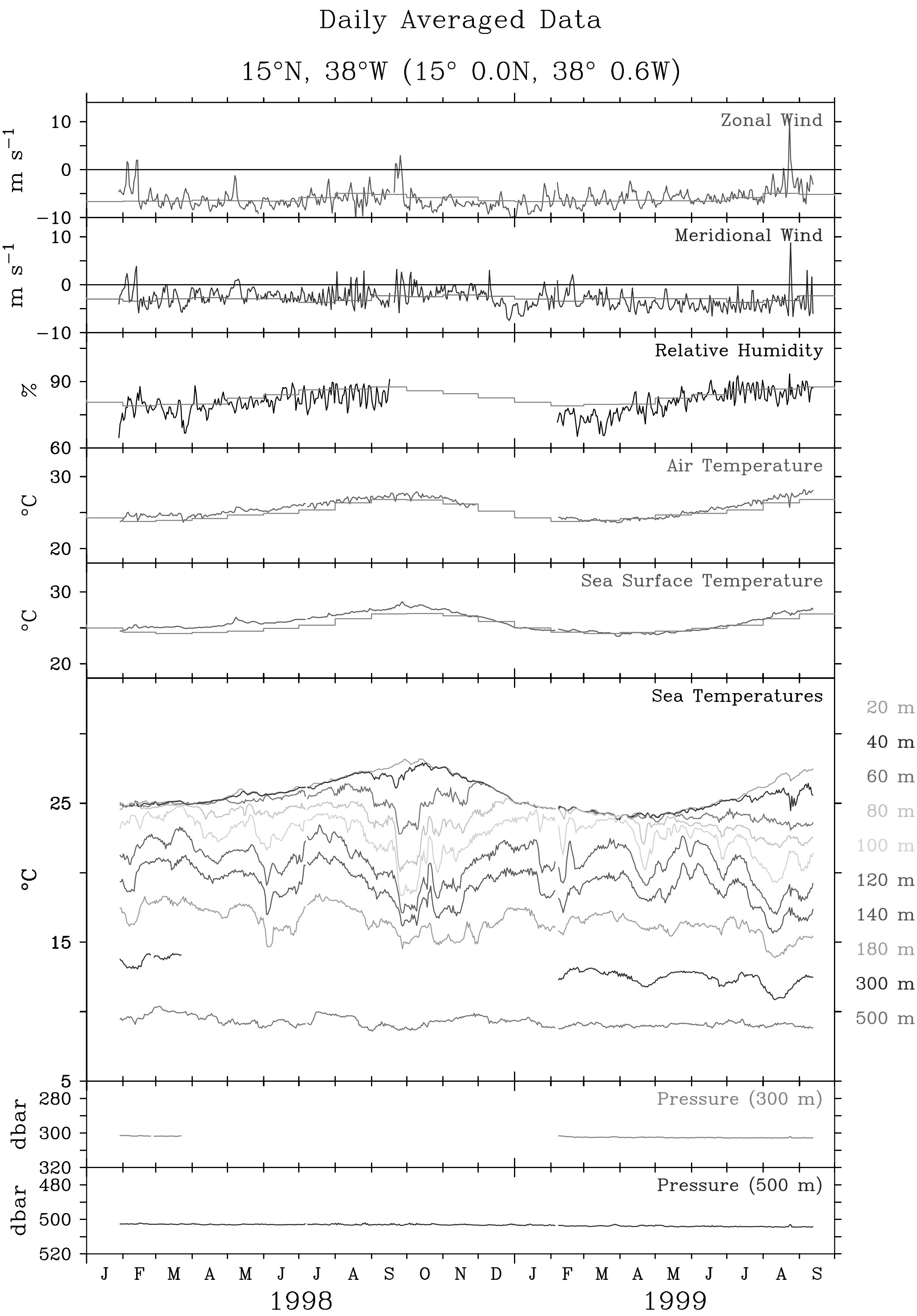

Fig. 4: as for Fig. 2, for the mooring at 15°N, 38°W

burden being placed on PMEL.

The COSTA Meeting (summary see this issue) was very successful in producing a first synthesis of all of the scientific issues contemplated by ongoing large scale oceanographic projects in the region, underlying the complementarity between these initiatives. The report of this important meeting may be obtained at the AOML website http://www.aoml.noaa.gov/phod/COSTA/report/

International resource commitments

PIRATA is realised as part of a multi-national effort involving Brazil, with INPE responsible for the national coordination, funding and technical work, and the ship time furnished by the Directory of Hydrography and Navigation (DHN) of the Brazilian Navy (which collaborates with the most extensive civil oceanographic programmes in Brazil); France, involves IRD in both the coordination, funding and ship time, and Météo-France and CNRS/INSU) with funding; and the US through the Pacific Marine Environmental Laboratory (NOAA/PMEL), being responsible for mooring construction, maintenance of systems and support in deployment operations, quality control and distribution of data through the Internet, construction and maintenance of the main PIRATA web page, as well as funding via NOAA/OGP.

During the pilot study (1997-2001) all the ATLAS mooring systems are being built by NOAA/PMEL at Seattle. NOAA/PMEL also funds and coordinates shipping to and from the theatre of operations, and participates in deployment as well recovery of mooring systems at sea. It is responsible for all calibration, laboratory check outs and instrument refurbishment. It maintains a data base of real-time and research quality delayed mode data (10 minute data) for all variables, which become available in the PIRATA web pages as soon as they are processed. However, Brazil has plans to develop a dedicated laboratory in the coastal city of Natal, northeast Brazil, to facilitate this complex logistics, and at the same time develop a better partnership with PMEL which will involve full refurbishments of moorings near the theatre of operations.

The logistical support in terms of ship time for developing and maintaining the PIRATA moored array is under the responsibility of Brazil and France (about 90 days per year of ship time for servicing the entire array). The Brazilian R/V Antares (DHN) services the western half of the array and the mid basin mooring at the Equator, departing from Fortaleza or Natal. Brazil will install wind and sea level data collection platforms at St. Peter and St. Paul Archipelago, Atol das Rocas, and at the coastal meteorological buoy (0°N-44°W). The French R/V Antéa (IRD) services the eastern half of the array from Abidjan, Côte d'Ivoire. France maintains a sea level data collection platform at São Tomé island (0.5°N-6.5°E).

All the PIRATA daily data are available at PMEL/NOAA-Seattle via the World-Wide-Web at http://www.pmel.noaa.gov/pirata, with an electronic link with IRD-Brest at http://www.ifremer.fr/orstom/pirata/piratafr.html, and INPE at http://www.cmcd.inpe.br/pirata.

Interactions with other programmes

As with the TAO programme in the Pacific, the PIRATA programme is not conceived as a self-sufficient programme. The main role of PIRATA is to offer high quality geographically fixed time series of ocean surface and subsurface measurements, to complement existing Lagrangian measurements offered by other projects in the tropical Atlantic, and to give verifiable elements to future model experiments. Consequently, many scientific interactions take place between PIRATA and other climate change programmes which are being developed in the tropical Atlantic region (see a partial list below). Such interactions are of mutual benefit to PIRATA and these other programmes.

International programmes:

CLIVAR (Climate Variability and Predictability), and its sub-programmes; CLIVAR-Africa, EuroCLIVAR, VAMOS (Variability of American Monsoon Systems);
GCOS (Global Climate Observing System), GOOS (Global Ocean Observing System);
Brazilian programmes:
GOOS-Brazil and its sub-programmes (e.g., National Drifter Program-PNBoia);
French programmes:
ECLAT (Etudes Climatiques dans l'Atlantique Tropical), Clipper-MERCATOR-CORIOLIS (Operational Oceanography);
USA programmes:
ACVE (Atlantic Climate Variability Experiment), PACS (Pan American Climate Studies), ACCE (Atlantic Climate and Circulation Experiment);

References

Chang, P., L. Ji, and H. Li, 1997: A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions. *Nature*, **385**, 516-518.

Mehta, V., 1998: Variability of the tropical ocean surface temperatures at decadal-multidecadal timescales. Part 1: the Atlantic Ocean. *J. Climate*, **11**, 2351-2375.

Servain, J.M, A. J. Busalacchi, M. J. McPhaden, A. D. Moura, G. Reverdin, M. Vianna, and S. Zebiak, 1998: A Pilot Research Moored Array in the Tropical Atlantic. *Bull. Am. Meteor. Soc.*, **79 (10)**, 2019-2031.

The PIRATA Executive Committee

It was during the 4th TAO Implementation Panel Meeting in 12-14 September, 1995, that a decision was made to prepare a proposal for a TAO array extension into the Tropical Atlantic. The first ad-hoc committee was formed with the task of preparing a proposal, and involving those parties that could make possible the funding and the ship time required, with the first meeting scheduled for February 1996, in Natal. The components of this first "PIRATA Executive Committee-PEC" were the present authors, plus Drs. Mike McPhaden (PMEL/NOAA), Antonio Divino Moura (INPE-in the move to IRI/NOAA), Gilles Reverdin (LEGOS/GRGS) and Steve Zebiak (LDEO/Columbia University), with Drs. Moura and Servain as co-chairs. The first version of the "PIRATA-Science and Implementation Plan for an Observing System to Support Tropical Atlantic Climate Studies" was discussed in the PIRATA-1 Meeting in Natal, where feasibility issues for initiating implementation in 1997 were first examined. Subsequent meetings (in Brest-1996; Seattle, March 1997; Rio de Janeiro, November 1997; Abidjan, November 1998) have been important to discuss the logistic and implementation issues of PIRATA. Last year, in the PIRATA-5 Meeting in November 1998 in Abidjan, Dr. Zebiak, who gave much of his time with ideas that made possible the materialization of PIRATA, rotated off the PEC. The PEC is now enlarged by Drs. Serge Planton (IRD), Ping Chang (Department of Oceanography, Texas A&M University) and Ilana Wainer (Instituto Oceanografico, Universidade de S. Paulo), with Dr. Servain now acting as Chairman.

On the risks of assimilating real time oceanic observations, limitations of a univariate assimilation scheme, and how to benefit from vandalism

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At ECMWF a near real time ocean analysis is performed on a quasi-operational basis with the HOPE global ocean circulation model in order to obtain initial conditions for seasonal forecasts (Stockdale et al. 1998). A univariate optimum interpolation scheme (Smith et al., 1991) is used to assimilate subsurface temperature observations obtained from TAO (Tropical Atmosphere Ocean) and PIRATA (Pilot Research Moored Array in the Tropical Atlantic) moorings, XBTs, and PALACE floats into the ocean model. Near real time sea level anomalies from TOPEX/Poseidon and ERS-2 are obtained from CLS (Collecte Localisation Satellite, Le Traon et al., 1997) and used to verify the sea level anomalies of the ocean analysis. Recently, the diagnosed sea level anomalies in the western equatorial Atlantic showed large negative anomalies on the order of 0.5 m, which were inconsistent with the altimeter observations. A corresponding control experiment without data assimilation, however, showed no spurious behaviour.

During the ensuing investigation it was found that the PIRATA mooring at 4°N, 38°W had measured a temperature drop of 10 K at 80 - 120m depth (Fig. 1). On the other hand, observed temperature changes were negligible at the surface and less than 1 K at 500m depth where temperature was slightly increased. At the same time the observed salinity decreased by 0.75 psu at 120 m depth (Fig. 2), thus partly compensating the cooling effect on density. Altimeter observations of sea level (Fig. 3, solid line) are compared with observed dynamic height (Fig. 3, crosses, also available at the PIRATA web-site, www.ifremer.fr/ird/pirata/pirata.html) to check whether the T and S variations could be realistic. The agreement between observed sea level and dynamic height for most of the values suggests that the observed temperature and salinity anomalies were real and not caused by faulty sensors. Differences between sea level and dynamic height are large only during the period from the end of March to May. Sea level from near real time altimeter data decreased, beginning at the end of March, by more than 10cm. The drop in observed dynamic height was stronger, because dynamic height was computed using a climatological T-S relationship, and therefore the com-

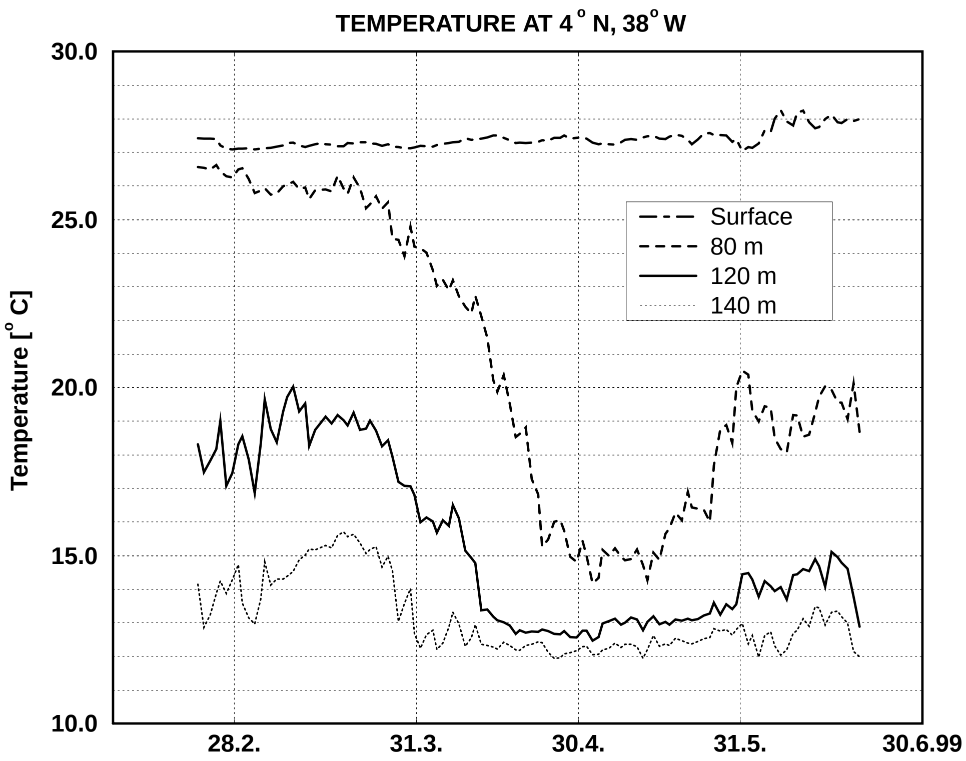

Figure 1: Time series of temperature as observed from the PIRATA mooring at 4°N, 38°W for the surface (dash-dotted), at 80 m depth (dashed), at 120 m depth (solid), and at 140 m depth (dotted).

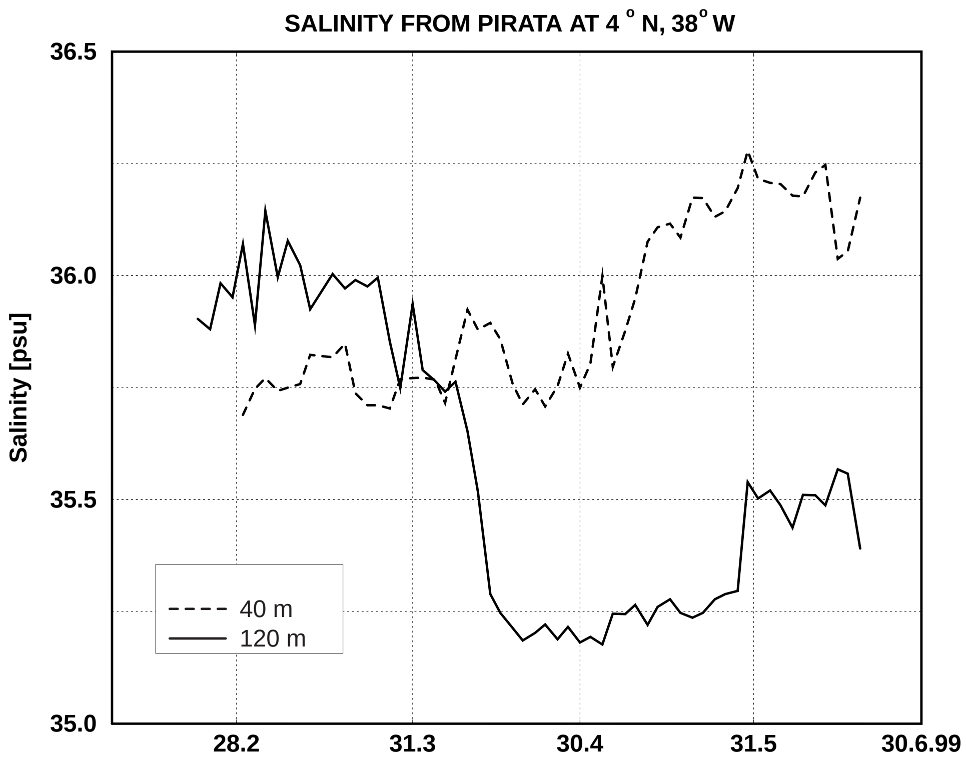

Figure 2: Time series of salinity as observed from the PIRATA mooring at 4°N, 38°W at 40 m depth (dashed) and at 120 m depth (solid).

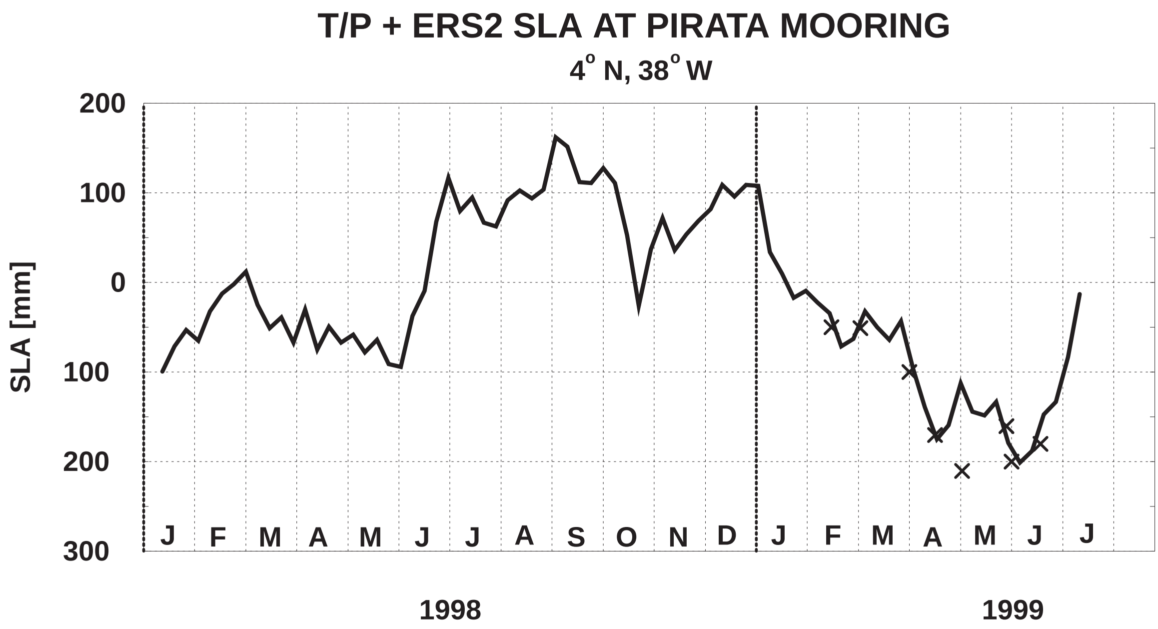

Fig. 3: Sea level anomalies observed by TOPEX/Poseidon and ERS-2 for 4°N, 38°W (solid line) and dynamic height anomalies from PIRATA temperatures, using a climatological T-S relationship (crosses). The difference between SLA and dynamic height is set to zero for February 1999.

pensating effect on sea level from the decrease in salinity was not taken into account. Fig. 3 implies that the impact of salinity changes on sea level in the equatorial Atlantic can be as large as 10 cm.

So, if the temperature observations were realistic, why did the ocean analyses system show an erroneous sea level? The optimum interpolation (Smith et al. 1991) is univariate in temperature: salinity is not used largely because real time salinity observations are so scarce. However, for much of the time this may be acceptable as the density of tropical upper ocean waters is to first order determined by temperature. The recent studies of Ji et al. (1999), and Segschneider et al. (1999) and also this investigation indicate, however, that such an assumption cannot really be justified. Because the OI-scheme is univariate in temperature, the negative salinity anomaly, which compensates the effect of the temperature drop on density to a large extent in the real ocean, is not assimilated into the ocean model. Furthermore, whereas the information from the observations is spread over quite a large area in the horizontal, no such distribution is done in the vertical: rather, the information is applied level by level. For the given observations (Fig. 1), the OI computed a temperature increment of about -3.5°C around 60 - 120m, but not below that depth (Fig. 4). This was sufficient to create unrealistic static instability and mid-depth convective adjustment, causing strong horizontal temperature gradients. As a consequence of the distorted pressure field, the equatorial under current was almost wiped out in the western Atlantic, while an eastward current of up to 0.7 m/s was simulated to the north of the equator.

The question then arose, as to whether the analysis was distorted as a consequence of the introduction of the PIRATA mooring in February 99, or whether it was because the T and S anomalies were anomalously strong. To investigate this, we examined T and S observations at nearby moorings, sea level from satellite and climatological Temperature and Salinity data (Levitus and Boyer, 1994). The Levitus data for the western equatorial Atlantic show that temperature variations of 6 K, presumably caused by meridional shifts of the ITCZ, are part of the average seasonal cycle. Salinity variations of the seasonal cycle explain less than 0.3 psu of the observed 0.75 psu signal. Also the backward extension of the NRT SLA-time series until January 1998 (Fig. 3), and the time series from the two nearest PIRATA moorings at 8°N, 38°W, and on the equator, 35°W suggest that the temperature and salinity changes observed at 4°N, 38°W were stronger than usual.

A further investigation of the operational analysis back to September 1996 showed that the simulated sea level in the western equatorial Atlantic fell already during 1998 by as much as 10 cm (not shown), whereas the control experiment without assimilation showed no drift. Fig. 4 shows that negative temperature increments at 100m depth, although weaker than in April 1999, were analysed already during 1998, i.e. before the PIRATA mooring started to transmit data. So, already the occasional XBT-observation was sufficient to deter the analysis. However, while a problem in the western Atlantic was present in the ocean analysis for some time, it was the more permanent data-flow from the PIRATA mooring combined with the anomalous strong T and S varia-

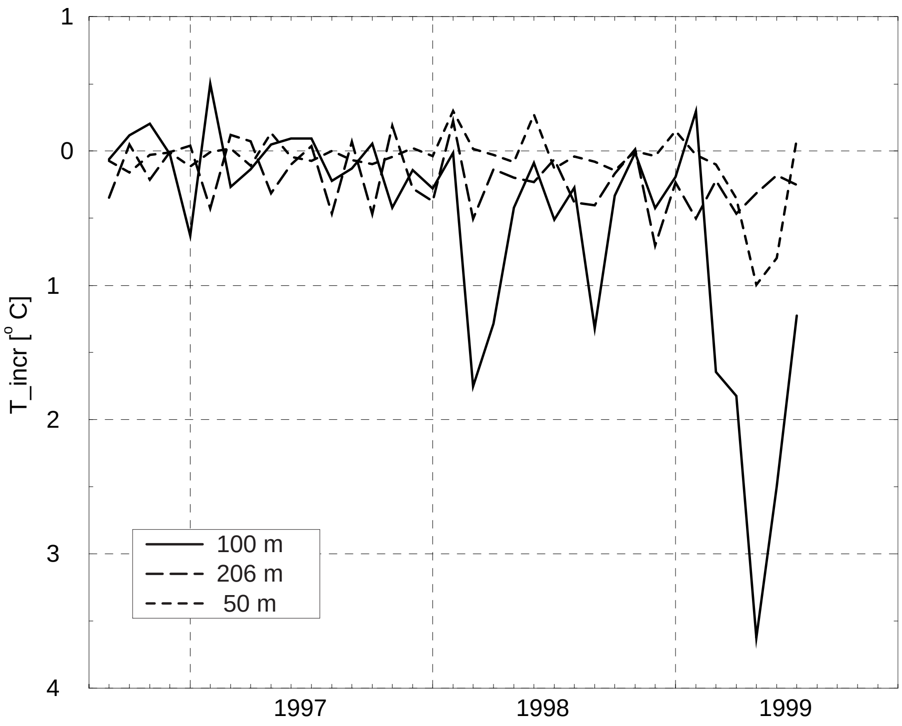

Fig. 4: Temperature increment obtained from the assimilation of subsurface temperatures in the area of 4°N, 38°W at 100 m depth (solid), 206 m depth (long-dashed), and at 50 m depth (dashed).

tions that caused severe problems.

The limitations of our ocean analysis system were partly compensated for by some unknown sailors. On 18.6.1999 the mooring at 4°N, 38°W failed to transmit any further data, indicating possible vandalism. Since then, the model's sea level has been slowly recovering. Several questions remain to be answered, though. First, from where does the water with quite different characteristics originate? River outflow from the Amazon-river would decrease salinity, but as no signal at the surface is present for the salinity we can rule out this source. A more likely source is a mixed form of sub-antarctic intermediate water, which has spread northward in the Atlantic at 500 m to 1,000 m depth (Wüst, 1935) and has been mixed and up-welled in the ITCZ area. The salinity and temperature of sub-antarctic intermediate water (T=10°C, S=34.6 psu) are similar to the observed values during April to June 1999 at 4°N, 38°W at 140 m depth. It is not clear yet, however, which processes caused the strong anomalies observed during April to May 1999, especially since the local wind speed and direction (also available from the PIRATA web-site) do not show strong variations at the onset of the T and S drop. Connections with the strong El Nino event during 1997 are possible. However, the signal to noise ratio is much smaller in the Atlantic than in the Pacific. Near real time altimeter maps (www.cls.fr/duacs) for the first half of 1999 show a slow westward propagation of a negative sea level anomaly from about 10°N at the eastern boundary of the Atlantic towards the equator at the western boundary. Whether this indicates Rossby wave propagation as part of variations comparable to ENSO oscillations in the Pacific is not clear yet. Further investigations have to be made to fully understand the physical mechanisms behind the strong temperature anomalies.

So far it can be concluded, that the extension of the ocean observing system to the Atlantic shows up temperature anomalies that are as strong as in the Pacific. Apart from forming an interesting research topic in their own right, these strong temperature changes are causing problems for the currently-used assimilation scheme. A quick fix for our ocean analyses system to cope with the strong temperature variations could be to update the quality control for example by including a check on static stability based on temperature only. In the long term, assimilation of subsurface salinity observations which go along with temperature observations are required if one wants to obtain a realistic representation of oceanic density fields. In the meantime, altimetry proved to be a useful tool for model verification. Whether the combined assimilation of subsurface temperatures and altimeter data can constrain the density field more efficiently is currently under investigation.

References

Ji, M., R.W. Reynolds, and D.W. Behringer, 1999. Use of TOPEX/Poseidon sea level data for ocean analyses and ENSO prediction: some early results. *J. Climate*, in press.

Levitus, S. and T. Boyer, 1994. World Ocean Atlas 1994, Vol. 3, Salinity and Vol. 4, Temperature. Natl. Environ. Satell. Data and Int. Serv., Natl. Oceanic and Atmos. Admin., Washington, 117pp.

Le Traon, P.Y., F. Nadal, and N. Ducet, 1998. An improved mapping method of multi-satellite altimeter data. *J. Atmos. Ocean. Technol.*, **15**, 522-534.

Smith, N. R., J.E. Blomley, and G. Meyers, 1991. A univariate statistical interpolation scheme for subsurface thermal analyses in the tropical oceans. *Prog. Oceanogr.*, **28**, 219-256.

Segschneider, J., D.L.T. Anderson, and T. Stockdale, 1999. Towards the use of Altimetry for Operational Seasonal Forecasting. *J. Climate*, submitted.

Stockdale, T.N., D.L.T. Anderson, J. Alves, and M. Balmaseda, 1998. Seasonal rainfall forecasts with a coupled ocean atmosphere model. *Nature*, **392**, 370-373.

Wüst, G., 1935. Schichtung und Zirkulation des Atlantischen Ozeans. Das Bodenwasser und die Stratosphäre. *Wiss. Ergebn. Dt. Atlant. Exped. “Meteor” 1925-27*, **6**, 1-288, Berlin.

Next Steps in Climate Forecasting and the Implications for Ocean Observing Systems

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Two broad classes of climate variability have been identified by CLIVAR which may provide some predictability on seasonal to longer time scales. Those modes of variability of the first class all have a tropical connection, associated with changes in tropical convection. In this class one might cite the ENSO in the Pacific, the north-south dipole in the Atlantic, the ENSO-type mode in the equatorial Atlantic, the east-west dipole in the Indian Ocean, the Pacific Decadal Oscillation. The second class is associated with changes in strength and location of zonal flows in middle and high latitudes. In this class one might think of the NAO (North Atlantic Oscillation), the Arctic Oscillation, and the subtropical gyral modes of the Pacific and Atlantic, and the Antarctic Oscillation. There is considerable controversy on the best way to characterise these modes, whether they are indeed independent, whether they are truly coherent coupled processes in the climate system, or just a selective response to noise forcing, albeit with some characteristic timescale. The signatures of these modes on rainfall and temperature have been documented to some degree. There is some scientific satisfaction in identifying various modes which may prove useful in understanding and quantifying predictability. An observing system should be capable of documenting and clarifying the nature of climate variability; however, its long term viability will to a great extent be determined by how it enhances predictability.

A basic global ocean observing system of remotely sensed and in situ observations exists that is of considerable use in studying this variability, but is inadequate for detailed documentation, long term continuity and understanding of the physics. The exception being the observing system in the near tropical Pacific, where the TAO array was implemented on an operational basis to provide measurements for initialization of forecast models and further research. However, even there some additional observations, i.e. salinity, are needed. Hence a better understanding of all of these classes of variability and more effective utilization of remotely sensed data requires an expansion of the current observing system. For example, we can not use altimetry to maximum effect if we do not have adequate temperature and salinity measurements. An additional consideration is that long term commitments is needed to some of the measurements that currently are part of short term research programmes.

The ENSO phenomena, especially major El Niño and La Niña events, represent extreme shifts of tropical rainfall. A number of institutions routinely produce multi season forecasts for tropical Pacific SST variability, i.e. El Niño. Arguably the most skilful of these use coupled general circulation models which utilise data assimilation to initialise the forecasts. Most of the skill in these forecasts geographically lies in the central and eastern Pacific. Experiences during the past two years indicate that forecasting of sea surface temperature anomalies in this area, i.e. the Niño 3.4 or Niño 3 areas, is just the first step in exploiting the predictability that might lie in the coupled system. During the last El Niño large SST and rainfall anomalies were present in the tropical Indian Ocean, in the Indonesian region, the far eastern Pacific, and the Atlantic which modelling and diagnostic studies have shown played a part in producing significant seasonal temperature and rainfall responses in different parts of the globe. Also a better understanding is required of the air-sea couplings involved in the intra seasonal phenomena in the Tropics, not only because of their potential role in determining the evolution of El Niño, but also for their own role in producing temperature and rainfall events.

Although an extensive observing system exists for the tropical Pacific, utilization of these data sets in data assimilation and coupled forecast systems is showing that this needs to be supplemented. This observing system consists of the TAO array, the sea level network, measurements from volunteer observing ships (VOS), and remotely sensed measurements of sea level variability (TOPEX/POSEIDON) and SST. One shortcoming of this system is the lack of salinity measurements, especially in those regions that experience large changes in precipitation. Shifts of rainfall occur not only zonally but also are associated with changes in the Intertropical and South Pacific Convergence Zones which lie outside areas sampled by TAO. Without realtime salinity measurements, use of historical temperature/salinity relationships can lead to steric estimates of sea level variability that differ considerably from those estimated from the tide gauges and the altimeter. Also to more fully utilise the TOPEX measurements, and those from JASON which will be more precise, profiles of salinity will be required outside the tropical areas. This will be especially true when the more subtle aspects of climate variability associated with decadal variability are being studied.

Although climate variability in the second class is of major importance for producing rainfall and temperature variability over large regions of the Northern Hemisphere, predictability prospects for these modes and their impacts remain very much a major topic for research. On subseasonal or seasonal time scales, these modes are very energetic but do not appear to result from coupled phenomena. The exception here are the modes in midlatitudes which have been observed in coupled simulations. Hence there appears to be little predictability on seasonal time scales other than that arising from initial atmospheric conditions. On decadal time scales, there is optimism that some predictability might arise because of coupling either in higher latitudes or in the subtropics.

Implications for Ocean Observing Systems

Continuity and improvement in remotely sensed ocean data is critical for an improved forecast capability. Improvements in ocean models and ocean initial conditions continue to be limited by the availability of high quality wind forcing data. ERS and NSCAT missions have shown the great utility of remotely sensed wind information. The altimetric measurement of sea level variability, especially those from TOPEX/POSEIDEN, have provided new insights into ocean variability and are proving to be valuable in ENSO prediction. Continuity of remotely sensed wind and altimetric measurements needs to be assured. Observations from current operational satellites for parameters such as SST, of course, also need to be continued.

Since the best prospects for improved predictability come from a better understanding of tropical rainfall variability, enhanced in situ measurements in the tropics and subtropics in all three ocean basins are clearly necessary. Understanding and being able to predict SSTs from the Indian Ocean, through the maritime continent, and across the tropical and subtropical Pacific is of paramount importance. Hence the expansion of observations is necessary westward from the TAO array and into the northern and southern hemisphere subtropics. Measurements poleward of the TAO array are needed because a) decadal variability and decadal variability of ENSO involve hypotheses and physics that extend outside the tropics; b) it is likely that east-west shifts of convection and changes in the locations of the ITCZ and the SPCZ are both important in generating responses over North America. An enhanced programme of measurements is also needed in the tropical and subtropical Atlantic. For regional forecasts these are of high priority. A better understanding of variability in the subtropical North Atlantic could provide the link to developing an understanding and possibly some predictability of the NAO. Also there is some potential impact of ocean variability in these regions on Atlantic hurricanes and this needs to be quantified.

The types of measurements that have been proposed to meet these needs are:

- ARGO arrays to provide T and S profiles
- expansion of TAO into the Indian Ocean
- long term continuity and expansion of the PIRATA array
- surface salinity sampling
- continued altimetric measurements of JASON accuracy
- improved winds from scatterometry
- surface flux measurements
- maintenance of the tide gauges
- measurements of boundary current transport

It is likely that the feedbacks involved in producing SST anomalies in the Indian Ocean, the Indonesian area, and the far western Pacific, and the off equatorial regions in the Atlantic are quite different than those in the central and eastern Pacific. In the latter region rather simple negative feedback mechanisms seem to be important, i.e. the atmosphere acts to kill the SST anomalies. In these other regions a better understanding of the air-sea-ocean circulation interactions will probably require an improved understanding of the surface fluxes. Whether this can be obtained from studies of the COARE data sets, results from the PIRATA programme, and better quality controlled surface marine data sets or requires routine specialised flux measurements is not clear to the authors. Also it is felt that the combination of altimetric measurements and profiles of T and S are adequate for studies of the interior of the gyres, but that specialised measurements will be required in the boundary current areas.

Expansion of measurements poleward of the subtropics both in the Pacific and the Atlantic is clearly necessary for CLIVAR research, but this may not lead to any short term gain in predictability. However, measurements in these regions are required to document the impacts of long term climate variability and to assess the potential impacts of variability on marine ecosystems.

The Southern Ocean: Scientific Issues and Challenges for an Ocean Observing System

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The Southern Ocean poses unique challenges for an ocean observing system. Southern Ocean processes operate at a wide range of space and time scales to influence regional and global climate. The region is remote, and the environment is hostile. Historical data is scarce, and as a result hypotheses regarding the climate influence of Southern Ocean processes have been difficult to formulate and test. However, recent advances in both measuring and modelling the Southern Ocean are providing substantial insights into the region's impacts on climate. These new results provide the foundation for development of a feasible, cost-effective observing system for the Southern Ocean. The purpose of this article is to highlight a few recent advances of particular relevance to CLIVAR, and to demonstrate that the objectives of CLIVAR are unlikely to be met without sustained observations of the mid- and high-latitude oceans of the southern hemisphere. While satellite observations are of particular importance in the poorly-observed Southern Ocean, in this brief article I focus on the need for in situ measurements.

The Southern Ocean has a profound influence on the mean circulation and stratification of the oceans, and hence a strong impact on climate. The Antarctic Circumpolar Current (ACC) is the primary means by which water, heat and other properties are exchanged between the ocean basins. This unique circumpolar connection permits a global-scale overturning (thermohaline) circulation to exist, and allows the transport of anomalies between basins. Density layers found from intermediate to abyssal depths at lower latitude shoal dramatically across the ACC. Where these layers outcrop, intense air-sea-ice interactions drive water mass transformations. By converting upwelled deep water into new intermediate and bottom water, the Southern Ocean ventilates a large fraction of the world ocean, and thus regulates the ocean's capacity to store heat and carbon.

While existing observations have been sufficient to establish the influence of the Southern Ocean on the mean state of the global ocean and climate, the extent to which Southern Ocean processes respond to or drive climate variability has been less clear. Recent studies, based on both observations and models, provide new insight into these interactions.

Sensitivity of high latitude stratification to climate change

The ocean stratification at high southern latitudes is delicately poised, and is stabilised by low salinity in the upper ocean. This marginal stability is sensitive to freshwater flux changes of either sign. For example, we anticipate that in a warmer world the hydrological cycle will become more intense: evaporation will increase at low latitude, and rainfall will increase at higher latitude. An increase in the net freshwater flux will increase the upper ocean stratification at high latitudes. Climate models suggest the impact of such changes is dramatic, particularly in the Southern Ocean (e.g. Sarmiento et al., 1998). The sinking of dense water in both hemispheres slows or ceases altogether in response to surface freshening, reducing the heat transported by the thermohaline circulation. Ocean uptake of carbon is also reduced. These model results need to be viewed with caution, given known weaknesses in present climate models (e.g. weak high latitude stratification in the control run and inadequate representation of intermediate and bottom water formation). Nevertheless, they illustrate the potential sensitivity of global climate and future atmospheric CO_2 concentrations to Southern Ocean processes.

The high latitude Southern Ocean is also sensitive to freshwater flux changes of the opposite sign. Decreases in freshwater flux can shift the system from the present “haline mode,” where the fresh cap is sufficient to maintain stability, to a “thermal mode,” causing open ocean deep convection as seen in the Weddell polynya of the 1970’s (Gordon, 1982). The polynya enhances heat exchange between ocean and atmosphere, cooling the ocean and driving changes to the atmospheric circulation throughout the southern hemisphere (Glowienka-Hense, 1995). A system of negative feedbacks involving ice, ocean and atmosphere contributions to the freshwater balance likely accounts for the relative stability of the present configuration, but these processes are not well understood. Sustained observations of upper ocean temperature and salinity profiles are needed to monitor the response of Southern Ocean stratification to changes in forcing.

Global overturning circulation

A number of recent studies have highlighted the Southern Ocean’s role in the global overturning circulation. In particular, North Atlantic Deep Water (NADW) exported from the Atlantic must somewhere be converted to less dense intermediate water which flows north in that basin to close the overturning cell. The traditional view is that this water mass conversion is accomplished by uniform upwelling of NADW into the thermocline. However, direct observations of mixing in the ocean interior show values an order of magnitude too small to support the required upwelling (e.g. Ledwell et al., 1993). Recent modelling and observational studies suggest that the required water mass transformation is accomplished by air-sea-ice interactions where the deep water layers outcrop in the Southern Ocean (Toggweiler and Samuels, 1998; Sloyan and Rintoul, 1999; Gnanadesikan, 1999).

It appears that the water mass transformations driven by active air-sea exchange in the Southern Ocean permit a vigorous global overturning circulation to exist despite weak mixing in the ocean interior. This fact has implications for the mechanism and time-scale of variability in the overturning (and hence climate). If the overturning is closed through interior diffusive mixing, the upwelling branch of the cell is likely to be steady on long time-scales (i.e. no direct link between deep mixing and changes in surface forcing). If the overturning is closed through air-sea interaction at high southern latitudes, then the response to a change in forcing may be rapid.

To evaluate the potential for Southern Ocean processes to modulate the overturning circulation, the observing system needs to monitor changes in transport and properties of water masses and contribute to improved estimates of air-sea fluxes for determining water mass formation rates.

Changes observed in the temperature and salinity of intermediate waters suggest the upper limb of the overturning circulation may already be responding to the polar freshening projected by climate models (e.g. Wong et al., 1999). Because the outcropping layers in the Southern Ocean provide a “window” to the interior ocean, monitoring changes in Southern Ocean water masses is potentially a powerful tool for the detection and attribution of climate change.

Some of the deep water which upwells in the Southern Ocean is converted to denser Antarctic Bottom Water (AABW), which is exported from the Southern Ocean to cool and ventilate the abyssal layers of the world ocean. Vigorous air-sea-ice interactions, particularly in coastal polynyas, drive the formation of AABW. As mentioned above, models suggest the formation of AABW may be sensitive to changes in freshwater flux, but the processes are not well enough understood to assess the realism of these projections. Broecker et al. (1999) highlight a discrepancy between AABW formation estimates derived from different tracers and interpret this as evidence for a significant decrease in the formation rate of AABW in recent times. To confirm this suggestion, AABW transport should be monitored in one or more key locations and tracer measurements are needed to measure changes in AABW properties.

Antarctic Circumpolar Wave

The coupled pattern of ocean, atmosphere and sea ice anomalies known as the Antarctic Circumpolar Wave (ACW) (White and Peterson, 1996) depends on the slow oceanic teleconnection provided by the circumpolar flow of the ACC. Recent studies suggest the ACW has a substantial impact on regional climate variability. For example, White and Cherry (1998) and White (1999) have shown that rainfall in New Zealand and southern Australia is more strongly influenced by the ACW than by ENSO, and suggest this link may provide some predictive skill at lead-times up to a year. However, the mechanism maintaining the ACW anomalies in the face of constant dissipation remains a topic of debate. Hypotheses for the ACW include forcing by ENSO-related atmospheric teleconnections; a coupled atmosphere-ocean instability “local” to the Southern Ocean; or a passive ocean response to stochastic or spatially-fixed atmospheric forcing. The lack of broad-scale observations of upper ocean temperature and salinity makes unravelling the dynamics of the phenomenon difficult, but the question is important as each mechanism has different implications for climate variability and predictability.

Variability of interbasin exchange of heat and other properties

Results from Southern Ocean WOCE suggest the interbasin exchange of heat varies significantly from year-to-year. For example, the heat flux entering the Pacific south of Australia varied by 0.6 x 10^{15} W (relative to 0°C) between 1991 and 1996 (Rintoul and Sokolov, 1999). The large-scale significance of this heat flux variability is difficult to interpret in the absence of other observations: changes in baroclinic heat transport south of Australia might be balanced by storage, either local or basin-scale; by zonal divergence of the ACC (although measurements at Drake Passage suggest this is not the case); by meridional divergence in the Indian and Pacific basins; by changes in air-sea heat flux; or by changes in barotropic flow. In any case, given that the observed variability is significant relative to the meridional heat transport in each basin, it is important the Southern Ocean observing system provides the measurements needed to assess its impact.

The transport of individual water masses changes around the circumpolar path of the ACC.

For example, more intermediate water enters the Atlantic through Drake Passage than exits south of Africa, the difference made up by export of NADW. South of Australia, more Subantarctic Mode Water (SAMW) enters the Pacific than leaves through Drake Passage; the inflow of SAMW balances the outflow of water through the Indonesian passages (Sloyan and Rintoul, 1999). If changes in air-sea forcing drive changes in water mass formation, the transport of anomalous water masses will carry the signature of the forcing anomaly into neighbouring basins where it may affect the climate there. Transport measurements at the Southern Ocean chokepoints, and basin-scale observations of T(z) and S(z), are needed to monitor and interpret ACC variability.

Measurements of ACC property transports constrain basin-scale budgets of heat and freshwater.

Direct estimates of heat and freshwater transports from oceanographic observations are generally more accurate than any alternative method presently available. Budget studies using transport and storage observations in the Southern Ocean are an important tool for improving our knowledge of the exchange of heat and freshwater between ocean and atmosphere.

Low latitude influence of southern hemisphere subtropical and subantarctic waters

The potential for oceanic advection of heat anomalies to produce delayed negative feedback, and hence oscillations, in the ocean-atmosphere system underlies several recent theories of decadal and interdecadal variability. Most of these studies have focused on the relatively well-measured northern hemisphere, where hypotheses are easier to test. But many of the large-scale anomalies which have received attention in the northern hemisphere have a signature in the southern hemisphere as well (e.g. White and Cayan, 1998). Moreover, water supplied from the south dominates the surface and thermocline waters of the equatorial Pacific (e.g., White and Cayan, 1998; Huang and Liu, 1999; Johnson and McPhaden, 1999). The tropical Atlantic is also supplied by waters from the south (e.g., Schott et al. 1998). Anomalies in the subduction, circulation, or properties of southern hemisphere water masses formed as far south as the ACC (e.g., SAMW) may therefore ultimately influence tropical SST. These studies suggest that advection of extratropical southern hemisphere anomalies to the tropics could drive low-frequency variability of tropical phenomena such as ENSO. Observations in mid- and high-latitudes of the southern hemisphere oceans are needed to explore how tropical—extratropical exchange modulates ENSO.

Variability of the Southern Hemisphere atmospheric circulation at mid- and high-latitudes

Numerous studies have documented interannual and longer period variability in the major spatial and temporal patterns of the southern hemisphere atmospheric circulation. For example, the semi-annual oscillation (SAO) explains more than half the mean annual variance of sea level pressure over large areas of the Southern Hemisphere (van Loon, 1972). The SAO is a coupled ocean-atmosphere phenomenon which results from phase differences in the annual cycle of temperature between the ocean-dominated mid-latitudes and the continent-dominated higher latitudes. A marked decrease in amplitude of the SAO after 1979 (Hurrel and van Loon, 1994) has been linked to changes in the annual cycle of SST near 50°S (Meehl et al., 1998). Further evidence of the importance of dynamical coupling between ocean, atmosphere, and sea ice to the SAO is provided by modelling studies. Manabe and Stouffer (1996) compared the response of an atmospheric model coupled to a dynamic ocean to that of the same model coupled to a non-dynamic mixed layer ocean. They found the two models produced similar temporal variability of surface temperature everywhere except at mid- and high-latitudes of the Southern Hemisphere, suggesting ocean dynamics are important there. Simmonds and Walland (1998) showed that ocean-atmosphere interactions at these latitudes drive low-frequency variability of the SAO. To explore connections between ocean dynamics and atmospheric variability, measurements of upper ocean temperature and salinity are needed, as well as drifters measuring sea surface temperature and sea level pressure (to improve atmospheric analyses and remove bias from satellite products).

A strategy for sustained observations in the Southern Ocean

An enhanced Southern Ocean observing system is needed to meet CLIVAR goals. Recent advances such as those highlighted here show that at least the following variables must be monitored on a sustained basis: temperature and salinity profiles on broad spatial scales; ACC property transport; sea surface temperature, salinity, and sea level pressure; full-depth profiles of T, S and tracers at key sites; and exchange between the Southern Ocean and lower latitudes.

While this is a challenging list, advances in technology and understanding mean that it is now possible to design a cost-effective observing system to meet this need (Rintoul et al., 1999). The minimum Southern Ocean in situ observing system must include at least the following elements:

- *Argo.* Southern Ocean Argo is critical: the only feasible way to obtain broad-scale measurements of T(z) and S(z) in such a remote region is with profiling floats. Float trajectories will also constrain transport estimates.
- *Repeat sections*. A combination of occasional repeat hydrography and more frequent XBT sections is needed to measure transports between basins, and between the Southern Ocean and lower latitudes. Repeat hydrography provides the only way to monitor changes in temperature, salinity, carbon and transient tracers throughout the full water column.
- *Drifters*. Measurements of sea surface temperature, sea level pressure, and sea surface salinity are essential to remove biases in satellite products and to improve the accuracy of air-sea flux products from atmospheric analyses.
- *Moorings/Time series stations*. Water properties and transport need to be monitored at key locations. Direct velocity measurements will complement the velocity information provided by floats, drifters and acoustic Doppler current profilers (ADCP).

The Southern Ocean is not only remote from shipping routes, it is also distant from densely-populated land masses. There is a risk, therefore, that the southern hemisphere oceans will be poorly sampled by the ocean observing system, simply because they are far away, rather than through a carefully argued scientific case that they are of little relevance to CLIVAR, GOOS and GODAE. The studies highlighted here suggest, on the contrary, that Southern Ocean processes exert a profound influence on regional and global climate, and therefore sustained observations of the Southern Ocean are essential if CLIVAR is to achieve its goals. By exploiting new technologies and building on insights gained from recent observations and modelling studies, it is now feasible to obtain these observations, despite the formidable logistical challenges.

References:

Broecker, W.S., Sutherland, and T-H. Peng, 1999: A Recent Slowdown of Deep Water Formation in the Southern Ocean? *Science*, submitted.

Gnanadesikan, A., 1999: A simple predictive model for the structure of the oceanic pycnocline. *Science*, **283**, 2077-2079.

Glowienka-Hense, R. 1995: GCM response to an Antarctic polynya. *Beitr. Phys. Atmosphäre*, **68(4)**: 303-317.

Gordon, A L, 1982: Weddell deep water variability, *J. Marine Res.*, **40 (Suppl.)**, 199-217.

Huang, B. and Z. Liu, 1999: Pacific subtropical-tropical thermocline water exchange in the National Centers for Environmental Prediction ocean model. *J. Geophys. Res.*, **104**, 11065-11076.

Hurrell, J. W. and H. van Loon, 1994: A modulation of the atmospheric annual cycle in the Southern Hemisphere. *Tellus*, **46A**, 325-338.

Johnson, G. C. and M. McPhaden, 1999: Interior pycnocline flow from the subtropical to the equatorial Pacific Ocean. *J. Phys. Oceanog*., submitted.

Ledwell, J. R., A. J. Watson, and C. B. Law, 1993: Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment. *Nature*, **364**, 701-703.

Manabe, S. and R. J. Stouffer, 1996: Low-frequency variability of surface air temperature in a 1000-y. integration of a coupled atmosphere-ocean-land surface model. *J. Climate*, **9**, 376-393.

Meehl, G. A., J. W. Hurrell, and H. van Loon, 1998: A modulation of the mechanism of the semiannual oscillation in the Southern Hemisphere. *Tellus*, **50A**, 442-450.

Rintoul, S. R. and S. Sokolov, 1999: Baroclinic transport variability of the Antarctic Circumpolar Current south of Australia (WOCE repeat section SR3). *J. Geophys. Res*., submitted.

Rintoul, S. R. et al., 1999: Monitoring and understanding Southern Ocean variability and its impact on climate: a strategy for sustained observations. Proceedings of the“The Ocean Observing System for Climate” conference, St. Raphael, France, October 1999, in press.

Sarmiento, J. L., T. M. C. Hughes, R. J. Stouffer, and S. Manabe, 1998: Simulated response of the ocean carbon cycle to anthropogenic climate warming. *Nature*, **393**, 245-249.

Schott, F.A., J. Fischer, and L. Stramma, 1998: Transports and pathways of the upper-layer circulation in the western tropical Atlantic. *J. Phys. Oceanog*., **28**, 1904-1928.

Simmonds, I. and Walland, D.J., 1998: Decadal and centennial variability of the southern semiannual oscillation simulated in the GFDL coupled GCM. *Climate Dynamics*, **14**, 45-53.

Sloyan, B. M. and S. R. Rintoul, 1999: The Southern Ocean limb of the global deep overturning circulation. *J. Phys. Oceanogr*., submitted.

Toggweiler, J. R. and B. Samuels, 1998: On the ocean's large-scale circulation near the limit of no vertical mixing. *J. Phys. Oceanogr*., **28**, 1832-1852.

van Loon, H., 1972: Wind in the Southern Hemisphere. Meteorology of the Southern Hemisphere. *Meteor. Monog*., **35**, Amer. Meteor. Soc., 87-100.

White, W. B., 1999: Influence of the Antarctic Circumpolar Wave on Australia precipitation from 1958-1996. J. Climate, submitted.

White, W. B. and D. Cayan, 1998: Quasi-periodicity and global symmetries in interdecadal upper ocean temperature variability. *J. Geophys. Res*., **103**, 21335 – 21354.

White, W. B. and N. J. Cherry, 1998: Influence of the Antarctic Circumpolar Wave upon winter temperature and precipitation over New Zealand. *J. Climate*, **12**, 960-976.

White, W. B. and R. Peterson, 1996: An Antarctic Circumpolar Wave in surface pressure, wind, temperature, and sea ice extent. *Nature*, **380**, 699-702.

Wong, A. P. S, N.L. Bindoff, and J.A. Church, 1999: Large-scale freshening of intermediate waters in the Pacific and Indian Oceans. *Nature*, **400**, 440-443.

The Relevance of the South Atlantic for Climate Studies

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Thermohaline Circulation

The Atlantic thermohaline circulation is one of the re search topics identified as scientifically relevant to CLIVAR. The thermohaline circulation may be equal or even more important to the global circulation system than the wind driven circulation, as it couples the full volume of global ocean to the atmosphere forming a global circulation network of mass and heat transports (Gordon, 1985, Schmitz, 1995).

The importance of the role than the South Atlantic plays in this circulation is indisputable. The classical picture of the conveyor belt (Broecker, 1991) indicates that the North Atlantic trades cold deep water for warm upper water coming from the South Atlantic. This thermohaline overturning cell is composed of northward transports of warm surface- and intermediate-layer waters in the upper 1000m, southward transport of North Atlantic Deep Water (NADW), and at the bottom northward flowing Antarctic Bottom Water. The net balance is to the north and, as a consequence, the Atlantic is a peculiar ocean because it is the only ocean that transfers heat northward across the equator.

Some intriguing and yet still not answered questions are: How much heat is transported into the North Atlantic and from where? How the upper limb of the "conveyor belt" circulation is supplied? How much is warm and salty upper layer water entering the region from the Indian Ocean? How much is colder and fresher water originating out of the Drake Passage? What are the main routes of these passages and the mechanisms that originates the transfers?

Most of these exchanges take place via the boundary currents, which are the major distributors of mass and heat across basins and oceans, and the rings shed at their retroflections.

There have been indications of recent warming which might be related to variability of deep convection and water mass transformation in the Weddell Sea. Hence, monitoring the various in- and outflows through the southern entrance of the South Atlantic is important for understanding decadal variability and has to be a prime objective of an ocean programme in CLIVAR.

One of the key questions when dealing with the thermohaline circulation in the South Atlantic is how much heat and salt is transferred from the Indian to the Atlantic Ocean. This inter-ocean exchange take place through the Benguela /Agulhas system, south of South Africa. The Agulhas Current, at its retroflection, shed energetic rings that carried salt and warm water into the South Atlantic. Approximately 3 to 7 rings per year are shed at the retroflection and in average, each one of the rings transports 1 SV of water. The Benguela Current, and its extension are the main conduits of Indian Ocean water into the Atlantic. Across 30°S, the Benguela Current is confined between the African continental shelf and the Walvis Ridge located between 2° and 4°E (Reid, 1989). In the early 90's an experiment called Benguela Sources and Transports (BEST), took place in the region. One of the main results of the BEST experiment was that while the mean transport of the Benguela Current remains approximately constant every year, there is a marked variability of the water masses from where the Benguela Current drain its sources (Garzoli and Gordon, 1996 and Garzoli et al., 1997). Further studies based on the BEST data and altimeter data, indicated that in addition to this variability, during the years when the Agulhas Current was stronger, most of the contribution to the Benguela Current was not from the Indian Ocean but from the South Atlantic (Garzoli and Goni, 1999). These results posed the question of why, when the Agulhas transport is higher than usual, less Indian Ocean water contributes to the Benguela Current? Modelling studies (Matano, personal communication) indicates that a stronger Agulhas Currents increases the inertia and a larger portion of the current is forced to flow over the shallower depths of the Agulhas plateau. The current gets trapped in the topography and as a result, fewer and larger rings are shed at the retroflection. Matano's theoretical results are in total agreement with the observations and provide a theoretical explanation to the results. These results have a direct implication on the thermohaline circulation. Further studies are needed to determine the causes of this variability and its impact in the conveyor belt.

Another phenomena related to the intensity of the Agulhas current, and of relevance to CLIVAR is the passage of the Natal pulse. Since the Natal pulse alters the path of the Agulhas Current, this has a direct effect on the interbasin exchange of water south of South Africa with important environmental consequences. Lutjerharms and de Ruijiter (1996) hypothesised that a change in the wind stress over the southern Indian Ocean will lead to a higher frequency of the Natal pulse. This will have as a consequence a slowing-down of the conveyor belt by reducing the amount of Agulhas water that enters the Atlantic Ocean. This phenomenon has a disruptive effect on pelagic fish recruitment along the southeastern coast of South Africa and causes a significant reduction of rainfall along this shoreline (Lutjerharms and de Ruijiter, 1996).

Sea Surface Temperature

Another topic of relevance to CLIVAR is the distribution of sea surface temperature (SST). The distribution of SST anomalies in the South Atlantic is important at the global scale for modelling and prediction. But in addition, because SST anomalies in the southwestern Atlantic affect the climate, and therefore living conditions, of the most densely populated region of the southern hemisphere: the seaward corridor between northern Brazil and southern Argentina. It has been shown that during the last few decades climatic variations have had an important economic and social impact on the region (SACS Document, 1996). Drought periods have produced changes in cattle population, drained the water supplies of large cities and caused shortages of hydroelectric power. A westward shift in precipitation patterns, that occurred during the '70s, has been related to a significant expansion of farming in the south of Argentina, Uruguay and southern Brazil. While the mechanisms behind these climatic fluctuations remain unclear the few existing observations point out to relations between climate variability and the large SST changes observed in the open ocean.

The most dramatic contrasts in SST of the entire South Atlantic occurs at its western boundary when the warm and salty waters of the southward flowing Brazil Current meet the colder and fresh waters of the northward flowing Malvinas Current. This encounter takes place at approximately 38°S originating a strong thermohaline front with temperature gradients as high as 1°C/100m that has been given the name of the confluence front (Gordon and Greengrove, 1986). After the confluence both currents turn eastward and flow offshore in a series of large-scale meanders. The mean offshore turning latitude of the Brazil Current is significantly displaced northward against the latitude of zero windstress curl, suggesting an important dynamic role of the Malvinas Current. The confluence zone migrates up and down the continental margin at seasonal, interannual and possibly longer time scales, which in turn impacts on the atmosphere, with likely effects on cyclogenesis and regional rainfall distribution. Besides the large-scale South Atlantic circulation, shelf waters that obtain their characteristics from inflow through the Straits of Magelan and river outflow, cause substantial SST variability on the wide shelf areas and seem to have an effect on local climate variations.

The Brazil/Malvinas confluence is one of the most energetic regions in the world ocean. In-situ and remote observations indicate that the location of the confluence varies, up to 900 km along the coast, on seasonal and interannual time scales (Olson et al., 1988; Garzoli and Garraffo, 1989). In both cases it has been attributed to variability in the latitude of separation of the currents from the coast. This variability leads to large SST variations both on a seasonal and interannual time scale. Podesta et al., (1991) and Provost et al., (1992) found that the annual signal in SST weakens to the south. The frequency of major oscillations appears to be tied to cycles in the transports of the Brazil and Malvinas currents forced by the subtropical winds or changes in the Atlantic circumpolar current transport (Matano et al. 1993, Smith et al., 1994). Anomalies in this fluctuation can be partially explained by changes in the local atmospheric patterns (Garzoli and Giulivi, 1993).

SST anomalies at annual and inter-annual periods have been associated to climatic variability over the continental land mass. Principal component analysis of SST patterns of the confluence region and precipitation records in Uruguay indicate that both registers are highly coherent (>0.8) and 90° out of phase. Olson (personal communication) showed that an anomalous warm December 1989 preceded a period of intense rain fall that lasted up to the end of April 1990. At the end of this rain period, SST in the SWA was anomalous cold (local SST anomalies exceeded 6°C). Rainfall anomalies are also associated with large positive SST anomalies in the southern Argentine Basin and northeastern Brazil (Hastenrath and Heller, 1977).

The first evidence of interdecadal variability in the South Atlantic was obtained by Venegas et al. (1996). A single value decomposition analysis was used to determined the coupled modes of variability of monthly sea surface temperature and sea level pressure. From this analysis they found that the first mode, which accounts for 63% of the total variance, represents an oscillation in the strength of the subtropical anticyclone with a 15 years period, that is accompanied by fluctuations on a north-south dipole structure in the SST. This mode appears to be linked to the global-scale interdecadal (15-years) joint mode on SST and sea level pressure that can be described as a “strong weak” subtropical anticyclone oscillation which forces a dipole structure in the ocean temperature.

References:

Broecker, W.S., 1991: The great ocean conveyor. *Oceanography*, **4**, 79-89.

Garzoli, S. L. and Z. Garraffo, 1989: Transports, Frontal Motions and Eddies at the Brazil-Malvinas Currents Confluence. *Deep-Sea Res.*, **36**, 681-703.

Garzoli, S. L., and C. Giullivi, 1993: What forces the variability of the southwestern Atlantic boundary currents? *Deep-Sea Res.*, **41**, 1527-1550.

Garzoli, S.L., and A.L. Gordon, 1996: Origins and variability of the Benguela Current. *J. Geophys. Res.*, **101**(C6), 987-906.

Garzoli, S.L., G. Goñi, A. Mariano, and D. Olson, 1997: Monitoring South Eastern Atlantic Transports using altimeter data. *J. Mar. Res.*, **55**, 453-481, 1997.

Garzoli, S.L., and G. Goni, 1999: Combining Altimeter Observations and Oceanographic Data for Ocean Circulation and Climate Studies. To be published in the ICSOS Book.

Gordon, A.L., 1985: Indian-Atlantic transfer of thermocline water at the Agulhas Retroflection. Sciences, N.Y., 227(4690), 1030-1033.

Gordon, A. L., and C. L. Greengrove, 1986: Geostrophic circulation of the Brazil-Falkland Confluence. *Deep Sea Res.*, **33**, 573-585.

Hastenrath, S., and L. Heller, 1977: Dynamics of climate hazards in northeast Brazil. *Q. J. Roy. Meteor. Soc.*, **103**, 77-92.

Lutjeharms, J.R.E., and W.P. de Ruijiter, 1996: The influence of the Agulhas Current on the adjacent coastal ocean: possible impacts of climate change, *J. Marine Systems*, **7**, 321-336.

Matano, R. P., M. G. Schlax, and D. B. Chelton, 1993: Seasonal variability in the southwestern Atlantic.. *J. Geophys. Res.*, **98**, 18,027-18,035.

Olson, D. B., G. P. Podesta, R. H. Evans, and O. B. Brown, 1988: Temporal variations in the separation of Brazil and Malvinas Currents. *Deep-Sea Res.*, **35**, 1971-1990.

Podesta, G. P., O. B. Brown, and R. H. Evans, 1991: The annual cycle of satellite-derived sea surface temperature in the southwestern Atlantic Ocean. *J. Climate*, **4**, 457-467.

Provost, C., O. Garcia, and V. Garcon, 1992: Analysis of satellite sea surface temperature time series in the Brazil Malvinas Currents Confluence region: Dominance of the annual and semiannual periods. *J. Geophys. Res.*, **97**, 17,841-17,858.

SACC Document, 1996: South Atlantic Climate Change, NOAA/AOML/PhOD Report, October 1996. Web site: http://www.oce.orst.edu/po/research/matano2/index.html.

Schmitz, W.J., Jr., 1995: On the interbasin-scale thermohaline circulation. *Rev. Geophys.*, **33**, 151-173.

Smith, L. T., E. P. Chassignet, and D. B. Olson, 1994: Wind-forced variations in the Brazil-Malvinas Confluence region as simulated in a coarse resolution numerical model of the South Atlantic. *J. Geophys. Res.*, **99**, 5095-5117.

Venegas, S. A., L. A. Mysak and D. Straub, 1996: Evidence for interannual and interdecadal climate variability in the South Atlantic. *Geophys. Res. Lettr.*, **23**, 2673-2676.

Climate Observing System for the Tropical Atlantic (COSTA)

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The Climate Observing System for the Tropical Atlantic (COSTA) Workshop was held at National Oceanic and Atmospheric Administration/Atlantic Oceanographic and Meteorological Laboratory in Miami from May 4 to May 7, 1999. Sixty-four scientists from Brazil, France, Germany, Morocco, South Africa, Venezuela, and the US attended the workshop. The objectives of the COSTA Workshop were to review the status of existing programmes in the Tropical Atlantic, determine the need for new observations in support of climate studies, and lay the groundwork for coordinated multi-national observing system in the Tropical Atlantic. This note summarises the discussions that took place during the workshop

Previous to the COSTA workshop, a large effort was already underway to study the tropical Atlantic and its importance for climate. On the global scale, the CLIVAR initial implementation plan underlines the need to establish a tropical Atlantic observing system based on the PIRATA array. EuroCLIVAR recommends that this array be maintained and makes recommendations on how to expand it. On the basin scale, the Atlantic Climate Variability Experiment (ACVE) prospectus also recommends observations of the tropical Atlantic for climate purposes.

The intent of the COSTA workshop, based in the CLIVAR (global) and ACVE (basin) experience, was to formulate the basis for an extended and more permanent tropical Atlantic observing system, regional building on the present PIRATA moored array, other existing monitoring programmes and process studies, and the current scientific underlayment.

The meeting started with a series of keynote presentations that established the importance and role of the tropical Atlantic in climate fluctuations followed by a revision of all existing programmes in the area. The keynote talks described climate variability in the Atlantic sector, its relationship to tropical Atlantic variability (TAV), especially sea surface temperature (SST), and to the North Atlantic Oscillation (NAO) and the meridional overturning circulation (MOC). They also summarised present scientific thinking as to the possible mechanisms behind tropical Atlantic SST fluctuations and their relation to climate, highlighting in particular the role of surface fluxes in the off-equatorial regions, the equatorial ocean-atmosphere interactions, and their relationships to movements of the Inter-Tropical Convergence Zone (ITCZ).

The scientific discussions provided the basis for forming separate working groups centred on four important themes: 1) sea surface temperature (SST) and surface fluxes; 2) sea level and subsurface structure; 3) circulation; and 4) modelling and data assimilation.

The recommendations provided by the working groups were presented and discussed in a plenary session on the last day of the workshop. They may be summarised as follows:

It was recommended:

- To maintain and enhance the present monitoring systems consisting of the PIRATA moored array, surface drifters, XBT observations from volunteer observing vessels (VOS) and to continue the current PALACE floats programme in the Tropical Atlantic.
- To implement process studies built on the existing observations, to enhance the design of the core observing system. Process studies will be directed to monitor the MOC, the western boundary currents and Caribbean passages, the mid tropical Atlantic circulation, the cold tongue and the upwelling regions.
- To perform modelling studies to enhance the physical understanding obtained from data sets and to unify the observations into integrated products through data assimilation.
- To produce integrated products (data and model products) available for scientific analysis and prediction activities.

The workshop also discussed how to proceed with the data collected and how to make it available to the community. The consensus was to continue the data collection and quality control through the existing data centres presently responsible for the observations Recommendations included the need to make the data available in near real time for model forecasts.

A copy of the complete Draft Report for the COSTA Workshop can be obtained at http://www.aoml.noaa.gov/phod/COSTA/

The COSTA Organization Committee was composed by:
Silvia L. Garzoli (NOAA/AOML; USA) Chairman
Mike McPhaden (NOAA/PMEL; USA)
Gilles Reverdin (CNES; France)
Joel Picaut (NASA/Goddard; France)
Marcio Vianna (INPE; Brazil)
Edmo Campos (Univ. of São Paulo; Brazil)

CLIVAR Science at the 1999 IUGG

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The International Union of Geodesy and Geophysics (IUGG) Assembly at the University of Birmingham, 18-30 July 1999, demonstrated the high profile of climate variability science, with many symposia devoted to topics identified within the CLIVAR Science Plan. In such a large meeting (over 4000 participants) any selection of "highlights" will reflect the biases of the selector, and his ability to move from symposium to symposium. The following reflects my biases, and the sessions I was able to attend.

The one stand-out feature of IUGG 99, in my opinion, was that both weeks of the conference were dominated by week-long symposia of crucial importance to CLIVAR. The first week had a week-long symposium "Improvements and intercomparisons of climate system models and their component models". This symposium examined sea-ice models, ocean and atmosphere models, land-surface parameterisations, and coupled models. I cannot remember such an intensive examination of models at previous IUGG, or IAMAS-IAPSO meetings. The papers presented indicated the rapid advances being made in models for climate. The impressions I carried away with me were the increasing belief that regional scale climate modelling is feasible, and the increasing evidence for the influence of land-surface on climate modelling.

The last two days of the first week also had a symposium on "Atmospheric and oceanic connections between the polar regions and lower latitudes", again a topic of importance to CLIVAR. As usual at IUGG meetings, the overlap between the subjects in concurrent symposia meant that no-one could get to all the papers of interest in their field.

The second week was dominated by the week-long symposium "Ocean/atmosphere variability and predictability". Sessions were devoted to phenomena on ever-increasing time-scales, starting with the El Niño - Southern Oscillation time-scale (including the role of the MJO on the 1997/98 El Niño), building through decadal variability of the El Niño - Southern Oscillation, and ending with inter-decadal and multi-decadal time-scales. Various sessions concentrated on different geographical regions, e.g. the Atlantic, and the monsoons. Scale-interactions received a lot of attention. As was the case with the model intercomparison symposium in the first week, having a concerted examination of all the time-scales and geographical regions allowed for much cross-fertilisation of ideas between participants.

Once again, other sessions of great importance to CLIVAR were held concurrently. A two-day symposium on "Detection and attribution of climate change" demonstrated, in the few papers I could get to, that increasingly sophisticated statistical techniques are being used in this area. I have the feeling, however, that perhaps we are now concentrating too much on the question "Are we affecting global climate?" (and searching for a statistically-significant answer), rather than "What effect are we having on global climate?".

Another symposium of great interest was "On the use of coupled models for paleoclimate studies". The message I derived from this symposium (again from only attending a few presentations) was that including interactive vegetation in the models is essential, if we are to simulate paleoclimate variations. The implication for shorter-term studies is that we must consider the possible effects of land surface changes in understanding regional climate changes through the 20th century. The real "stand-out" image was a figure showing the observed depth of the thermocline across the equatorial Pacific at 21,000 BP!

The enormous amount of work related to CLIVAR, spread across many symposia (there were quite a few others that I have not mentioned here, simply because I could not get to them), indicates the importance of CLIVAR, and the interest in CLIVAR topics amongst atmospheric and ocean scientists. The great disappointment was the many concurrent sessions of interest to CLIVAR scientists. This did, to some extent, reduce the opportunities for interactions. Perhaps the next IUGG Assembly will be the place for a major CLIVAR symposium, organised by the PRAs, to enhance scientific involvement in CLIVAR, and to facilitate cross-fertilisation across the various CLIVAR time-scales and geographical regions of interest.

CLIVAR Calendar

1999	Meeting	Location	Attendance
October 18 - 22	OOPC/CLIVAR Conference on Ocean Observations for Climate	St. Raphael, France	Open
October 25 - 27	TOPEX/Poseidon/Jason-1 SWT	St. Raphael, France	Limited
November 8 - 12	PAGES/CLIVAR Meeting	Venice, Italy	Invitation
December 6 - 10	CLIVAR Asian-Australian Monsoon Panel, 3rd Session	Honolulu, USA	Invitation
December 13 - 17	AGU Fall Meeting	San Francisco, USA	Open
2000	**Meeting**	**Location**	**Attendance**
January 8 - 15	80th AMS Annual Meeting	Long Beach, USA	Open
January 24 - 28	AGU Ocean Sciences Meeting	St. Antonio, USA	Open
Feburary 20 - 24	SOLAS Open Science Conference	Damp, Germany	Open
March 13 - 17	Joint Scientific Committee of WCRP, 22nd Session	Tokyo, Japan	Invitation
April 3 - 7	6th International Conference on Southern Hemi-sphere Meteorology and Oceanography	Santiago, Chile	Open
April 8 - 10	CLIVAR VAMOS Panel 3rd Session	Santiago, Chile	Invitation
April 25 - 29	European Geophysical Society, XXV Assembly	Nice, France	Open
May 1 - 5	CLIVAR SSG - 9th Session	Honolulu Hawaii	Invitation

For more information, please contact the ICPO or check out our web-page: **http://www.dkrz.de/clivar/latest.html**

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