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The El Niño–Southern Oscillation (ENSO) Observing System*

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Abstract – *This paper reviews contributions of the El Niño–Southern Oscillation (ENSO) Observing System to improved detection, monitoring, forecasting, and understanding of ENSO-related climate swings, with emphasis on the 1997–98 El Niño and subsequent La Niña. Highlights include detecting the rapid onset and sudden demise of the 1997–98 El Niño, initializing and verifying ENSO model forecasts, and documenting the importance of intraseasonal timescale variations in affecting the evolution of the ENSO cycle. The case is made for continuation of the ENSO Observing System for the foreseeable future, subject to possible adjustments in sampling strategies to optimize performance. In addition, recommendations are advanced to enhance the observing system with more salinity, ocean velocity, and surface flux measurements. Expansions into the Indian Ocean and higher latitudes of the North and South Pacific are also recommended based on the possible influences of those regions on ENSO variability and predictability.*

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 not 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 for observing and forecasting 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 (Fig. 1). The observing system 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 wind, sea surface temperature, and sea level variability 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; Fig. 2), but also the best ever

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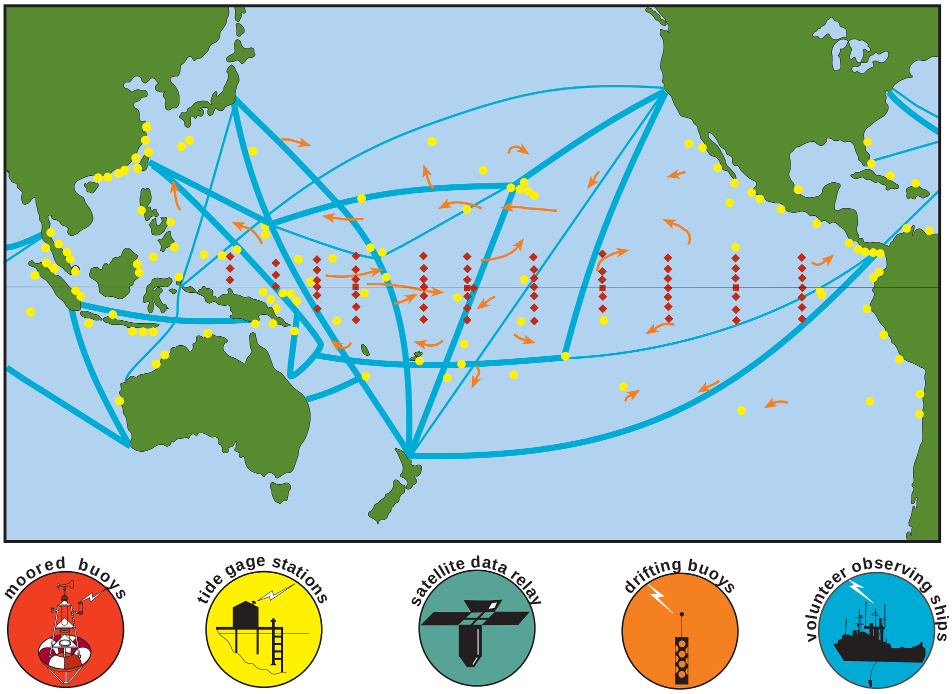

Figure 1. The El Niño–Southern Oscillation (ENSO) Observing System was set up to understand, monitor, and predict ENSO variations. The ocean-based components, shown here, relay data in real time via satellites. The main components are a volunteer ship program (blue lines), an island and coastal tide-gauge network (yellow circles), a system of drifting buoys (arrows), and the TAO array of moored buoys (red diamonds and squares). 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 and salinity, 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 program. It is now being continued in support of operational climate forecasting as well as research on ENSO dynamics.

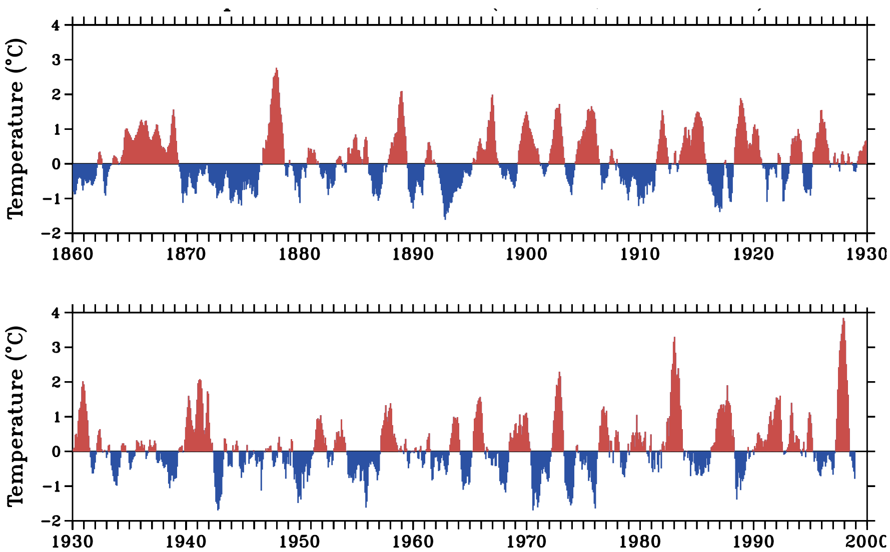

Figure 2. Sea surface temperature anomalies for the region 5°N–5°S, 90°W–150°W from a combination of the shipboard data through 1991 (Kaplan et al., 1998) and a blended satellite/in situ data analysis afterwards (Reynolds and Smith, 1994).

documented (McPhaden, 1999). The 1997–98 El Niño developed so rapidly 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 at between 28–29°C, which is near the maximum sustainable temperatures possible in the open ocean (Fig. 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.

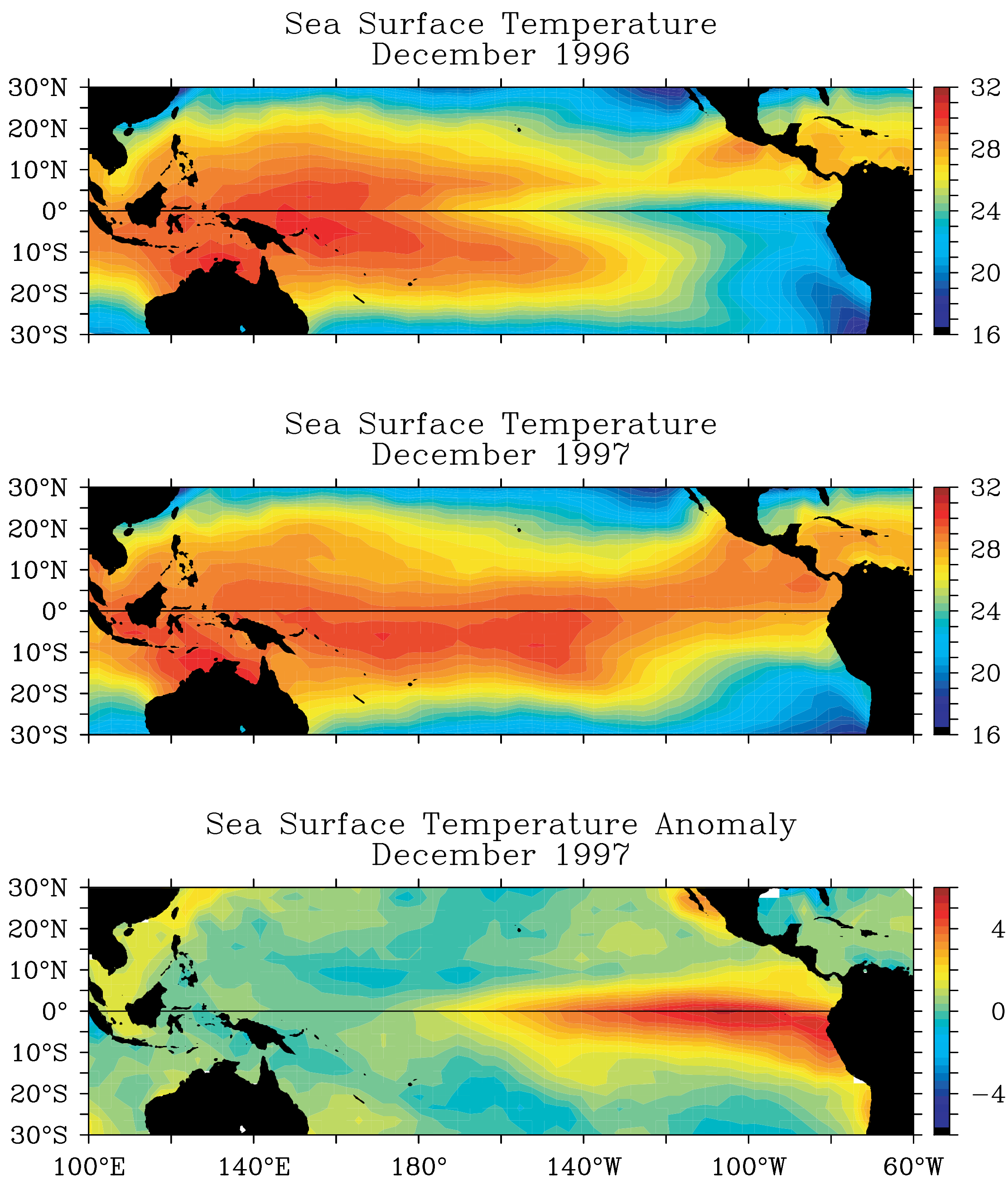

Figure 3. Monthly averaged sea surface temperature (in °C) for December 1996 (top) and for December 1997 (middle). Monthly average sea surface temperature anomaly for December 1997 (bottom). These charts are based on the Reynolds and Smith (1994) SST analysis.

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, and (3) improved understanding. Details of how the data are processed, quality-controlled and widely distributed are described elsewhere (Legler et al., 2000). A full review of the scientific contributions of the ENSO Observing System prior to the 1997–98 El Niño can be found in McPhaden et al. (1998).

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 sea surface temperature (SST) 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-Julian Oscillation (MJO) over the western Pacific. In late 1996 and 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. Zonal wind-driven ocean currents reversed and flowed eastward over thousands of kilometres (Fig. 6; see also Kitamura et al., 1998) with eastward volume transport anomalies of over 60 Sv (1 Sv = $10^6/m^2/s^{-1}$) in the surface layer and upper thermocline (Johnson et al., 2000) in response to these westerly winds. 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 thermocline depth mediated the intense warming at the surface observed during 1997.

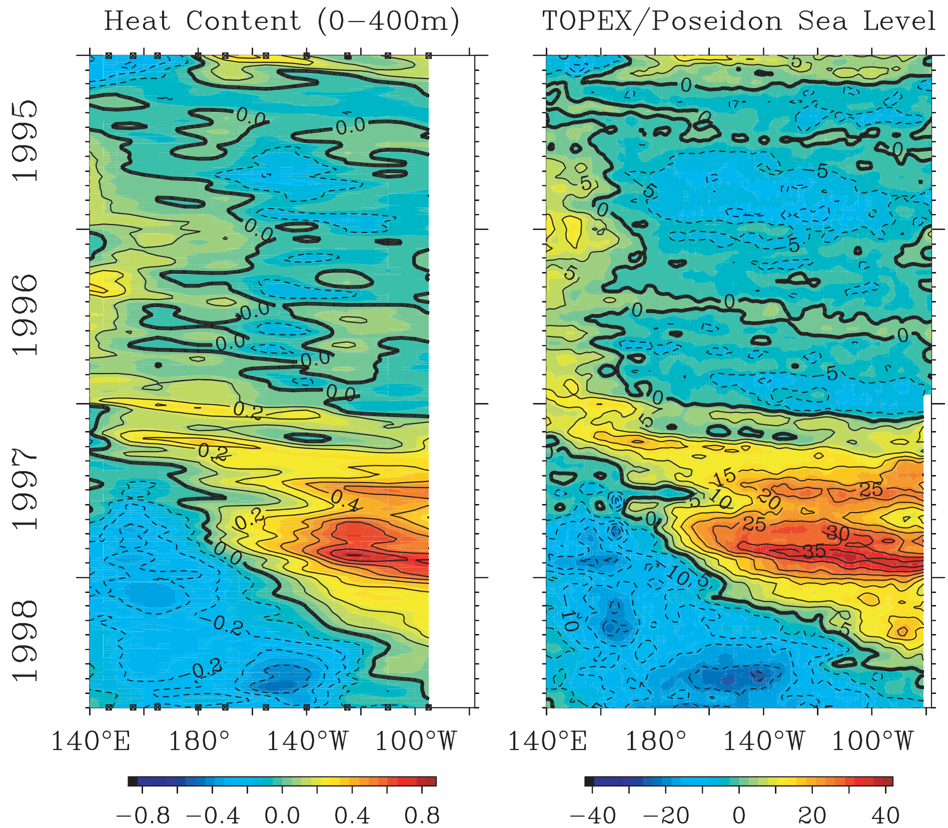

Figure 4. Heat-content anomalies averaged between 2°N and 2°S along the equator from TAO data (in 1010 Jm^3, left) and sea level anomalies along the equator from the TOPEX/Poseidon altimeter (in cm, right). Temporal resolution is 5 days for TAO data and 10 days for the altimeter data. A mean seasonal cycle has been removed from each time series. White areas indicate missing data.

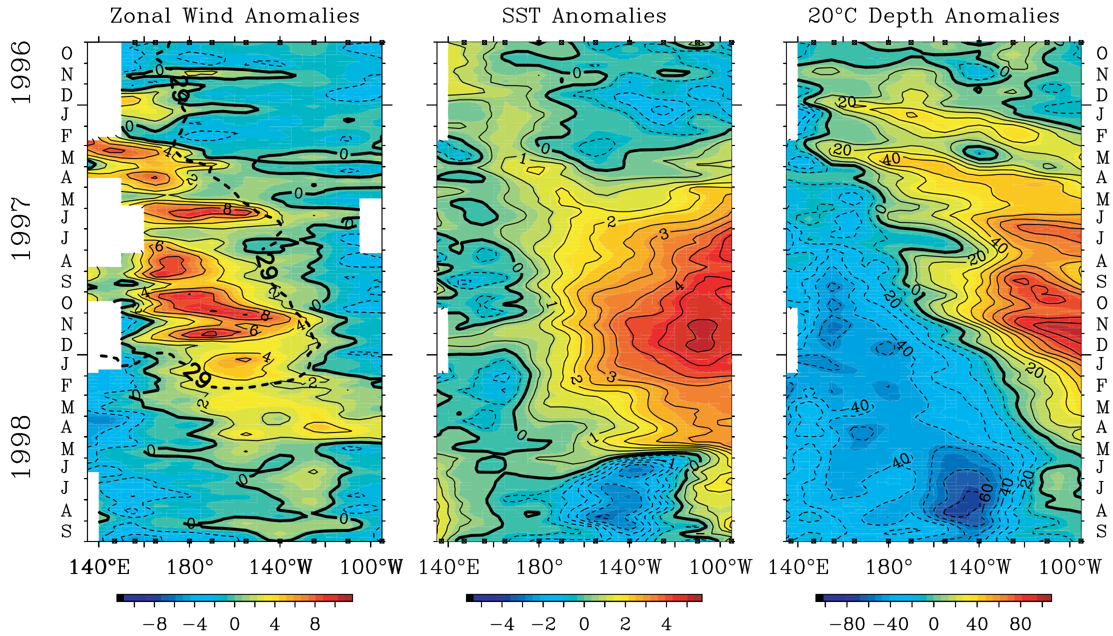

Figure 5. Anomalies in surface zonal wind (in m s–1, left), sea surface temperature (in °C, middle), and 20°C isotherm depth (in m, right) from October 1996 to September 1998. Analyses are based on 5 day averages of moored time series data between 2°N–2°S from the Tropical Atmosphere Ocean (TAO) Array.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

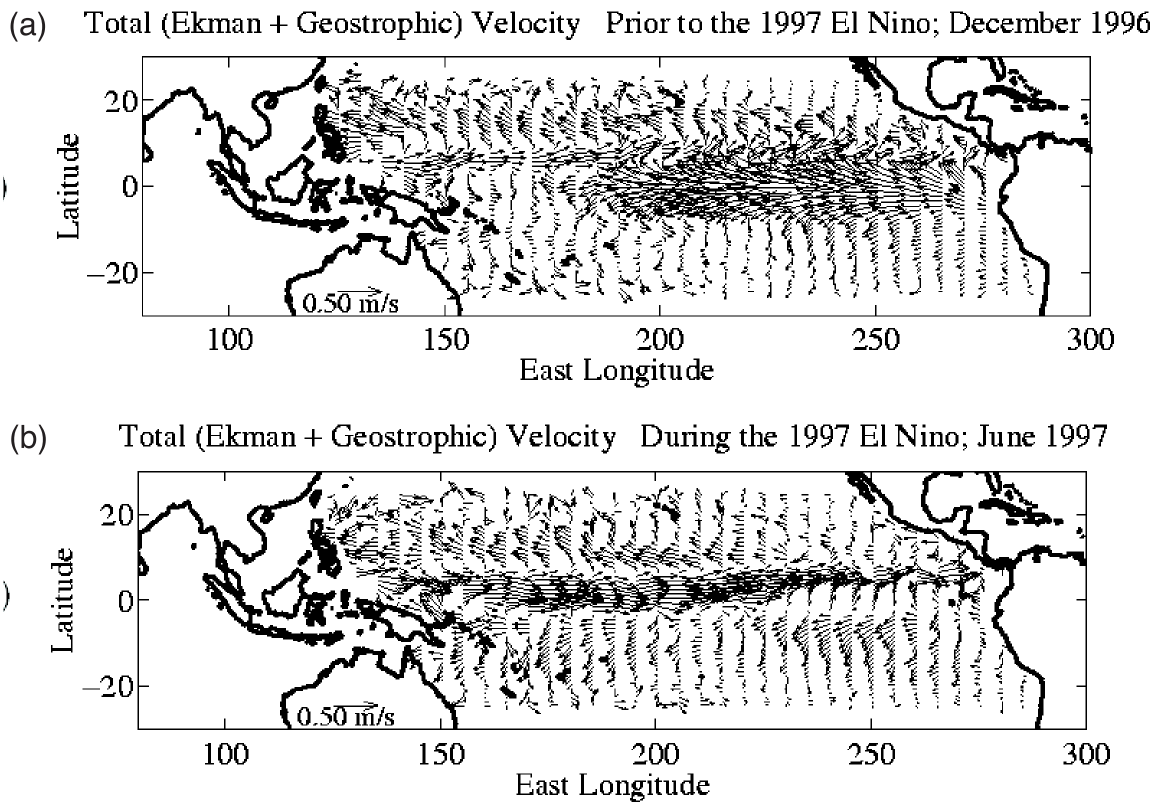

Figure 6. Surface currents for the month of December 1996 before the onset of the 1997–98 El Niño, and June 1997 during the El Niño. From Lagerloef et al. (1999).

In early 1998, SSTs in the eastern Pacific exceeded 29°C (Figure 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. The 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). Thus, climatic conditions in the equatorial Pacific shifted from one of the strongest El Niños on record to cold La Niña conditions in a space of a month.

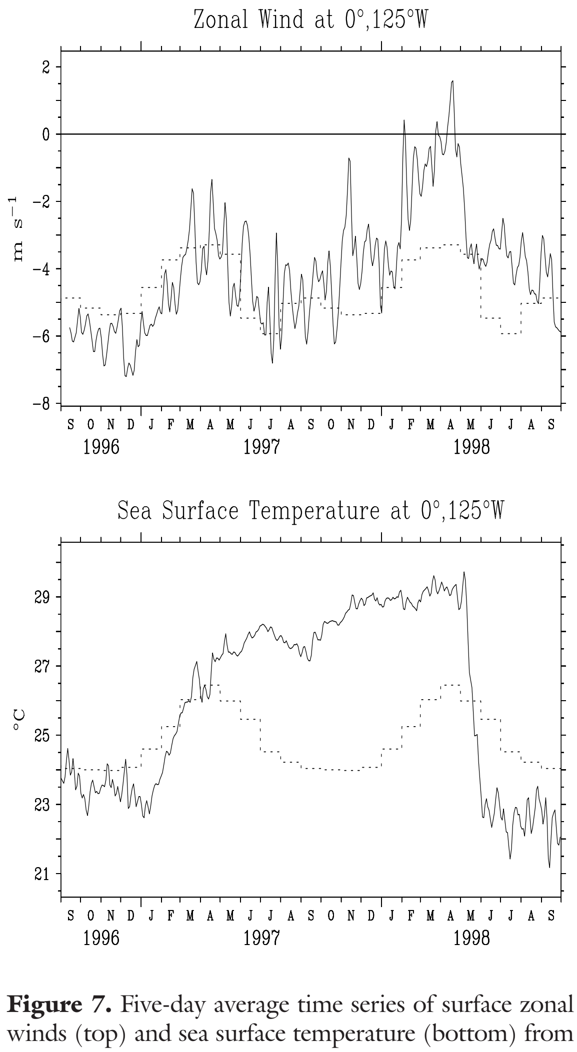

Figure 7. Five-day average time series of surface zonal winds (top) and sea surface temperature (bottom) from a mooring station on the equator at 125°W. The mean seasonal cycle is shown by dashed lines.

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. Once developed, large-scale SST anomalies will persist for at least 1–2 seasons, especially during the latter half of the calendar year. So, for example, as SSTs reached historic highs and the thermocline flattened out along the equator in mid-1997, it was a 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, often serves as a benchmark for evaluating the skill of more sophisticated ENSO forecasting schemes.

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. The Lamont model (Cane et al., 1986), with a long record of prior success, consistently predicted that 1997 would be an unusually cold year in the tropical Pacific. Moreover, several models that performed reasonably well in forecasting the onset of the 1997–98 El Niño did not predict its demise with equal skill, while some models that predicted the onset poorly did better with the termination phase of the event (Landsea and Knaff, 2000). These failures do not diminish the significance of recent advances in ENSO forecasting, but instead underscore the challenges that must be surmounted to improve the accuracy of short-term climate predictions.

The ready availability of data from the ENSO Observing System has been crucial for the development of models used in ENSO forecasting and for forecast initialization and validation (McPhaden et al., 1998). In assessing the role these observations played in the specific case of forecasting the 1997–98 El Niño, two points become clear.

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

   Some of the most skillful forecasts of the onset 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 atmospheric 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, volunteer observing ships (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, the National Center for Environmental Prediction (NCEP) and the European Center for Medium Range Weather Forecasts (ECMWF) made use of TAO and VOS/expendable bathythermograph temperature (XBT) 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 for the onset and evolution 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 (aproxy 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). Using NSCAT wind data for initializing forecasts of the 1997–98 El Niño would likewise have improved forecast skill of the Lamont model (Chen et al., 1999). Of course, availability of high-quality oceanic data is not the only determinant in the skill of seasonal to interannual climate forecasts. The 1997–98 El Niño nonetheless emphasized that fact that real improvements can be expected from the judicious use of such data sets for model initialization.

2. 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 unusually 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 in 1986–87 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 US, Japan, and Australia in April and May 1997.

Improved understanding

Data from the ENSO Observing System have also provided 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 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 the delayed oscillator theory have recently been proposed, involving 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 helped both to identify these potentially important processes, and 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., 2000; Wang and McPhaden, 2001).

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 winds lasting typically 1–3 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 westerly 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 westerly 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 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 (Moore and Kleeman, 1999). Episodic surface winds associated with the MJO are one manifestation of stochastic forcing, and these winds have been implicated in affecting the onset and intensity of the 1997–98 El Niño (Kessler and Kleeman, 2000).

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 timescale 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).

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 US 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 buoys replaced ATLAS buoys between 137°E and 156°E, and as of 1 January 2000 the moored buoy array was officially designated as the TAO/TRITON array. In addition, an expansion and enhancement of this array along 95°W began 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 regions 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). Shipboard measurements of sea surface salinity (SSS) have increased by about 250% between 1992 and 1999 due to expansion of the French VOS thermosalinograph program and to the instrumentation of ships servicing the TAO/TRITON array with thermosalinographs. Real-time transmission of SSS data has been operational on most vessels since mid-1998.

With regard to satellite wind vector measurements, the NASA scatterometer (NSCAT) on the Japanese Advanced Earth Observing Satellite (ADEOS-1) failed prematurely in mid-1997 after only 8 months in orbit. However, NASA's QuikSCAT satellite was launched in June 1999 and is now providing even higher quality satellite data. The ADEOS-2 mission carrying the NASA Seawinds scatterometer (of the same design as the sensor on QuikSCAT) will be launched in 2002. The TOPEX/Poseidon altimeter continues to function well beyond its 3 year nominal design lifetime. Continuity with TOPEX/POSEIDON altimetric measurements will be provided by the launch of the US/French Jason-1 mission in 2001.

Future directions

As the example of the 1997–98 El Niño illustrates, data from the ENSO Observing System have proven to be valuable for monitoring ENSO timescale variations, for improving our understanding of ENSO dynamics, and for initializing and verifying ENSO forecasts. However, our knowledge of the processes responsible for ENSO variations is still incomplete, and there is a broad range of relevant timescales (intraseasonal to decadal) whose interactions and impacts on ENSO are not well understood. Moreover, our ability to predict El Niño, though certainly better now than it was at the start of the TOGA program, is still far from perfect (e.g. Landsea and Knaff, 2000).

While the ENSO Observing System may have proved its worth in the case of the 1997–98 El Niño, we have too few realizations of El Niño and La Niña events since the observing system was completed in 1994 to make unambiguous statements about whether it is optimal for forecasting purposes. Furthermore, forecast skill depends on more than just the availability of appropriate data sets. It depends also on the adequacy of forecast models and on the effectiveness of data assimilation schemes used to produce analyses for forecast initialization. Statistical forecast models cannot by their nature capture extremes or unusually rapid transitions between warm and cold conditions in the tropical Pacific, and dynamical forecast models at present are deficient in their ability to accurately represent key physical processes that govern the ENSO cycle (e.g., Slingo et al., 1996; Bennett et al., 1998; Stockdale et al., 1998; Delecluse et al., 1998; Niiler, this volume). Various data assimilation systems are presently used to produce ocean analyses that serve as initial conditions for coupled model forecasts (Anderson et al., this volume).

These systems are predicated on simplified approximations of complex model and data error statistics, and none takes full advantage of existing data sets. Both models and assimilation techniques are continually being refined, a process which is expected to accelerate in the near future with the advent of the Global Ocean Data Assimilation Experiment (GODAE) (Le Traon et al., this volume). The tropical Pacific will provide an ideal test bed for developing advanced assimilation techniques because of the existence of ENSO Observing System and the importance of the ENSO cycle in global climate variability (Busalacchi, 1996).

Therefore, in order for the value of the ENSO Observing System to be fully realized for both research and forecasting, continuation of key measurements for the foreseeable future is essential. This does not mean the observing system should remain static in its design. Rather, it should constantly undergo evaluation as to how effectively it meets its goals of providing data for improved detection, understanding and prediction of ENSO variability and related phenomena. It should also embrace change when new technologies arise that can demonstrably improve system performance and cost-effectiveness. This change must be managed with care, however, to ensure essential climate records are not broken, or degraded by premature termination or transition to alternative technologies (NRC, 1994, 1999). Model-based observing system simulation experiments can be valuable for this purpose. However, such experiments can be misleading if not properly formulated and interpreted (Anderson et al., this volume). Given the decade-long international effort to design and implement the ENSO Observing System, serious modifications to the existing structure should proceed deliberately and cautiously. To quote from the US National Research Council Report on its appraisal of Ocean–Atmosphere Observations Supporting Short-Term Climate Prediction (NRC, 1994): 'Conservatism should be weighted heavily: Do not disrupt long oceanographic or meteorological time series in the absence of clear evidence that they are redundant or too imprecise to be useful for measuring climate variations.'

An example of evolutionary change that is affecting the design of the ENSO observing system is the implementation of a global array of profiling floats for temperature, salinity, and deep reference velocities (Argo Science Team, this volume). This emerging technology is expected to eventually replace broad-scale VOS/XBT measurements in the global ocean in general, and in the tropical Pacific in particular (Smith et al., this volume). There will still be need for moorings however, because Argo does not measure air–sea interaction parameters or resolve energetic high frequency oceanic fluctuations. There will still be need for drifters and other elements of the ENSO observing system as well, since Argo is not designed to measure SST, surface circulation, or short space and timescale variations. Identifying synergies between new and existing observing system elements from this point of view is as important as identifying possible redundancies.

On the assumption that essential *in situ* components of the ENSO Observing System shown in Figure 1 will continue for the foreseeable future, we propose the following recommendations directed specifically at improving our understanding and ability to predict ENSO timescale variations. These recommendations 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. However, as a corollary to our assumption that *in situ* components of the ENSO Observing System will continue for the foreseeable future, we expect that there will also be long-term continuity of satellite measurements for sea level, winds and SST as part of this ocean observing system.

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; Kessler, 1999; Lagerloef and Delcroix, this volume). 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, the storage of heat in the upper ocean, and the evolution of SST. Salinity affects dynamic height, horizontal pressure gradients, and ocean circulation. In addition, it can be a valuable tracer for the meridional overturning circulation in the tropical and subtropical oceans.

Analyses of CTD data show that lack of surface and subsurface salinity observations can sometimes lead to errors in dynamic height that are a comparable in magnitude to ENSO dynamic height signals. 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., 2000). New methods for deriving the upper ocean salinity profiles using SSS data, mean T-S curves (e.g. Vossepoel et al., 1999) and/or empirical orthogonal functions (EOF) analysis (Maes et al., 2000) have been developed. 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. In addition, more subsurface salinity measurements are needed. At present, most subsurface salinity measurements in the tropical Pacific derive from conductivity temperature depth (CTD) casts made by ships servicing the TAO/TRITON array, with over 130 CTD sections made between 8°N and 8°S in the past 8 years (e.g. Johnson et al., 2000). Additional subsurface salinity measurements are available from occasional research cruises, from XCTD sections along high-density VOS/XBT lines that cross the equator, and from a small number of TAO and TRITON moorings. The present spatial and temporal distribution of subsurface salinity measurements is inadequate to define large-scale seasonal to interannual variations or to constrain model analyses of the upper ocean salinity field. The number of salinity measurements can and should be significantly increased in the tropical Pacific by increasing the number of salinity sensors

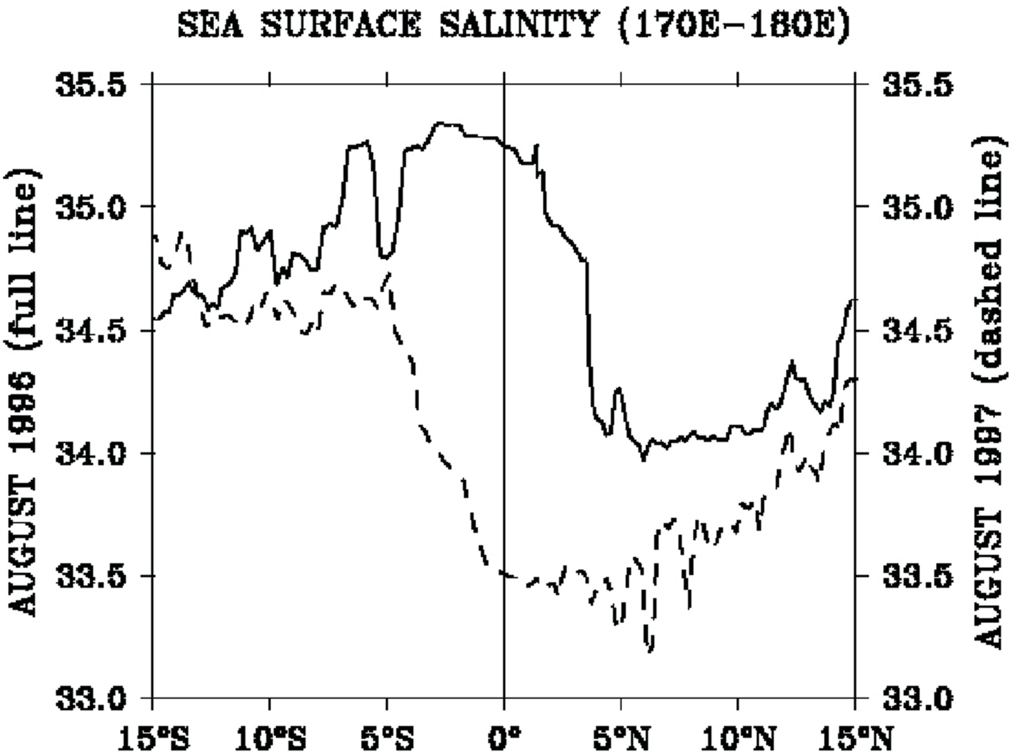

Figure. 8. One-hour average meridional sections of sea surface salinity (in psu) from thermosalinograph measurements onboard a merchant ship steaming along the line Fiji–Japan crossing the equator at 173°E longitude. The sections are shown for August 1996 (solid line) during a La Niña event and for August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

Pacific by increasing the number of salinity sensors on selected TAO and TRITON moorings, by increasing VOS/XCTD measurements, and by fully implementing the Argo array of profiling floats equipped with salinity sensors.

Finally, satellite missions are presently being proposed to space agencies for remote sensing of ocean surface salinity (Johanessen et al., this volume; Lagerloef and Delcroix, this volume). 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.

Velocity

The upper tropical Pacific Ocean is characterized by swift wind-driven zonal flows, shallow meridional overturning cells, equatorial upwelling, and strong low-latitude western boundary currents. This three-dimensional ocean circulation system plays an essential role in the dynamics of the mean seasonal cycle, ENSO, and decadal timescale variations such as the Pacific Decadal Oscillation. How this complex current system responds to changes in atmospheric forcing, how variations in ocean circulation affect the heat content of the upper ocean in such a way as to feed back on the atmosphere, and how the tropical Pacific Ocean circulation connects to the subtropics, to higher latitudes, and to the Indian Ocean via the Indonesian Throughflow are questions of great significance for understanding and predicting seasonal to decadal timescale variations.

Presently, the ENSO Observing System provides direct velocity measurements from surface circulation drifters, moored current meters, and shipboard ADCPs on vessels servicing the TAO/TRITON array. Additional shipboard acoustic Doppler current profiler (ADCP) data are available from occasional research cruises in the region. Indirect geostrophic velocity estimates are available from VOS/XBT data, from CTD sections made on research cruises, and from satellite altimeters. Lagerloef et al. (1999) have also recently developed a monthly surface velocity product from blending satellite altimetric data with *in situ* data, constrained by a model for wind-driven frictional flow near the equator (Fig. 6). These data and data products are valuable for describing upper ocean circulation patterns, for diagnosing the mechanisms responsible for observed variability, and for validating ocean models used in climate forecasting and analysis.

Precise definition and comprehensive understanding of the circulation in the tropical Pacific, however, requires an increase in the number of direct velocity measurements within the ENSO Observing System. Presently, only a few moorings along the equator are equipped with current meters, surface drifters undersample the eastern and central Pacific equatorial upwelling zones because of persistent Ekman divergence there, and ships transit tropical latitudes too infrequently to resolve energetic high-frequency motions. Geostrophic velocity estimates do not suffice by themselves because the geostrophic approximation for meridional velocity breaks down near the equator, and is too sensitive to noise contamination for zonal velocity. Also, geostrophic estimates do not include the effects of frictional flows in the Ekman layer and, computed from satellite altimeters, they are confined to the surface only. Moreover, model-derived velocities are subject to considerable uncertainty because of the sensitivity to errors in wind forcing and frictional parameterizations.

Additional sustained velocity measurements will therefore be needed to better define and understand the dynamics of near equatorial flows in the surface layer and the upper thermocline. Increasing the number of direct velocity measurements on moorings of the TAO/TRITON array, implementing ADCP measurements on volunteer observing ships, and deploying floats at shallow thermocline depths would all be valuable additions to the ENSO Observing System. Direct velocity measurements at a depth of 2000 m will also routinely be provided by Argo once it is implemented. These data will be valuable for referencing shallower geostrophic flows, as well as defining the patterns of deep circulation at 2000 m depth.

There is at present no regular program of monitoring western boundary current transports in the low latitudes of the tropical Pacific. Variations in these currents affect the heat and mass balance of the tropics, and thus influence the development of ENSO and longer-term climate fluctuations. Developing new techniques, such as autonomous gliders, to measure in western boundary current regions, should be a high priority.

At present, velocity data from the tropical Pacific are not routinely assimilated into ocean models used for studying in the ocean's role in climate. Such data are too few in number, too sparsely distributed in space and time and, in principle, not as strong a constraint as temperature on the evolution of low-frequency large-scale flows except near the equator. However, velocity measurements, if available in increased numbers, could be assimilated into ocean models to improve model-based analyses and initial conditions for coupled ocean–atmosphere model forecasts of ENSO variability.

Surface Fluxes

Fluxes of heat (turbulent and radiative), fresh water (evaporation and precipitation), and momentum (wind stress) at the air–sea interface are important ocean forcing functions. To the extent that they affect SST, these fluxes mediate ocean–atmosphere interactions on a range of time and space scales of relevance to climate (Taylor et al., this volume). 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 timescale 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 timescales 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, to foster improvements in coupled models used in ENSO forecasting, and to improve our understanding of ocean–atmosphere interactions in the tropical Pacific, 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 such as TOGA-COARE to improve bulk algorithms (see also Taylor et al., this volume).

North and South Pacific Ocean

As noted earlier, 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 (Chen et al., 1995; Balmaseda et al., 1995; Goddard and Graham, 1997). 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 (involving, for example, the Pacific Decadal Oscillation), 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 timescale thermohaline processes, gyre-scale interactions, western boundary current dynamics, and ocean–atmosphere feedbacks (Kessler et al., this volume). Pacific basin decadal timescale 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 timescale 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.

Indian Ocean

The Indian Ocean is characterized by dramatic seasonal reversals of surface winds and ocean currents related to the Asian–Australian monsoons. Superimposed on and interacting with these seasonally varying circulations are intense intraseasonal variations associated with the MJO, year-to-year variations associated with the recently discovered Indian Ocean Dipole (Saji et al., 1999; Webster et al., 1999), and longer-term changes such as the surface temperature warming trend since the 1970s (Slingo et al., 1999). However, the ocean–atmosphere–land interactions that give rise to these phenomena are poorly documented and understood, and the limits of predictability for the monsoons are not yet established.

There is also a significant but poorly understood coupling between the monsoons and ENSO, which has major consequences for both regional and global climate. Atmospheric variations on intraseasonal to interannual timescales develop in the Indian Ocean region and propagate eastward into the Pacific basin to affect evolution of the ENSO cycle. These interbasin atmospheric teleconnections were highlighted during 1997–98 by interaction between the MJO and the El Niño as described above. ENSO likewise can affect monsoon rainfalls in Asia, Australia and East Africa. However, regional factors may amplify or override ENSO influences as was evident during the 1997–98 El Niño. This event coincided with the development of an Indian Ocean Dipole which accentuated the drought in Indonesia and the rains in east Africa. Conversely, Indian monsoon rainfall was near normal during the boreal summer of 1997, and parts of South Africa did not experience drought as was expected, given the warmth of the tropical Pacific. ENSO teleconnections to the Indian Ocean also appear to be modulated on decadal timescales for reasons that are not well understood.

TOGA focused mainly on developing an ocean observing system in the tropical Pacific. More recently, through efforts like PIRATA (Servain et al., 1998), 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 timescale 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. (this volume).

Summary

The scientific value of the ENSO Observing System was evident by the end of TOGA even though it was not completed until the last month of the program (McPhaden et al., 1998). However, the 1997–98 El Niño, the first for which the observing system was in place from start to finish, dramatically underscored its importance for improved detection, monitoring, understanding, and prediction of seasonal-to-interannual timescale variability. Moreover, as a scientific investment, the ENSO Observing System is returning significant dividends by virtue of the socio-economic benefits that accrue from the availability of better climate analyses and skillful ENSO forecasts (Changnon, 1999; Buizer et al., 2000; Glantz, 2000).

With success comes opportunities and challenges. In situ components of the ENSO Observing System are the first and only example of a climate observing system developed for research purposes, and then transitioned to operational support. Sustained support encourages meaningful consideration of ways to enhance, expand, and optimize the observing system for climate forecasting and research. Examples of opportunities discussed in this paper include incorporation of new measurement capabilities (e.g. salinity, ocean velocity, surface fluxes), technological advances (e.g. Argo), and geographical extensions (Indian Ocean, mid-latitude Pacific). The greatest challenge, on the other hand, is to ensure that the basic observing system elements have the proper institutional and financial support to ensure their long-term viability. Operational support indeed does not necessarily mean adequate support. The demise of the radiosonde network in the atmosphere by 50% since the early 1980s, when it was enhanced for the Global Weather Experiment (NRC, 1999), is a reminder that careful management, constant vigilance, and adequate resources are required to sustain critical observing systems against the erosive forces of competing budgetary priorities, inflationary pressures, and shifting short term political winds.

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