THE ENSO OBSERVING SYSTEM

Michael J. MCPHADEN[1], Thierry DELCROIX[2], Kimio HANAWA[3], Yoshifumi KURODA[4], Gary MEYERS[5], Joel PICAUT[6], and Mark SWENSON[7]

[1]NOAA/PMEL, Seattle, WA, [2]ORSTOM/IRD, Noumea, New Caledonia, [3]Tohoku University, Japan, [4]JAMSTEC, Yokosuka, Japan, [5]CSIRO, Hobart, Australia, [6]IRD/ORSTOM (presently at Goddard Space Flight Center, Greenbelt, MD), [7]NOAA/AOML, Miami, FL

***ABSTRACT** — This paper reviews the status of the ENSO (El Niño/Southern Oscillation) Observing System, with emphasis on the Pacific Ocean during the recent 1997–98 El Niño and subsequent La Niña. Contributions of this system to detection, monitoring, forecasting, and understanding of ENSO related climate swings will be described. Recommended enhancements and extensions to the observing system will also be presented.*

1 – INTRODUCTION

The 1982–83 and 1997–98 El Niños are bookends on a remarkable chapter in the history of climate research. The 1982–83 El Niño, which was the strongest on record prior to 1997–98, was neither predicted nor was it even detected until nearly at its peak. This failure exposed our inadequate comprehension of the underlying physical mechanisms responsible for the ENSO cycle, as well as woefully inadequate capabilities to observe and forecast climatic variations in the tropical Pacific. Remedying these inadequacies consequently became a central theme of the Tropical Ocean-Global Atmosphere (TOGA) research program which took place from 1985 to 1994.

It was within the context of TOGA that the ENSO Observing System was developed (McPhaden *et al.*, 1998). This system consists of the Tropical Atmosphere Ocean (TAO) array of moored buoys, an array of drifting buoys, volunteer observing ship (VOS) measurements, and a network of island and coastal sea level measurement stations (Figure 1). It took 10 years to build, requiring contributions from many nations, and it was not until the final month of the TOGA program (December 1994) that it was completed. A key feature of the observing system is the fast delivery of oceanographic and surface meteorological data within hours to days of its collection for monitoring of evolving climatic conditions, scientific analyses, and ENSO forecasting. Complementing this suite of ocean-based measurements is a constellation of satellites measuring surface winds, sea surface temperature, and sea level from space.

The 1997–98 El Niño was the first for which the ENSO observing system was in place from start to finish. Thus, this event was not only the strongest on record (as measured by the NINO3 SST index; Figure 2), but also the best ever documented (McPhaden, 1999). The 1997–98 El Niño developed so explosively that every month between June and December 1997 set a new record high for sea surface temperatures in the eastern equatorial Pacific. By December 1997, most of the equatorial Pacific was covered with water between 28–29°C, which is near the maximum sustainable temperatures possible in the open ocean (Figure 3).

The global impacts of this El Niño were equally spectacular in keeping with the extreme conditions observed in the tropical Pacific. At the same time, the wealth of new data, combined with model forecasts, greatly heightened public awareness about ENSO and its global consequences on climate and marine ecosystems. This awareness lead to mitigation efforts on an unprecedented scale in many countries around the world.

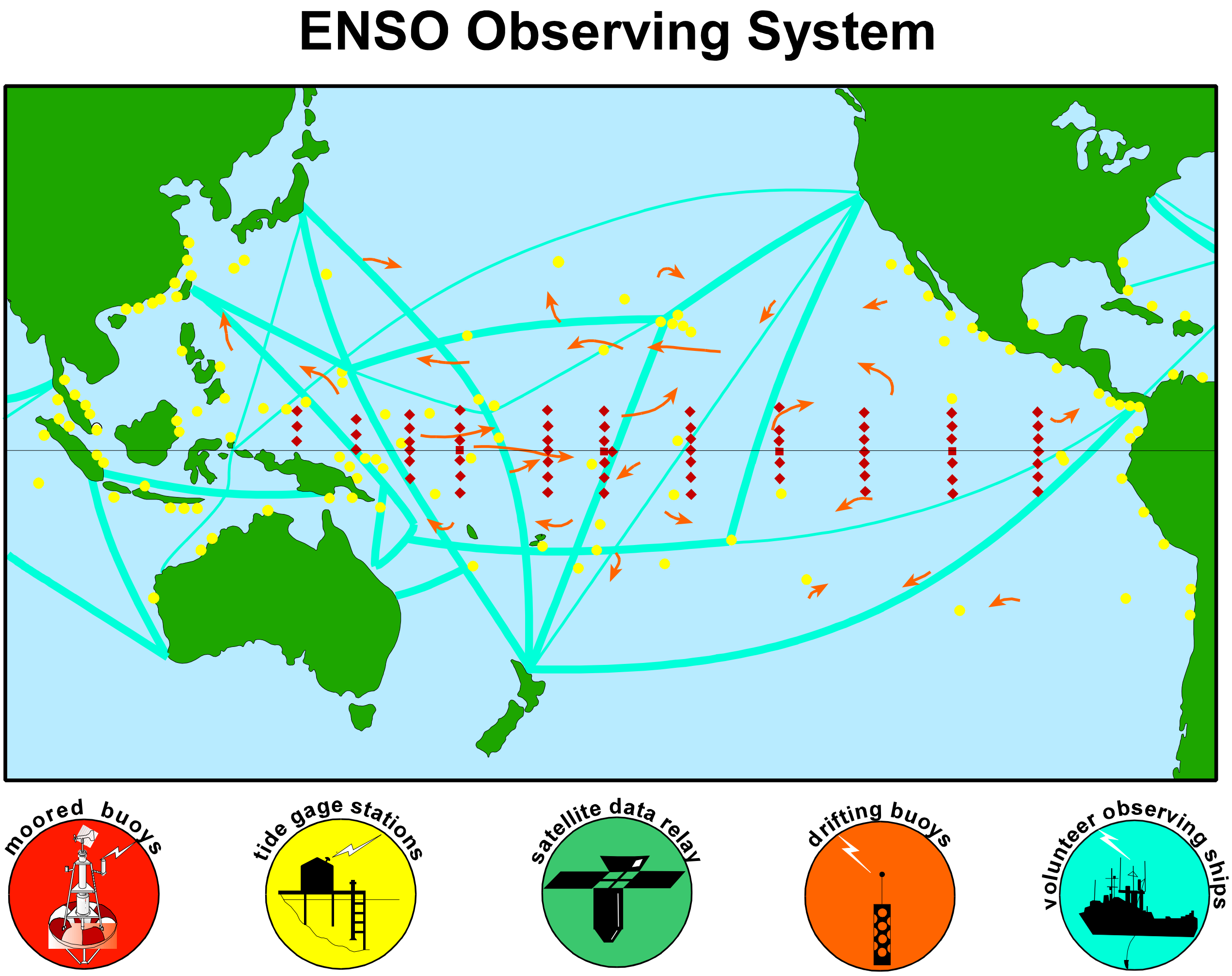

Fig. 1: The El Niño/Southern Oscillation (ENSO) Observing System was set up to understand, monitor, and predict ENSO variations. The Earth-based components, shown here, relay data in real time via satellites. The main components are a volunteer ship programme (blue tracks), an island and coastal tide-gauge network (yellow), a system of drifting buoys (orange arrows), and the TAO array of moored buoys (red). Complementing this network are satellites that provide data from space with near-global coverage. They include the US/French TOPEX/Poseidon mission; the European Space Agency Earth Remote Sensing satellites; US Department of Defense satellites; and NOAA's polar-orbiting weather satellites. Taken together, this ensemble of instrumentation delivers data on surface and subsurface temperature, wind speed and direction, sea level, and current velocity. The ENSO Observing System was completed in 1994 at the end of the 10-year international Tropical Ocean Global Atmosphere programme. It is now being continued in support of operational climate forecasting as well as research on ENSO dynamics.

2 – SCIENTIFIC BENEFITS

The scientific benefits of the ENSO Observing System were dramatically illustrated during 1997–99. The following summary briefly describes these benefits in terms of 1) monitoring and detection; 2) ENSO forecasting; 3) improved understanding. Details of how the data are processed, quality-controlled and widely distributed are described elsewhere in this volume (Legler *et al.* and Freitag *et al.*).

2.1 – Monitoring and Detection

For at least a year prior to the onset of the 1997–98 El Niño, there was a build up of heat content in the western equatorial Pacific, which is often viewed as a precursor of warm ENSO events (Fig. 4). This buildup was due to stronger than normal trade winds in 1995–96, and was associated with elevated SST

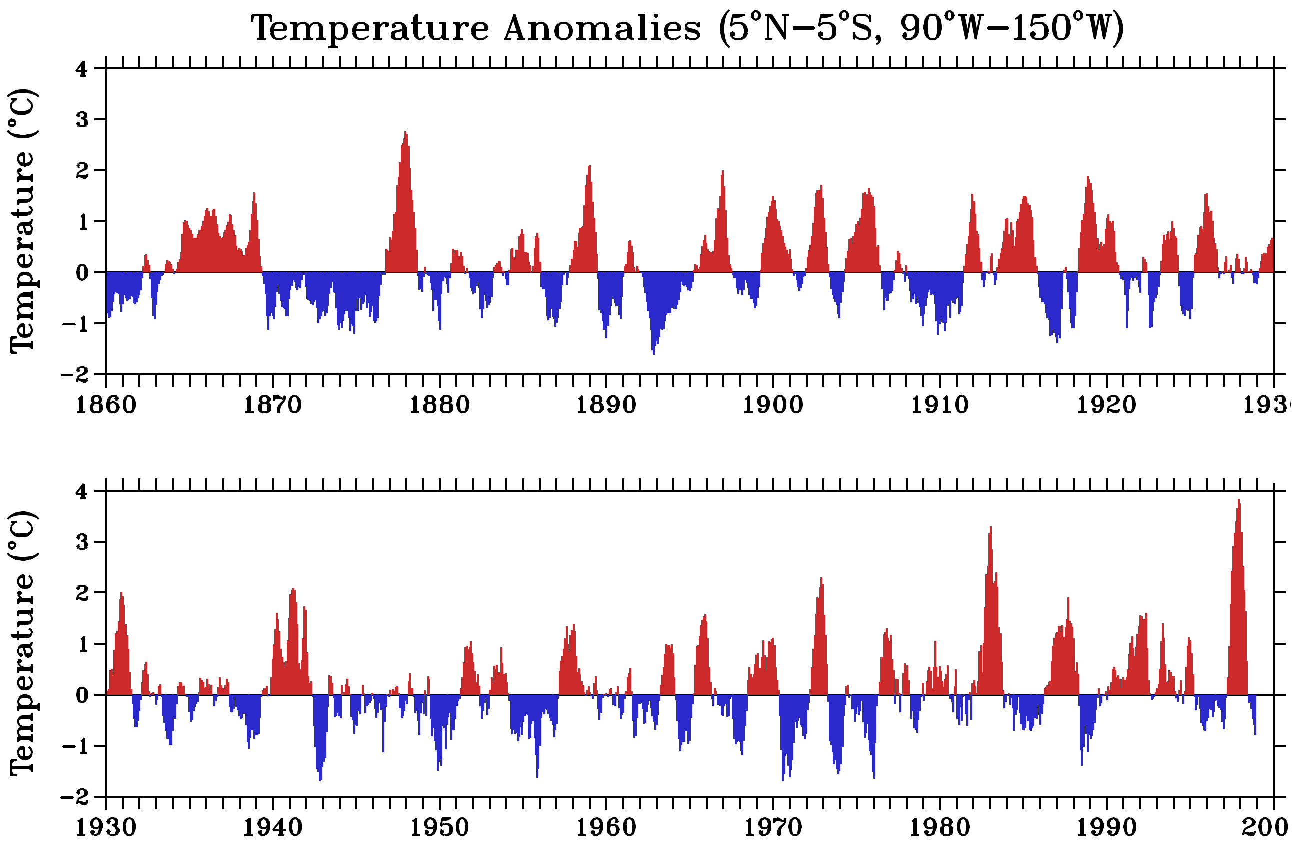

Fig. 2: Sea surface temperature anomalies for the region 5°N–5°S, 90°W–150°W from a combination of the shipboard data through 1991 (Kaplan *et al.*, 1998) and a blended satellite/in situ data analysis afterwards (Reynolds and Smith, 1994).

and sea level in the far western Pacific (Figs. 4 and 5). However, the onset of the El Niño did not occur until the boreal winter seasonal intensification of the Madden and Julian Oscillation (MJO) over the western Pacific. In early 1997, surface winds along the equator were punctuated by a series of westerly events of increasing intensity and/or fetch (Fig. 5) associated with enhanced MJO activity. The ocean currents forced by these westerly winds (Fig. 6; see also Kitamura *et al.*, 1998) drove warm water eastward near the equator. Westerly events also excited downwelling equatorial Kelvin waves that propagated into the eastern Pacific, depressing the thermocline by over 90 m in late 1997. These rapid changes in wind-forced zonal currents and subsurface thermal field variations mediated the intense warming at the surface observed during 1997.

In early 1998, SSTs in the eastern Pacific exceeded 29°C (Fig. 5) as warm anomalies were superimposed on the usual seasonal warming that occurs at this time of year. Westerly wind anomalies, though weaker than earlier in the El Niño event, migrated eastward in tandem with the 29°C water. Thermocline shoaling, initially confined to west of the international date line, slowly progressed into the central and eastern Pacific. However, SSTs remained anomalously high east of the date line, because the local winds were weak there in early 1998. It was not until the trade winds abruptly returned to near normal strength in the eastern Pacific in mid-May 1998 that the cold subsurface waters could be efficiently upwelled. SSTs in the equatorial cold tongue then plummeted because of the close proximity of the thermocline to the surface. At one location (0°, 125°W), SST dropped 8°C in 30 days, more than 10 times the normal cooling rate at that time of year (Fig. 7). The climate system shifted from one of the strongest El Niños on record to cold La Niña conditions in a space of a month.

Advances in understanding and predicting ENSO depend on an accurate definition of oceanic variability in the tropical Pacific like that presented above. In addition, the ability to quickly and clearly detect climatically relevant oceanic and atmospheric variations in the tropical Pacific has tremendous practical implications for short term weather forecasting, navigation, fisheries management, and other activities. Knowledge about the state of the tropical Pacific also implies a limited climate forecasting capability since, once developed, large-scale SST anomalies will persist for at least 1–2 seasons. So as SSTs reached historic highs and the thermocline flattened out along the equator in mid-1997, it was a

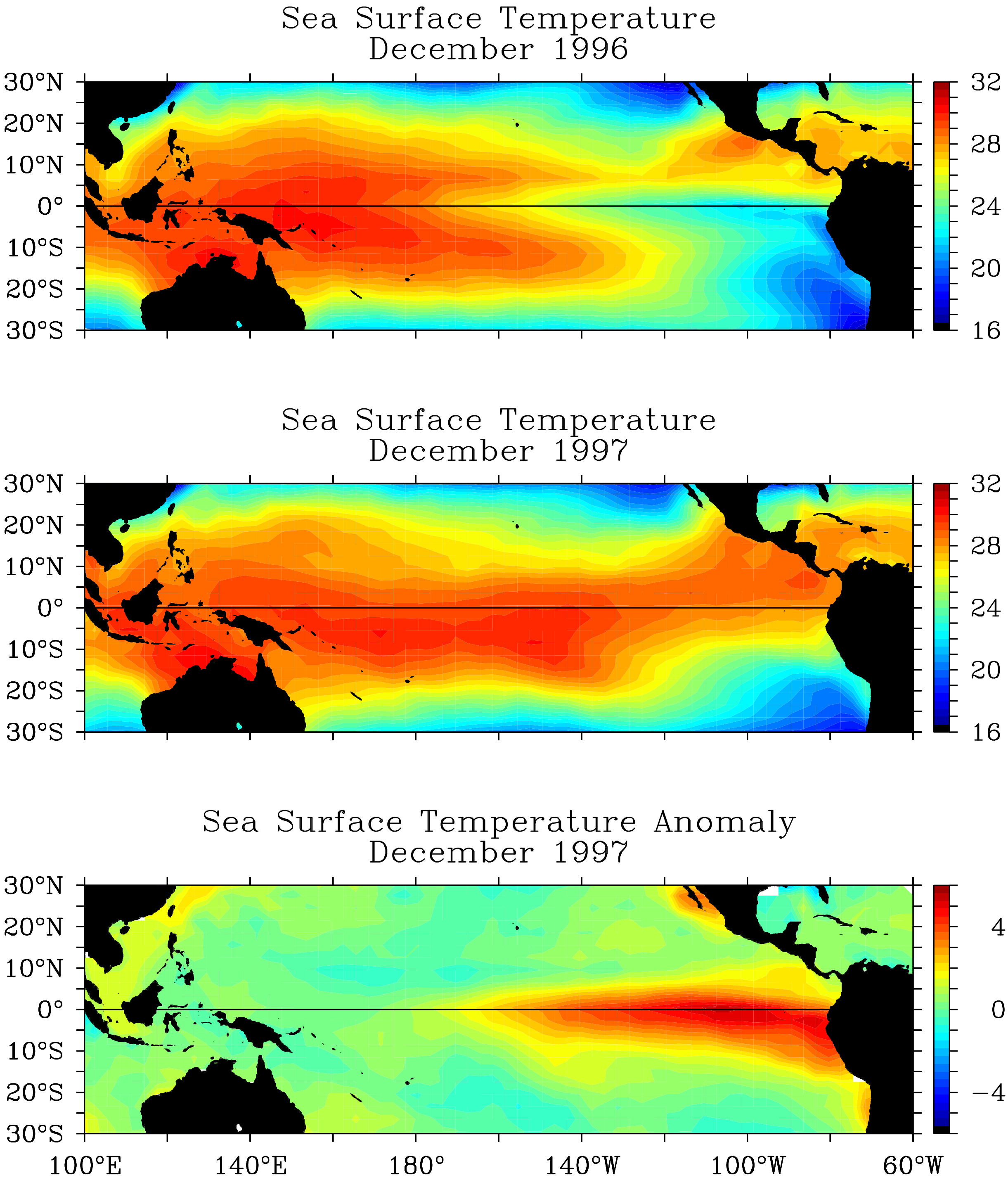

Fig. 3: Monthly averaged sea surface temperature (in °C) for December 1996 (top) and for December 1997 (middle). Monthly average sea surface temperature anomaly for December 1997 (bottom). These charts are based on the Reynolds and Smith (1994) SST analysis.

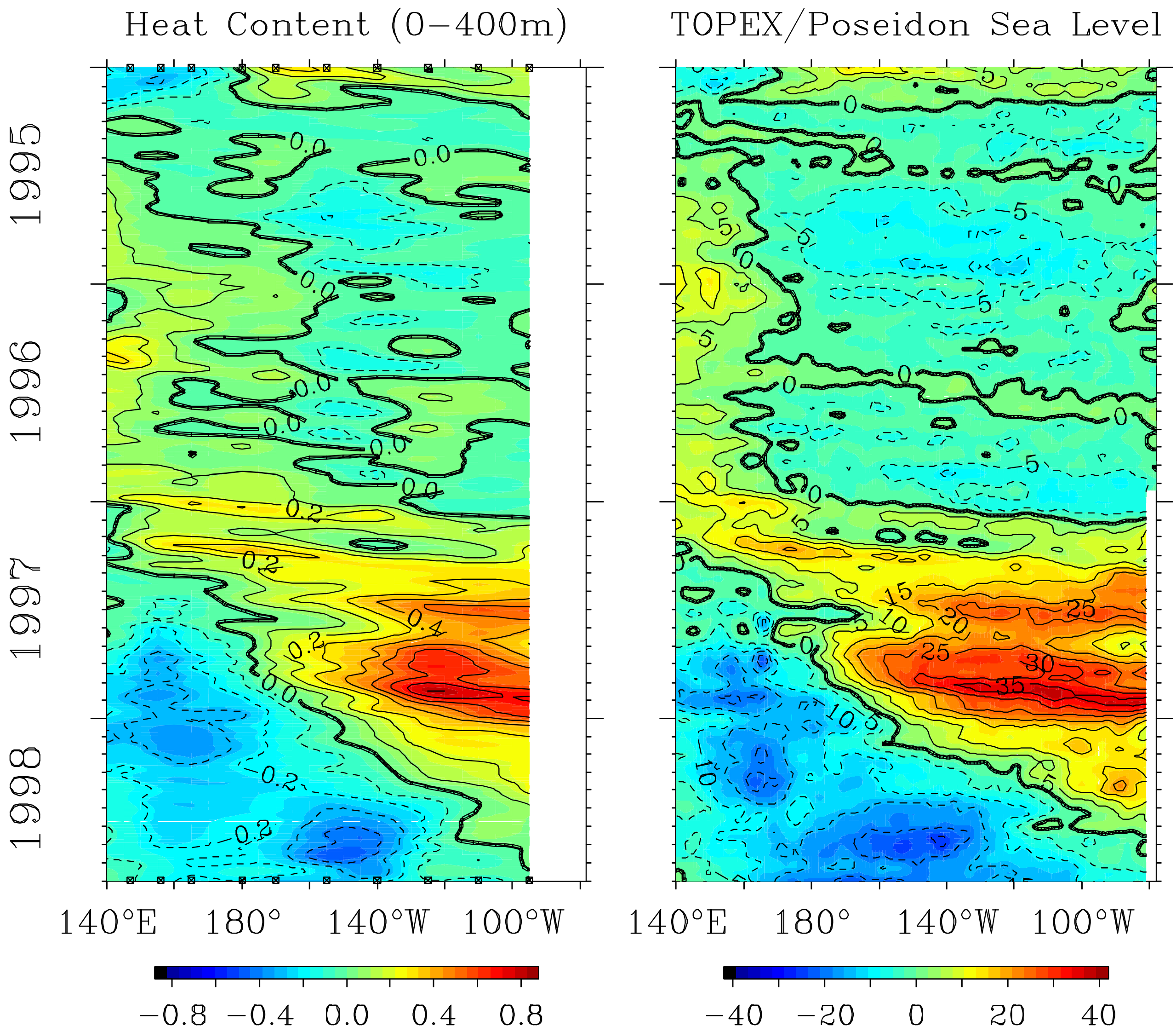

Fig. 4: Heat content anomalies averaged between 2°N and 2°S along the equator from TAO data (in 10^{10} J m^{-3}, left) and sea level anomalies along the equator from the TOPEX/Poseidon altimeter (in cm, right). Temporal resolution is 5-days for TAO data and 10-days for the altimeter data. A mean seasonal cycle has been removed from each time series.

fairly safe bet that warm equatorial Pacific conditions would persist into the boreal winter season. This persistence, based on the thermal inertia of the upper ocean, serves as a benchmark for evaluating the skill of more sophisticated ENSO forecasting schemes.

2.2 – ENSO Forecasting

Several forecast models, both statistical and dynamical, successfully predicted 6–9 months in advance that 1997 would see the development of warm SST anomalies in the eastern equatorial Pacific (Barnston *et al.*, 1999). These successes highlighted the remarkable progress in the ENSO forecasting over the past 15 years (see also Anderson *et al.* in this volume). However, there were some notable forecasting failures as well. No forecast scheme accurately predicted both the rapid development and the ultimate intensity of El Niño SSTs from initial conditions in late 1996. Moreover, the Lamont model, with a long record of prior success, consistently predicted that 1997 would be an unusually cold year in the tropical Pacific.

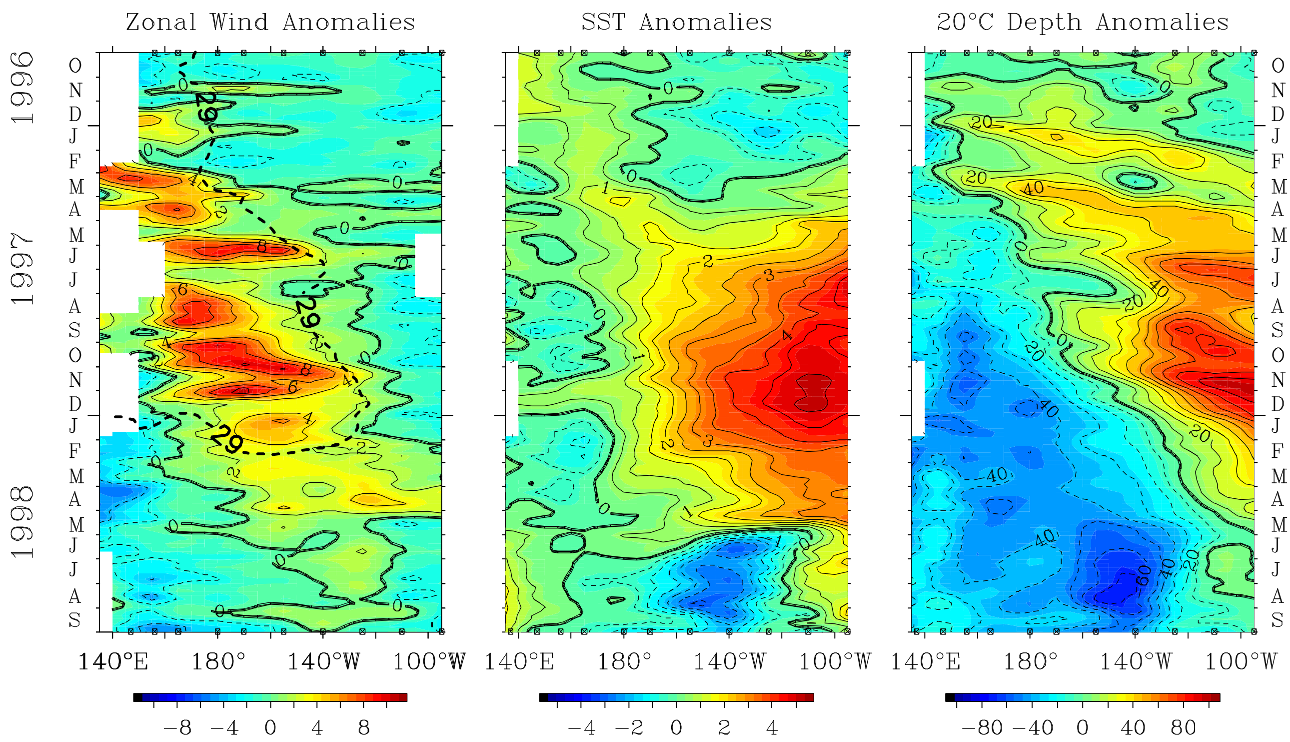

Fig. 5: Anomalies in surface zonal wind (in m s^{-1}, left), sea surface temperature (in °C, middle), and 20°C isotherm depth (in m, right) from October 1996 to September 1998. Analyses are based on 5-day averages of moored time series data between 2°N–2°S from the Tropical Atmosphere Ocean (TAO) Array. Heavy dashed line in the left panel is for the 29°C isotherm through early 1998.

In assessing the role of observations in forecasting the 1997–98 El Niño, two points become clear:

- *Data from the ENSO Observing System significantly contributed to model forecast skill in 1997–98.*

Some of the most skillful forecasts of the 1997–98 El Niño were made with coupled ocean-atmosphere general circulation models (GCMs) (Kerr, 1998; Trenberth, 1998). Dynamical models explicity represent processes affecting seasonal-to-interannual climate variability in the tropics, and GCMs represent these processes more realistically than do simplier oceanic and atmopheric models. This realism is advantageous for producing more detailed predictions, and for initializing those predictions with oceanic data sets.

The memory of the climate system resides in the slow evolution of the upper ocean thermal field, so that accurately initializing ocean temperatures is an important determinant in ENSO forecast skill. Ocean model initialization procedures include forcing with the time history of the surface wind stress, and in some cases assimilation of ocean temperature data (e.g., Ji and Leetmaa, 1997). TAO, VOS, and satellite winds were used in the development of many surface wind products to initialize coupled model forecasts of the 1997–98 El Niño. Similarly, NCEP and ECMWF made use of TAO and VOS/XBT temperature profiles for initializing subsurface thermal structure. The Reynolds blended satellite/in situ SST product was also used for initializing surface temperatures. The availability of these ocean data was a significant factor in constraining coupled model forecasts of the 1997–98 El Niño.

The utility of ENSO Observing System data for predicting the 1997–98 El Niño was underscored ex post facto by the development of a revised version of the Lamont model (LDEO3) which included sea level data (a proxy for upper ocean heat content) in its initialization scheme. This revised model, which was initialized with data from 34 tide gauges in the tropical Pacific in addition to surface wind stresses, could have predicted that 1997–98 would be unusually warm in the tropical Pacific had it been implemented prior to the El Niño (Chen *et al.*, 1998). Improvements in forecast skill of the Lamont model were also achieved using NSCAT wind data (Chen *et al.*, 1999). Of course, availability of

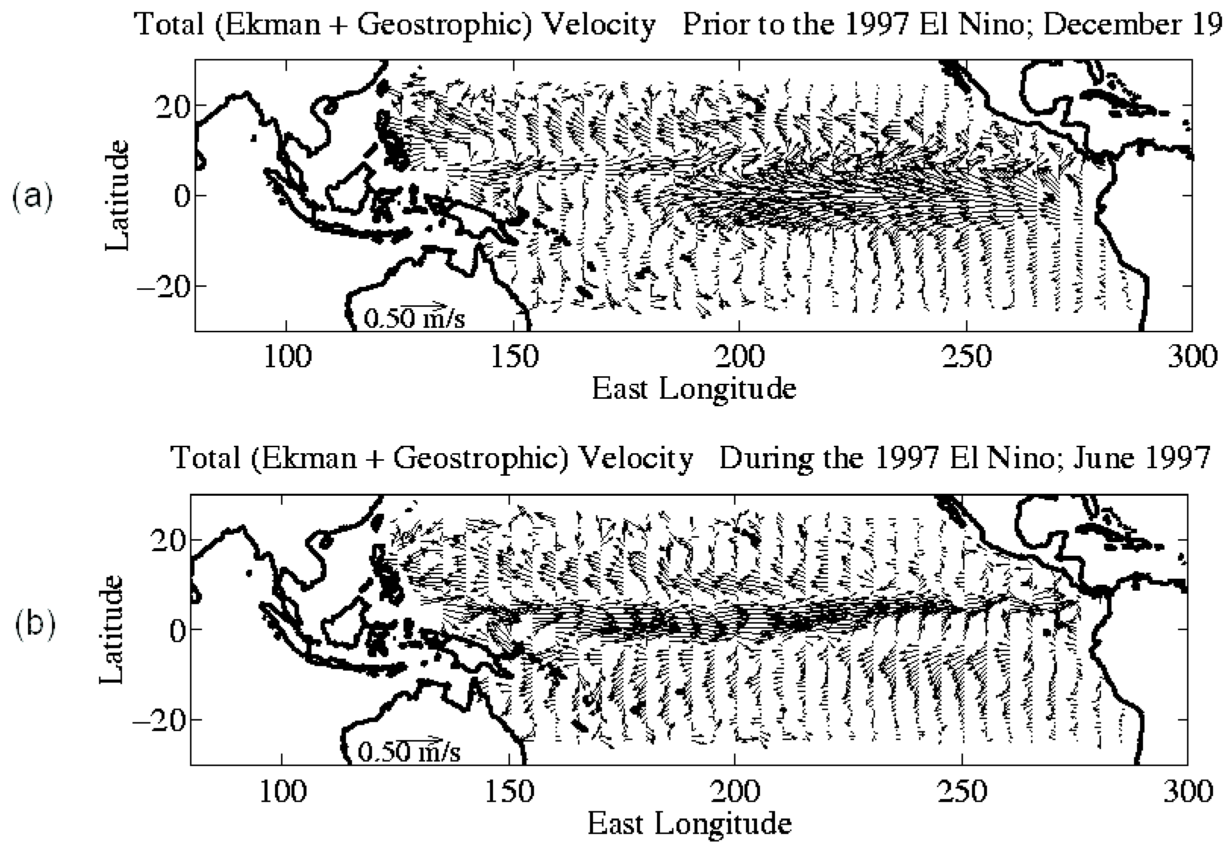

Fig. 6: Surface currents for the month of December 1996 before the onset of the 1997–98 El Niño, and June 1997 during the El Niño. From Lagerloef *et al.* (1999).

high-quality oceanic data is not the only determinant in the skill of seasonal-to-interannual climate forecasts. But experience during the 1997–98 El Niño emphasized that fact that real improvements can be expected from the judicious use of such data sets for model initialization.

- *Data from the ENSO Observing System were critical for real-time validation of model forecasts.*

Throughout 1996, original versions of the Lamont coupled model had consistently predicted that 1997 would be usually cold near the equator. These forecasts contrasted with those from other dynamical and statistical models, which suggested that 1997 would be an El Niño year. However, there was a widely held perception that the Lamont forecast model was the community standard, because it was the first to successfully predict an El Niño and because of recent improvements in its initialization procedures (Chen *et al.*, 1995). In the May 1997 issue of Sea Technology, Chen (1997) gave expression to this perception very succinctly: "During the last decade, a number of ENSO models...have shown predictive skills...and they are now being used for routine ENSO prediction. Among them, the Lamont model is the earliest and is still 'the model to beat.' "

As a result of the conflicting forecasts in late 1996 and early 1997 between the various models, there was considerable confusion as to whether an El Niño would actually develop. The confusion eventually disappeared once the ENSO Observing System detected the emergence of SST anomalies in excess of 1°C in the equatorial Pacific. These observations were critical in prompting the first issuance of official ENSO Advisories in the U.S., Japan, and Australia in April and May 1997.

2.3 – Improved Understanding

Data from the ENSO Observing System are providing an unprecedented opportunity to test hypotheses concerning the dynamics of the ENSO cycle. One of the leading paradigms for ENSO is the delayed oscillator, involving unstable ocean-atmosphere interactions along the equator and equatorial wave

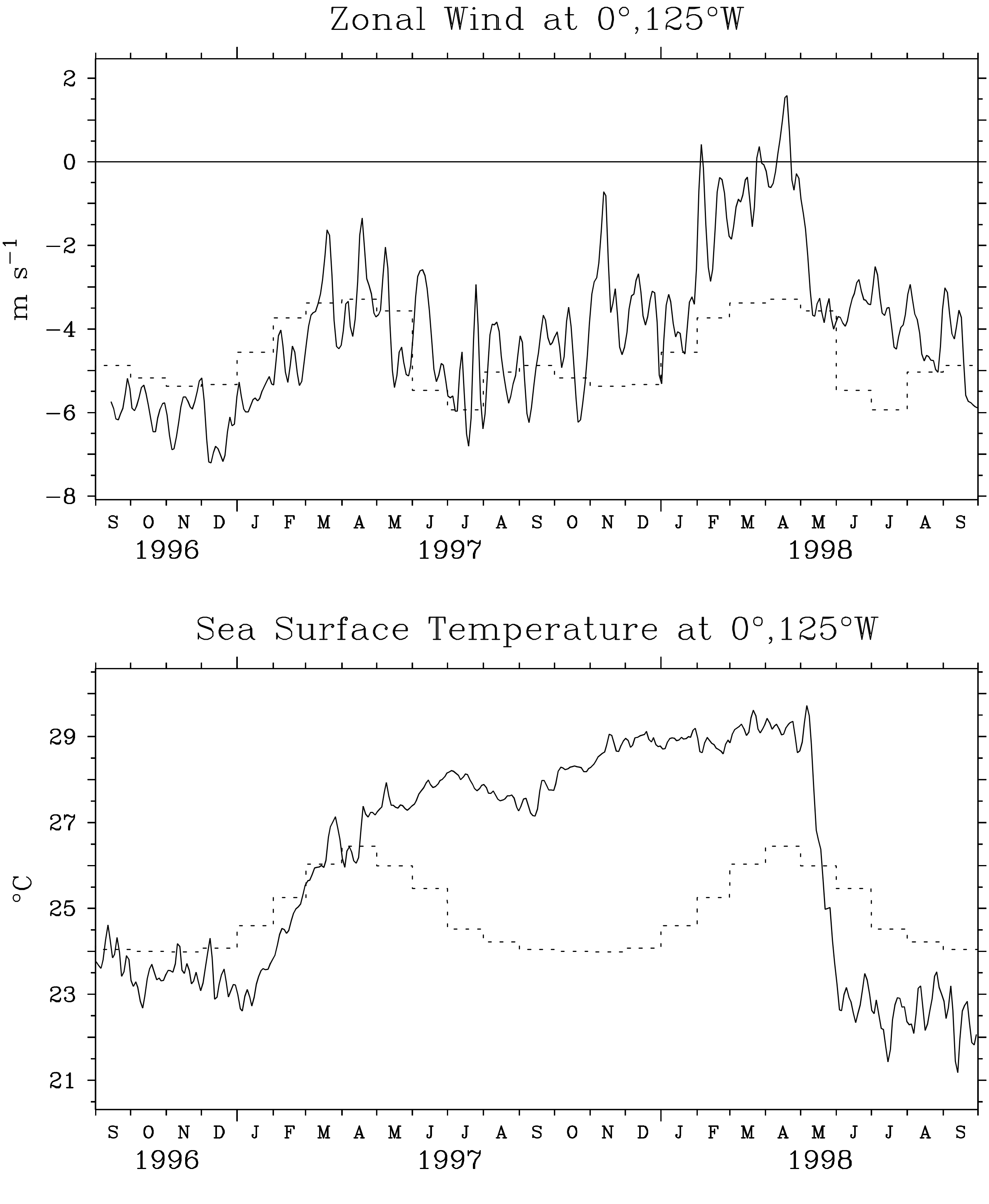

Fig. 7: Five-day average time series of surface zonal winds (top) and sea surface temperature (bottom) from a mooring station on the equator at 125°W. The normal seasonal cycle is shown by dashed lines.

processes (Battisti, 1988; Schopf and Suarez, 1988). This theory ascribes a key role to western boundary reflections for the onset and termination of ENSO events, and presumes that the ENSO cycle can be understood by considering variability confined to only the tropical Pacific basin. Various refinements to delayed oscillator have recently been proposed, involving for example a greater emphasis on zonal advection in the central equatorial Pacific (Picaut *et al.*, 1996), eastern boundary reflections (Picaut *et al.*, 1997), and ocean-atmosphere interactions over the western Pacific warm pool (Weisberg and Wang, 1997). Extensive, high quality, finely resolved (in space and time) data sets provided by the ENSO Observing System have both helped to identify these potentially important processes, and are also being used to examine the extent to which they were operative during the 1997–98 El Niño (e.g., Boulanger and Menkes, 1999; McPhaden and Yu, 1999; Delcroix *et al.*, 1999).

In addition, data from the ENSO observing system have highlighted the role played by higher frequency atmospheric fluctuations, and in particular the MJO, during the onset and termination phases of the 1997–98 El Niño. All El Niños from the 1950s to the present have been associated with elevated levels of intraseasonal westerly surface wind forcing (Luther *et al.*, 1983; Verbickas, 1998). In each case, several episodes of westerly wind forcing lasting typically 1 to 3 weeks developed before and during the El Niño events. These winds were related to the MJO and other phenomena such as tropical cyclone formation and cold air outbreaks from higher latitudes. However, episodic wind forcing is not a sufficient condition for El Niños to occur, since such forcing is evident during non-El Niño years as well. It has also been argued that episodic wind forcing is not even a necessary condition for the development of El Niños, since many coupled ocean-atmosphere models simulate ENSO-like variability without it. Nonetheless, recent model studies (e.g., Moore and Kleeman, 1999) indicate that stochastic forcing can amplify and markedly alter the evolution of the ENSO cycle if it occurs on time and space scales to which the ocean is sensitive, and when background oceanic and atmospheric conditions are conducive to the rapid growth of random disturbances. These studies have explicitly implicated the MJO in affecting the onset and intensity of the 1997–98 El Niño (Kessler and Kleeman, 1999).

Likewise, though low frequency oceanic waves caused the thermocline to shoal in the eastern Pacific so as to set the stage for an end of the El Niño, it was a relatively sudden strengthening of the trade winds in May 1998 that produced sufficiently strong upwelling to initiate surface cooling (McPhaden and Yu, 1999). This sudden wind change may also have been related to the MJO (Takayabu *et al.*, 1999). Part of the reason for irregularity in the ENSO cycle in terms of frequency, duration, and amplitude of warm and cold events may therefore be attributed to the nonlinear interaction of higher frequency weather variability with lower frequency ocean-atmosphere dynamics. Moreover, the potential importance of the MJO, which originates over the Indian Ocean, implies that forcing external to the tropical Pacific may be important in the ENSO cycle.

Other factors that may have influenced the evolution of the 1997–98 El Niño include interactions with naturally occurring decadal time-scale fluctuations and global warming trends. The Pacific Decadal Oscillation (PDO; Mantua *et al.*, 1997), for example, involves a basin scale, decadally varying pattern of surface winds, air pressure, and ocean temperatures extending from the tropics to higher latitudes. The PDO has generally been in a warm phase since the mid-1970s, elevating temperatures in the tropical Pacific and affecting the background conditions on which ENSO events develop. Similarly, the two warmest years on record for global mean temperatures were 1998 and 1997, in that order. The 1997–98 El Niño contributed to these record highs because global temperatures generally rise a few tenths of a degree C following peak El Niño warmings. However, underlying the extreme global mean temperatures in 1997–98 is a century long trend that may be due to anthropogenic greenhouse gas warming. Corresponding to these basin and global scale climatic changes, there have been more El Niños than La Niñas since the mid-1970s, the early 1990s was a period of extended warmth in the tropical Pacific and the extremely strong 1997–98 El Niño followed by only 15 years the previous record-setting El Niño of 1982–83 (Fig. 2).

3 – PRESENT STATUS

The ENSO Observing System has been maintained more or less in a stable configuration since the end of TOGA, with a multi-national base of support for both in situ and satellite components. Noteworthy developments in the past few years include the commissioning of the NOAA ship Ka'imimoana in 1996. This ship is dedicated to servicing the TAO array at and east of the international date line. Also, the U.S. Congress passed a bill in November of 1997 to provide long-term operational funding for in situ components of NOAA-maintained portions of the ENSO Observing System. The new Japanese

TRITON buoy program was launched in 1998 with the commissioning of the R/V *Mirai* operated by JAMSTEC, and with the deployment of TRITON buoys along 156°E. In 1999 TRITON will eventually replace ATLAS buoys of the TAO array between 137°E and 156°E. In addition, an expansion and enhancement of the TAO array along 95°W will begin in late 1999 as part of the Eastern Pacific Investigation of Climate (EPIC), a 5-year process study under auspices of the Pan American Climate Studies (PACS) to improve our understanding of ocean-atmosphere interactions in the cold tongue/ITCZ region of the eastern Pacific.

The number of drifting buoys deployed in the tropical Pacific between 30°N and 30°S is at present nearly the same (252) as at the end of TOGA (263). Thermosalinograph measurements of shipboard sea surface salinity (SSS) have increased by about 250% between 1992 and 1999, and real-time transmission of the data is operational on most vessels since mid-1998 (Delcroix *et al.*, this volume).

With regard to satellite wind vector measurements, although the NASA scatterometer (NSCAT) failed prematurely in mid-1997 after only 8 months in orbit, NASA's QuickSCAT satellite was launched in June 1999 and is now providing NSCAT quality satellite vector winds. The Japanese Advanced Earth Observing Satellite (ADEOS-2), also carrying a NASA scatterometer, will be launched in 2000. The TOPEX/Poseidon altimeter continues to function well beyond its three-year nominal design lifetime. Continuity with TOPEX/Poseidon altimetric measurements will be provided by the launch of the US/French Jason-1 mission in 2000.

4 – FUTURE DIRECTIONS

Recommendations in this section are directed specifically at improving our understanding of ENSO dynamics, and the predictability of ENSO. They fall into two broad categories, namely enhanced measurement capabilities, and geographical expansions. Our emphasis is on in situ measurements, since satellite issues are covered in other papers of this volume. An underlying premise of our recommendations is that the basic in situ elements of the ENSO Observing System shown in Fig. 1 will continue for the foreseeable future. A corollary statement is that we expect there to be long-term continuity of satellite measurements for sea level, winds and SST as part of this ocean observing system.

4.1 – Salinity

The western and central equatorial Pacific are characterized by large interannual variations in surface and subsurface salinity (Fig. 8; see also Delcroix *et al.*, 1998, and Kessler, 1999). These variations affect vertical buoyancy gradients and the formation of salt stratified barrier layers (Lukas and Lindstrom, 1991; Ando and McPhaden, 1997). As a result, they also affect the vertical distribution of turbulent energy production, the storage of heat in the upper ocean, and the evolution of SST. Salinity affects dynamic height, horizontal pressure gradients, and ocean currents. In addition, it is a valuable tracer for the meridional overturning circulation in the tropical and subtropical oceans.

Analyses of CTD show that lack of surface and subsurface salinity observations can sometimes lead to errors in dynamic height that are a comparable in size to the ENSO signals of interest. Errors in dynamic height affect the pressure field and large-scale ocean circulation and, if uncorrected, lead to errors in initial conditions for coupled ocean-atmosphere model ENSO forecasts (Ji *et al.*, 1999). New methods to derive the upper ocean salinity profiles using SSS data, mean T-S curves (e.g., Vossepoel *et al.*, 1999) and/or EOF analysis (Maes *et al.*, 1999) are under development and show promise. These methods, in combination with more surface and subsurface salinity observations, can help to optimize the assimilation of altimetry data into ocean models used in ENSO forecasting.

The continuation and enhancement of in situ SSS measurements with real-time transmission, especially in the western Pacific warm pool from VOS, TAO/TRITON, and drifting buoys, is thus strongly recommended (see also Delcroix *et al.* in this volume). In addition, subsurface salinity measurements should be increased in the tropical Pacific by increasing the number of salinity sensors on selected TAO and TRITON moorings, by increasing VOS/XCTD measurements, and by deploying profiling floats with temperature and salinity sensors. Finally, satellite missions are presently being proposed to space agencies for remote sensing of ocean surface salinity. If approved, these missions, in combination with in situ data used for calibration, validation, and development of blended products, will result in SSS analyses that are expected to resolve large scale climatological variations in the tropics. It is recommended that these satellite missions be endorsed by CLIVAR, GOOS, and GCOS.

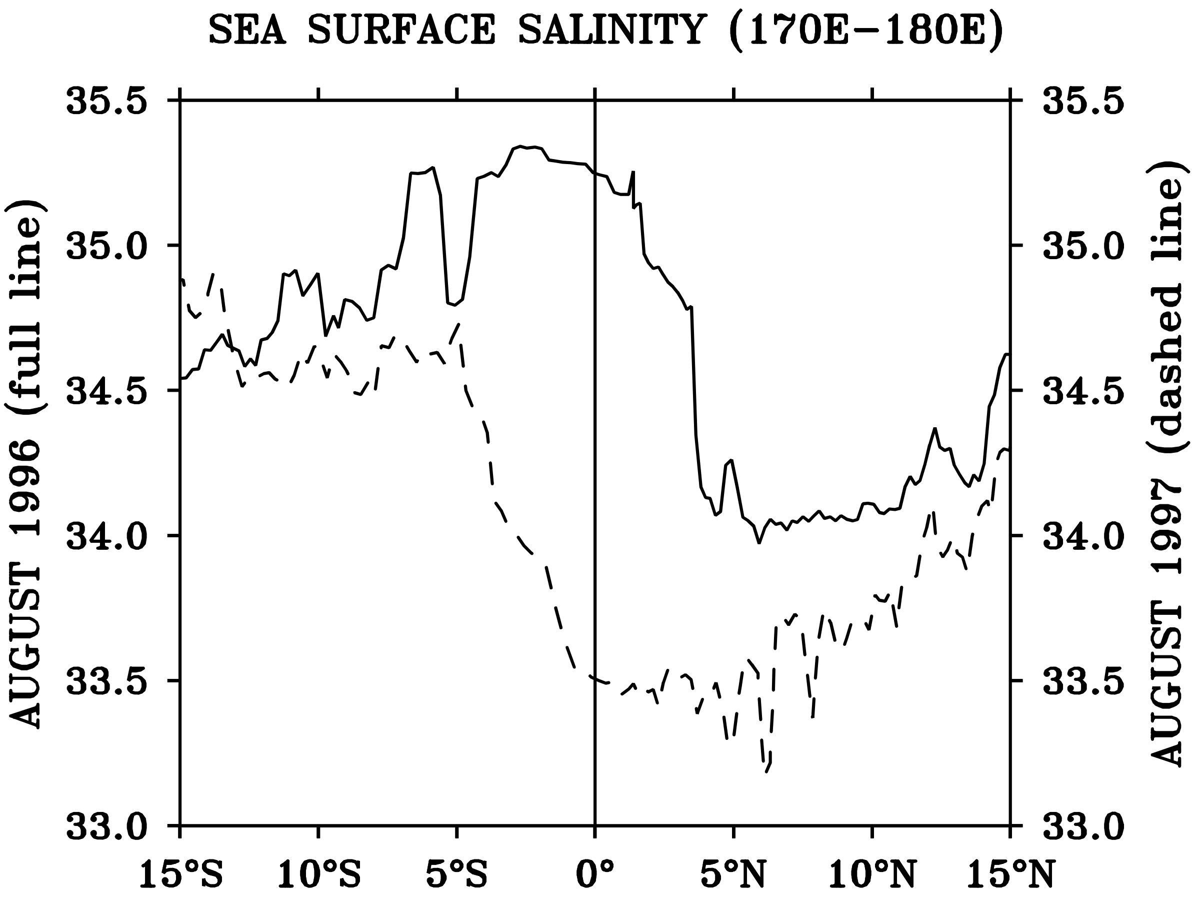

Fig. 8: One-hour average meridional sections of sea surface salinity (in PSU) from thermosalinograph measurements onboard a merchant ship steaming along the line Fiji-Japan crossing the equator at 173°E longitude. The sections are shown for August 1996 (full line) during a La Niña event and for August 1997 (dashed line) during an El Niño event.

4.2 – Surface Fluxes

Fluxes of heat (turbulent and radiative), fresh water (evaporation minus precipitation), and momentum (wind stress) at the air-sea interface are important ocean forcing functions. To the extent that they affect SST, these fluxes help mediate ocean-atmosphere interactions on a range of time and space scales of relevance to climate. During TOGA, significant progress was made in improving surface wind field analyses for ENSO forecasting and diagnostics. Nonetheless, there continue to be large differences in currently available wind stress products, and a great sensitivity in tropical Pacific Ocean model simulations forced with these different products. Accurate determination of heat and fresh water fluxes received less emphasis during TOGA than surface winds. Heat fluxes represent a large negative feedback on ENSO time scale SST anomalies in the equatorial cold tongue and are important for generating SST anomalies in the western Pacific warm pool. Evaporation and precipitation affect surface layer water mass variability, upper ocean stratification, and therefore the surface layer heat balance. From a meteorological perspective, precipitation is an integral measure of tropospheric heating which drives the general circulation of the atmosphere.

Present flux estimates based on VOS measurements, numerical weather prediction model output, and satellite data exhibit differences in the tropical Pacific on seasonal to interannual time scales that are sometimes as large as the climate signals of interest. Moreover, surface fluxes are frequently poorly simulated in coupled ocean-atmosphere models used for climate analysis and forecasting. In these situations, ad hoc flux corrections are required in order to prevent climate drift.

Therefore, it is necessary to improve currently available satellite, in situ, and model-based surface flux products for heat, fresh water, and momentum. This will require an ongoing and systematic validation effort. Recommendations include implementing a combination of carefully calibrated long-term mooring time series stations for heat and fresh water fluxes, high accuracy surface marine measurements on selected VOS routes, and specialized field studies like TOGA-COARE to improve bulk algorithms (see also Taylor *et al.* in this volume).

4.3 – North and South Pacific Ocean

As noted in the previous section, the intensity, frequency, and duration of warm and cold ENSO events undergoes decadal modulations. There is also a decadal modulation in the predictability of ENSO with, for example, higher predictability for tropical Pacific SST anomalies in the 1980s and lower predictability in the 1970s and early 1990s. The precise reasons for these decadal modulations are unclear. However, several hypotheses have been advanced regarding possible causative mechanisms, ranging from stochastic forcing, nonlinear chaotic interactions with the seasonal cycle, interactions with the higher latitudes (e.g., the PDO), and global warming. These hypotheses may not be mutually exclusive. Moreover, more than one kind of tropical-extratropical ocean interaction has been suggested, involving decadal time scale thermohaline processes, gyre scale interactions, western boundary current dynamics, and ocean-atmosphere feedbacks (Kessler *et al.*, this volume). Pacific basin decadal time scale variability is poorly documented in existing data bases, particularly below the surface and in the southern hemisphere. Hence, at present it is not possible to unambiguously distinguish between competing hypotheses, or to develop models with useful skill in forecasting decadal time scale fluctuations of the ENSO cycle.

It is therefore recommended that the in situ ENSO Observing System be expanded northward and southward into the higher latitudes of the Pacific. In many cases, key processes and relevant scales of variability are poorly defined, so that this expansion will be an evolutionary process aided by pilot observational efforts and model design studies. An initial design however could be based on existing technologies successfully deployed for climate studies to date (e.g., drifters, moorings, VOS measurements, tide gauge stations, profiling floats) in combination with sustained satellite observations. Sampling strategies may differ in the northern and southern hemispheres because of hemispheric differences in ocean circulation, atmospheric forcing and teleconnection patterns, and historical data coverage.

4.4 – Indian Ocean

Ocean-atmosphere-land interactions in the Indo-Pacific region affect the evolution and the predictability of the Austral-Asian monsoon on intraseasonal, seasonal, biennial, interannual and longer time scales. These interactions are poorly documented and understood, and the limits of predictability for the monsoons are not well known. There is also a significant but poorly understood coupling between the monsoons and ENSO, which have major consequences for regional and global climate. Monsoonal variations on intraseasonal to interannual time scales develop in the Indian Ocean region and propagate into the Pacific basin to affect the evolution of ENSO. These interbasin atmospheric teleconnections were highlighted during 1997–98 by the interaction between the MJO and ENSO cycle as described above. ENSO likewise can affect monsoon rainfalls in Asia, Australia and East Africa. However, as evident during the 1997–98 El Niño, there are factors (possibly related to the development of significant warm Indian Ocean SST anomalies), that can moderate ENSO influences in the region.

TOGA focused mainly on developing an ocean observing system in the tropical Pacific. More recently, through efforts like PIRATA (Servain *et al.*, 1999), initial steps have been taken to improve the in situ climate data base in the tropical Atlantic (see also Garzoli *et al.*, this volume). In contrast, the Indian Ocean has the most poorly developed in situ ocean observing system in the tropical belt. Given the potential for increasing the skill and lead time of ENSO forecasts, and the enormous societal impacts of monsoon rainfall variability in the Indo-Pacific region, consideration should be given to developing a permanent observing system in the tropical Indian Ocean to support climate analyses and forecasting. Some specific strategies are described in Meyers *et al.* and Hacker *et al.* in this volume.

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