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CELEBRATING 50 YEARS OF THE
INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

A TOGA RETROSPECTIVE

BY MICHAEL J. MCPHADEN,
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DAVID L.T. ANDERSON

"THERE MUST BE A BEGINNING OF ANY GREAT MATTER, BUT THE CONTINUING UNTO THE END UNTIL IT BE THOROUGHLY FINISHED YIELDS THE TRUE GLORY."

—SIR FRANCIS DRAKE, 1587

ATLAS moorings of the TAO array, like this one being serviced by the NOAA Ship *Ronald H. Brown*, are instrumented to collect upper ocean and surface meteorological data for early detection and warning of El Niño and La Niña events. *Photo taken in 1999 by Lieutenant Mark Boland, NOAA Corps*

ABSTRACT. The Tropical Ocean Global Atmosphere (TOGA) program was a 10-year international climate research effort carried out between 1985 and 1994 under the auspices of the World Climate Research Programme (WCRP). TOGA's goals were to determine the predictability of the coupled ocean-atmosphere system in the tropics on seasonal-to-interannual time scales, to understand the mechanisms responsible for that predictability, and to establish an observing system to support climate prediction. The US contribution to TOGA focused mainly on the El Niño/Southern Oscillation (ENSO) phenomenon, which is the most prominent climate signal on seasonal-to-interannual time scales. One of TOGA's great strengths was that it forged the three fields of observation, theory, and modeling into a coherent program. TOGA also included climate impact studies from the very beginning by collaborating with scientists outside the field of physical climate research. This article highlights some key successes of TOGA and assesses its legacy from a perspective of progress over the past 15 years. It also celebrates the fiftieth anniversary of the Intergovernmental Oceanographic Commission (IOC), established within the United Nations Educational, Scientific and Cultural Organization to promote international cooperation in marine research, services, and observations. IOC, together with the World Meteorological Organization and the International Council of Science, co-sponsored not only TOGA, but also antecedent and follow-on climate research programs under WCRP. The continuity of these research programs over the time span of decades is one of the reasons for their long-term successes.

LAYING THE GROUNDWORK

The origins of The Tropical Ocean Global Atmosphere (TOGA) program can be traced to the work of Sir Gilbert Walker in the early twentieth century (Walker, 1924; Walker and Bliss, 1932). In an attempt to develop a method to forecast Indian monsoon rainfall, Walker identified a large-scale, year-to-year fluctuation in surface atmospheric pressure he called the Southern Oscillation. The causes of this oscillation remained a mystery until the Norwegian meteorologist Jacob Bjerknes linked it to the Pacific oceanographic phenomenon El Niño in the 1960s (Bjerknes, 1966, 1969). Bjerknes realized that El Niño, previously viewed as a local warming of the waters off the west coast of Ecuador and Peru, affected the entire tropical Pacific basin. He further connected coupled ocean-atmosphere interactions in the tropical Pacific to weather patterns over North America and saw the potential of using computer models for long-range weather prediction.

Bjerknes (1969) observed that the tropical Pacific cycled between periods of unusually warm sea surface temperature (SST) when the trade winds were relatively weak and periods of cold SST when the trade winds were relatively strong (Figure 1). He argued that during these periods trade wind and SST tendencies were mutually reinforcing through positive feedbacks involving oceanic and atmospheric dynamical processes. He could not answer the question of how the turnabout occurred from one state to another and noted that "an additional key to the problem may have to be developed by the science of dynamical oceanography."

Enter Klaus Wyrtki who hypothesized that eastward propagating equatorial Kelvin waves, generated by weakening of the trade winds in the central Pacific, were the cause for oceanic warming in the eastern Pacific at the

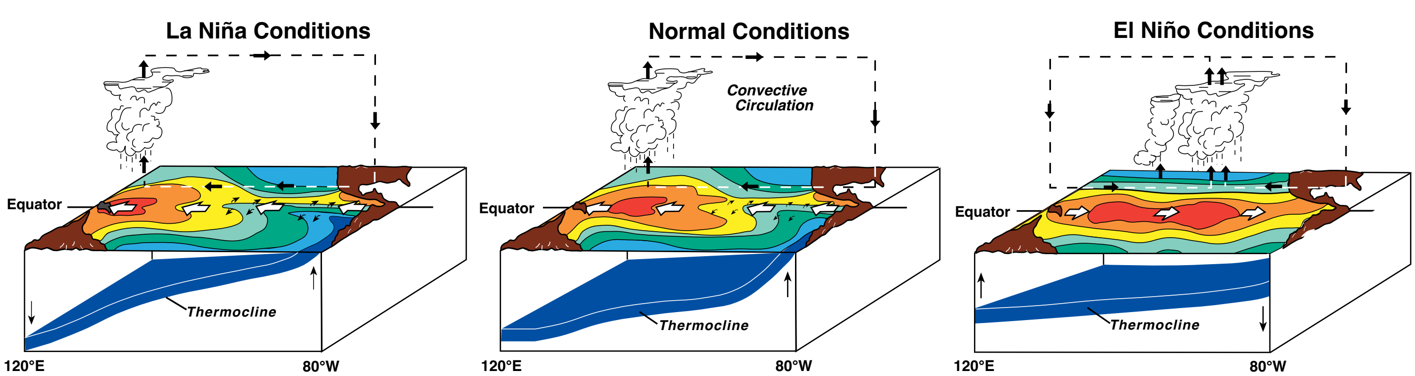

Figure 1. Schematic showing the El Niño/Southern Oscillation cycle of warm events (El Niño), cold events (La Niña), and normal conditions in the tropical Pacific.

onset of El Niño (e.g., Wyrtki, 1975). The concept of remotely forced Kelvin waves mediating the development of El Niño was supported by contemporaneous theoretical and modeling studies (McCreary, 1976; Hurlburt et al., 1976). Together, these ideas paved the way for observational and modeling programs in the mid to late 1970s such as the Equatorial Pacific Ocean Climate Studies (EPOCS) program sponsored by the National Oceanic and Atmospheric Administration (NOAA), and the North Pacific Experiment (NORPAX) sponsored by the National Science Foundation (NSF) and the Office of Naval Research (Halpern, 1996). These programs were designed to describe changes in ocean circulation related to El Niño, to understand the mechanisms by which coupling between the ocean and atmosphere produced El Niño, and to explore the potential that El Niño might be predictable. One of the early successes of EPOCS and NORPAX was the first unambiguous detection of oceanic Kelvin wave propagation over thousands of kilometers along the equator (Knox and Halpern, 1982). Related modeling studies highlighted how extremely powerful wind-forced equatorial wave dynamics were as a diagnostic tool for understanding seasonal-to-interannual time scale variations in tropical Pacific Ocean circulation associated with the El Niño/Southern Oscillation (ENSO; Busalacchi and O'Brien, 1980, 1981).

During this period, the Intergovernmental Oceanographic Commission (IOC) and the International Council of Science (ICSU)/Scientific Committee on Ocean Research (SCOR) established the Committee for Climatic Changes and the Ocean (CCCO) in 1978 with Roger Revelle as its first chairman (Intergovernmental Oceanographic Commission, 1980). CCCO's charge was to "assess the role of the ocean in climate change and variability…and ways in which oceanic research can contribute to the understanding and prediction of climate change with priority to periods of several weeks to tens of years." Adrian Gill, who developed elegant theories for how the ocean and atmosphere interacted in the tropics (Gill, 1982), was a charter member of CCCO and later became the first chairman of the TOGA Scientific Steering Group.

In the early 1980s, the World Climate Research Programme (WCRP) began planning a major international 10-year climate research program that would become known as the Tropical Ocean Global Atmosphere (TOGA) program. In the midst of this planning, the 1982–1983 El Niño occurred. This El Niño, the strongest of the twentieth century up to that time, caught the world completely by surprise. It was not predicted because no El Niño forecast models existed. Even more startling was the fact that it was not even detected until nearly at its peak (McPhaden et al., 1998). Fledgling efforts by the scientific community to monitor the tropical Pacific were confounded by a lack of real-time, in situ data. Moreover, satellite SST retrievals were biased cold by contamination from stratospheric aerosols due to the coincidental eruption of the volcano El Chichón in March–April 1982. The community was also fooled because presumed El Niño precursors, which were part of a prevailing and overly simplistic "canonical" view of how El Niños developed, did not appear (Rasmusson and Carprenter, 1982).

When finally exposed, the 1982–1983 El Niño attracted considerable public attention because of the worldwide swath of destruction left in its wake from the droughts, floods, heat waves, and other extreme weather events (Canby, 1984). Failure to predict and detect this El Niño crystallized priorities in planning for TOGA. Improved understanding was clearly essential, but development of reliable climate forecasting techniques and a real-time ocean observing system became imperative. Early efforts to design an observing system in the tropical Pacific relied mainly on satellite SST retrievals complemented by sparse in situ arrays of tide gauges, surface drifters, current meter moorings, and ship-of-opportunity transects (Figure 2, top). These efforts fell short of providing a fully adequate capability to describe the detailed evolution of the ocean-atmosphere system because of the space/time sampling limitations of existing measurement technologies.

TOGA was launched in January 1985 and continued through December 1994. It was international in scope and meant to address ocean-atmosphere variability in all three tropical ocean basins. However, the United States focused primarily on the Pacific

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because of El Niño's impacts on North America, as dramatically revealed during 1982–1983. Financial support for TOGA in the United States came principally from NOAA, NSF, and the National Aeronautics and Space Administration (NASA). J. Michael Hall, director of NOAA's US TOGA Project Office, was a particularly effective advocate for US involvement in and scientific leadership of TOGA.

WHAT TOGA ACCOMPLISHED

TOGA was a highly successful program whose many accomplishments were highlighted in a special issue of the *Journal of Geophysical Research* in 1998. One of the most notable achievements was establishment of an ocean observing system to support research and forecasting of ENSO warm (El Niño) and cold (La Niña) events (McPhaden et al., 1998). The observing system consisted of a collection of in situ components complemented by a constellation of Earth observing satellites, most of which were launched after the start of TOGA.

In situ components included the ship-of-opportunity program for upper ocean thermal structure, coastal and island tide gauges for sea level, drifting buoys for SST and surface circulation, and the Tropical Atmosphere Ocean (TAO) array of moored buoys (Figure 2, bottom). TAO was a bold new concept conceived by Stan Hayes of NOAA/Pacific Marine Environmental Laboratory (Hayes et al., 1991). It was based on the Autonomous Temperature Line Acquisition System (ATLAS) mooring, which was designed as a relatively low-cost variant of earlier successful equatorial current meter moorings (Halpern, 1987) minus the expensive current meters. ATLAS

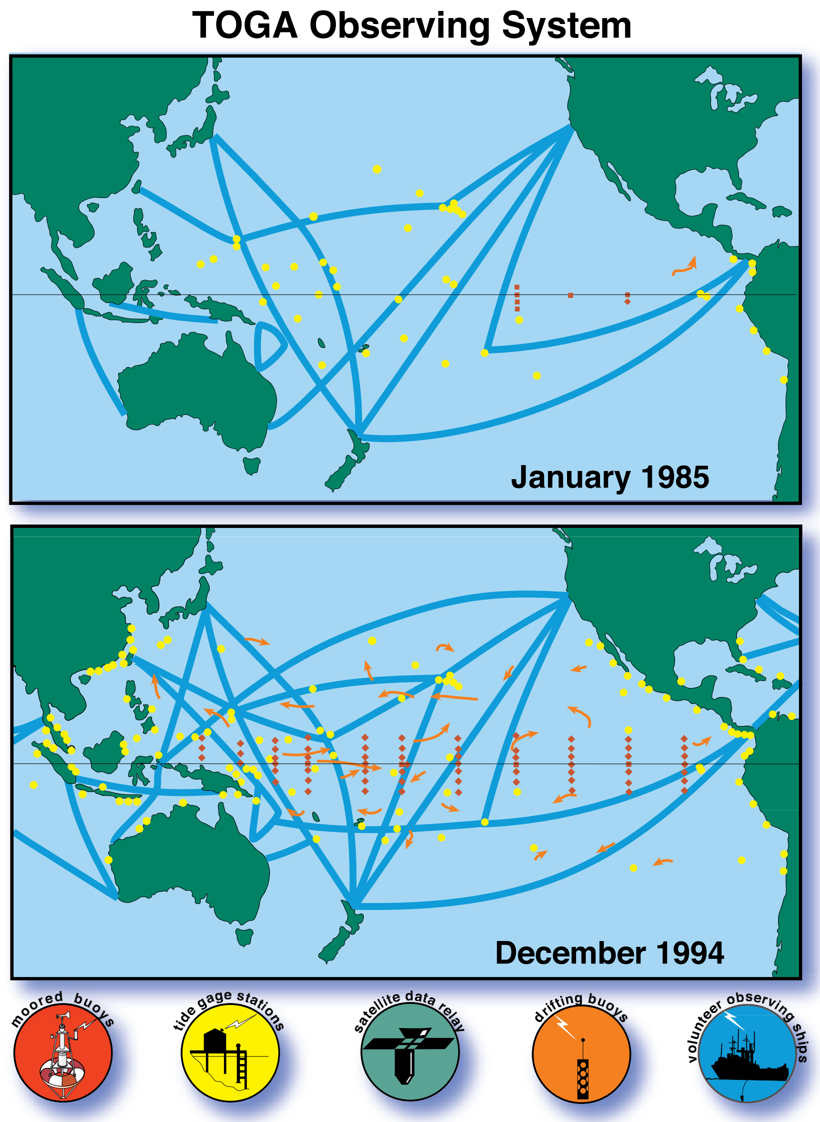

Figure 2. In situ components of the Tropical Ocean Global Atmosphere (TOGA) observing system at (top) the start of TOGA in January 1985 and (bottom) the end of TOGA in December 1994. Color coding indicates the moorings (red symbols), drifting buoys (orange arrows, one for approximately every 10 drifters), ship-of-opportunity lines (blue), and tide gauges (yellow). *After McPhaden et al., 1998*

(Figure 3, right) measured surface wind, SST, and upper ocean temperature, transmitting the data to shore in real time via satellite relay with hourly to daily resolution. TAO, consisting of nearly 70 ATLAS moorings spread across the tropical Pacific, became the cornerstone of the TOGA observing system.

The in situ components of this observing system were complemented by satellites, which, though not specifically launched for TOGA, provided comprehensive global measurements that were thoroughly exploited by the TOGA community. Especially important were NOAA polar-orbiting weather satellites with Advanced Very High Resolution Radiometer (AVHRR) infrared sensors for measuring SST; several radar altimeter missions for

BOX 1. IOC AND THE OCEAN'S ROLE IN CLIMATE

The Intergovernmental Oceanographic Commission (IOC) has played a fundamental role in advancing research on the ocean's role in climate since its inception in 1960. One major milestone was the establishment in 1978 of the Committee for Climatic Changes and the Ocean (CCCO) and its ocean basin panels with Roger Revelle as the first chairman. CCCO was jointly sponsored by IOC and the International Council of Science/Scientific Committee on Ocean Research (ICSU/SCOR) to advise the World Climate Research Programme (WCRP) on promising research areas related to the ocean and its effects on the climate system.

CCCO and its basin panels provided valuable input in the early 1980s to the research plan for the Tropical Ocean Global Atmosphere (TOGA) program, the first major international WCRP program. The basin panels, chaired initially by Bruce Taft (Pacific), Michelle Fieux (Indian), and George Philander (Atlantic) were especially influential in guiding the early design and implementation of the TOGA ocean observing system. Along with the World Meteorological Organization (WMO), ICSU, and other organizations, IOC also co-sponsored the 1984 Liège Colloquium on coupled ocean-atmosphere modeling. This colloquium brought together leading scientists from around the world on the eve of TOGA to discuss state-of-the-art modeling of seasonal-to-interannual climate variability. The 767-page proceedings (Nihoul, 1985) served as a benchmark to gauge later progress in coupled modeling during TOGA.

WCRP, which is co-sponsored by IOC, WMO, and ICSU, supported the International TOGA Project Office initially under the direction of Rex Fleming, then later John Marsh, to coordinate execution of the TOGA scientific plan. IOC and WMO also co-sponsored the TOGA Board, chaired by Antonio Moura, whose mission it was to marshal and coordinate resource commitments from various nations. At the conclusion of TOGA, WCRP initiated the Climate Variability and Predictability (CLIVAR) program to carry on the work of TOGA and its sister program, the World Ocean Circulation Experiment (WOCE).

TOGA and WOCE established the scientific framework for the sustained Global Ocean Observing System (GOOS), inaugurated in 1992 with climate as one of its principal themes. The Ocean Observing System Development Panel (OOSDP) co-sponsored by IOC, WMO, and ICSU and chaired by Worth Nowlin, formulated the initial GOOS design (Nowlin et al., 2001). When OOSDP completed its work, the Ocean Observations Panel for Climate (OOPC), with IOC as a co-sponsor, was commissioned to guide the implementation of GOOS under the chairmanship of Neville Smith. Thus, IOC has influenced all aspects of modern ocean studies related to climate through co-sponsorship of major international research and observing system programs since the 1970s.

measuring sea surface height variations, most notably Topography Experiment (TOPEX)/Poseidon (Figure 3, left), which was jointly sponsored by NASA and the French Centre National d'Études Spatiales (CNES); US Department of Defense satellites with passive microwave sensors for measuring scalar wind speed; and the European Space Agency (ESA) Remote Sensing Satellite (ERS-1) with a scatterometer for measuring vector wind speeds.

Access to data in real time or near-real time (i.e., within hours to days of collection) was a key attribute of the TOGA observing system. Such data made it possible to routinely monitor the tropical Pacific so that detection of developing El Niño or La Niña conditions would never be an issue again. Also, real-time and near-real-time data were necessary to initialize dynamical seasonal forecast models for predicting the future evolution of ENSO events.

TOGA also fostered development of new theories for the ENSO cycle in the tropical Pacific (Schopf and Suarez, 1988; Battisti and Hirst, 1989; McCreary and Anderson, 1991; Neelin et al., 1998). Central to these theories was the importance of positive feedbacks between anomalous trade wind and SST variations during the developmental phase of ENSO events, combined with delayed negative feedbacks involving large-scale equatorial waves (the so-called "delayed oscillator" theory and its variants). These feedbacks provided an explanation for the growth, maturation, and decay of individual ENSO events as well as for the apparent oscillation between warm and cold phases of the cycle.

New seasonal forecast models were developed, with emphasis on ENSO in

Figure 3. (left) TOPEX/Poseidon spacecraft. (right) ATLAS mooring of the TAO array being serviced from the NOAA ship *Ronald H. Brown*.

the tropical Pacific. These ranged from simple formulations based on statistical precursors observed in previous El Niños to highly complex coupled ocean-atmosphere general circulation models that explicitly took into account the importance of ocean-atmosphere coupling and ocean dynamics. Efforts to develop a forecasting capability led to the first successful prediction of an El Niño in 1986 (Cane et al., 1986; Barnett et al., 1988) and a new area of research was born. By the end of TOGA, centers such as NOAA's National Centers for Environmental Prediction (NCEP) were routinely issuing ENSO forecasts using models with measurable skill that outperformed persistence at lead times of six to nine months. The skill and lead time of dynamical-model-based forecasts was found to depend critically on ocean initial conditions. For short lead times of one to three months, SST was most important. However, for lead times beyond one season, upper ocean heat content was essential (Latif et al., 1998).

The availability of comprehensive measurements from the TOGA observing system stimulated development of new and innovative data products to support the demands of TOGA research, modeling, and forecasting. Some of these products were pure observational analyses, such as the Florida State University winds (Legler et al., 1989), blended satellite-in situ SST analyses (Reynolds and Smith, 1994), and upper ocean thermal field analysis (Smith, 1995). Moreover, borrowing from the example in meteorology, model-based ocean analysis systems that could routinely provide initial conditions for coupled forecast models were also developed. Ants Leetmaa established the first such operational ocean data assimilation system for climate in 1986 at NCEP using an ocean general circulation model developed by NOAA's Geophysical Fluid Dynamics Laboratory (Leetmaa and Ji, 1989).

Operational ocean analysis systems, however, could not benefit from delayed-mode data because they ran in near-real time. Also, they were not suitable for climate research because model formulations were changed periodically to improve forecast skill. These changes would introduce artificial jumps into the historical model record that could obscure real climate variations. Thus, TOGA scientists played a key role in initiating retrospective model-based oceanic and atmospheric reanalyses at NCEP, NASA's Goddard Space Flight Center, and the European Center for Medium Range Forecasts (ECMWF). Reanalysis made use of all available observations, including those not available in real time, in a consistent dynamical framework, allowing for climate research and predictability studies. The first reanalyses spanned only 5–15 years to encompass some or all of the TOGA decade, but they laid the groundwork for later more extended reanalysis efforts.

Advancing TOGA's goals required a better understanding of ocean-atmosphere coupling in the tropics. Thus, during the second half of TOGA, hundreds of scientists from over 20 nations undertook a monumental process-oriented field study in the western Pacific warm pool. This region encompasses the warmest surface waters in the world's ocean and is a key area for ocean-atmosphere interactions associated with ENSO. Under the leadership of Peter Webster and Roger Lukas, the TOGA-Coupled Ocean Atmosphere Research Experiment (COARE), the largest and most comprehensive of several TOGA process studies, was designed and executed (Webster and Lukas, 1992). TOGA-COARE explored the role of pronounced atmospheric variability on intraseasonal time scales associated with westerly wind bursts and the 30–60 day Madden-Julian Oscillation (MJO), and the impact of that variability on the lower-frequency evolution of the climate system (Godfrey et al., 1998). TOGA-COARE improved our understanding of these multi-time-scale interactions and, in addition, led to improved cumulus parameterization schemes for atmospheric models, better understanding of ocean mixing, and improved bulk parameterization schemes for air-sea fluxes.

"ONE OF TOGA'S GREAT STRENGTHS WAS THAT IT FORGED THE THREE FIELDS OF OBSERVATION, THEORY, AND MODELING INTO A COHERENT PROGRAM."

Aside from scientific and technical accomplishments, TOGA brought about fundamental cultural and institutional changes as well. ENSO could only be understood by studying the coupled nature of the ocean and atmosphere, and so required an unprecedented level of cooperation between the oceanographic and meteorological communities. Thus, TOGA "…increased the number of 'amphibious' scientists, those who are equally at home with research in the atmosphere and in the ocean, or at least have a clear understanding of the nature of the coupled system" (National Research Council, 1996).

TOGA also led to a new culture of open data access in oceanography. This policy represented a radical break from oceanographic tradition in which principal investigators would typically withhold new observations from circulation for years while they analyzed their data for publication. Open access to data in real time or near-real time from the TOGA ocean observing system rapidly advanced community-wide research activity and enabled ENSO forecasting efforts. Widespread, unencumbered distribution of ocean data was accelerated by the advent of the Internet revolution and became the norm for future large-scale sustained ocean measurement programs.

TOGA laid the foundation for establishment of the International Research Institute for Climate Prediction (IRI), an ambitious effort to capitalize on the predictability of the climate system for societal and economic benefit. IRI (later renamed the International Research Institute for Climate and Society and presently hosted at the Lamont-Doherty Earth Observatory) was chartered to advance seasonal climate forecasting and its practical application, with emphasis on the developing world where the risks are great and the vulnerability high. IRI established a unique institutional setting for physical and social scientists to collaboratively translate climate science into usable knowledge for agriculture, fisheries, water resource management, energy generation, and other climate-sensitive activities.

Finally, the scientific community argued successfully for sustaining the TOGA observing system after the end of TOGA (National Research Council, 1994). The TAO array, for example, was not completed until the last month of the program (December 1994), and the full benefit of this and other observing system components had not been fully realized by then; ten years was simply too short to critically determine the value of the TOGA observing system for understanding and predicting seasonal-to-interannual climate variability. Thus, the observing system was continued and later adopted as an initial contribution to the Global Ocean Observing System for climate.

The 1997–1998 El Niño provided one gauge of TOGA's success. This El Niño was by some measures stronger than even the 1982–1983 El Niño (McPhaden, 1999). In stark contrast to the confusion that surrounded events 15 years earlier, evolution of the 1997–1998 El Niño was tracked day by day with dramatic clarity via space-borne and in situ sensors of the TOGA observing system (Figures 4 and 5). High-temporal-resolution, real-time data from the TAO array highlighted the role of episodic westerly wind burst forcing associated with the MJO in the onset, amplification, and demise of El Niño (Figure 5). Development

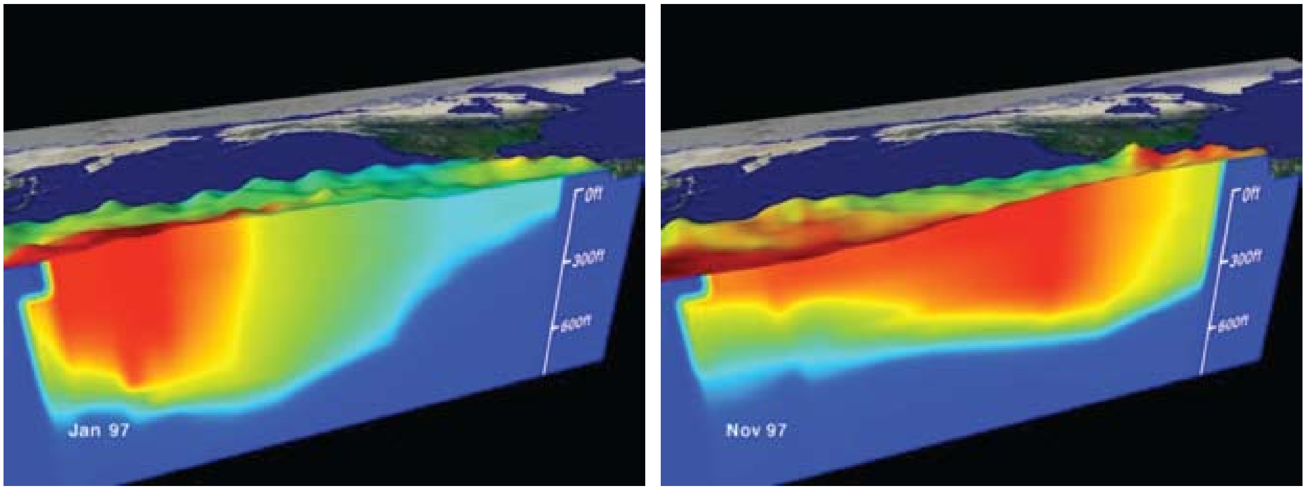

Figure 4. Sea surface topography from the US National Aeronautics and Space Administration/French Centre National d'Études Spatiales TOPEX/Poseidon altimeter, sea surface temperatures from the US National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite sensor, and subsurface temperature as measured by the Tropical Atmosphere Ocean (TAO) array of moored buoys for January 1997 (before the 1997–1998 El Niño) and November 1997 (near the height of the 1997–1998 El Niño). The three-dimensional relief map shows an anomalous sea level rise along the equator in the eastern Pacific Ocean in November 1997 of up to 34 cm with the red colors indicating an associated anomalous change in sea surface temperature (SST) of up to 5.4°C. Subsurface temperatures illustrate how the thermocline is flattened along the equator by El Niño. Ocean temperatures (in color) range from 30°C (red) to 8°C (dark blue).

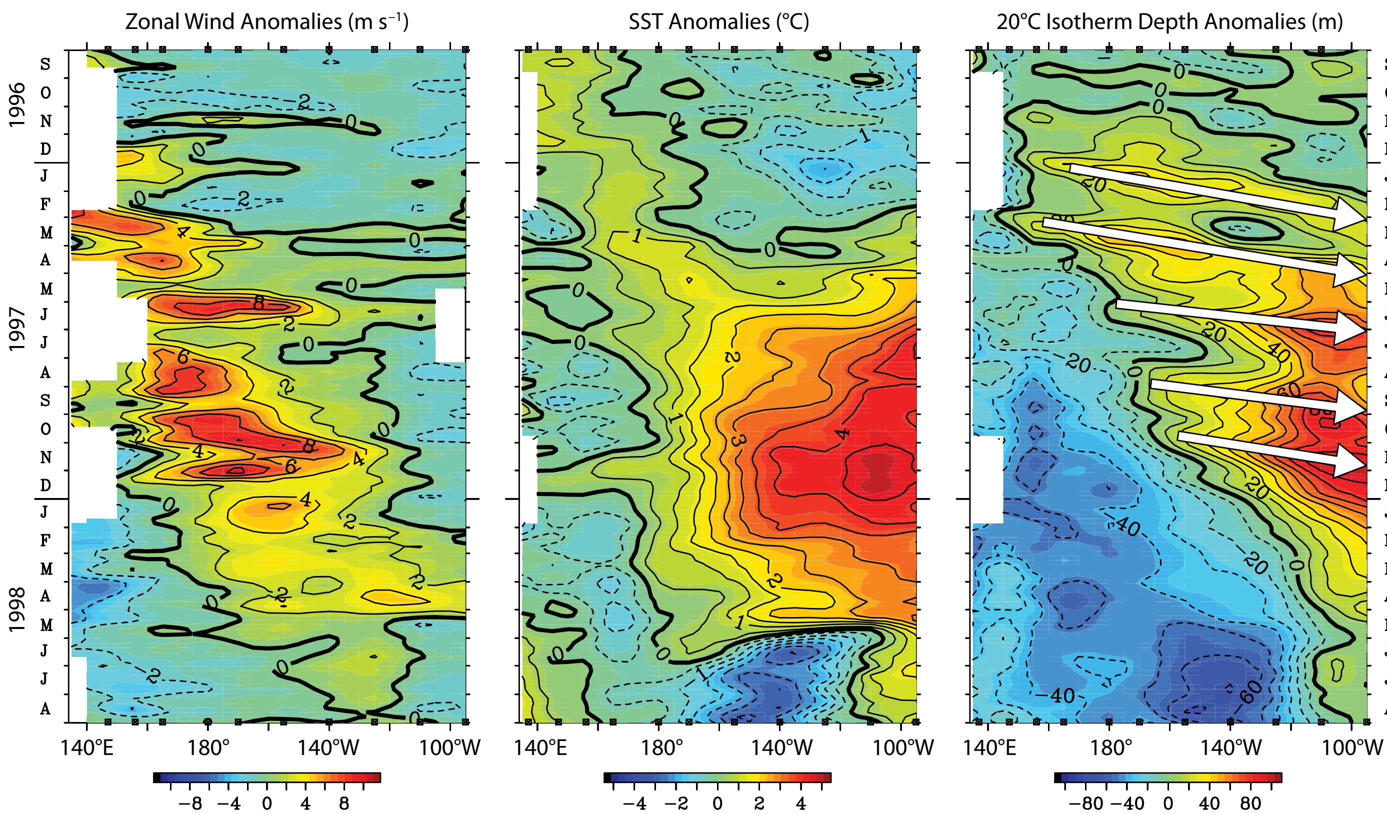

Figure 5. Time versus longitude sections of anomalies in surface zonal wind (left), SST (middle), and 20°C isotherm depth (right) from September 1996 to August 1998. Analysis is based on five-day averages of moored time-series data from the TAO array between 2°N and 2°S. Anomalies are relative to monthly climatologies that were cubic spline fit to five-day intervals. The 20°C isotherm is an indicator of thermocline depth along the equator. Black squares on the abscissas indicate longitudes where data were available at the start (top) and end (bottom) of the time series. Arrows indicate the eastward propagation of downwelling equatorial Kelvin waves in response to the episodic westerly wind burst forcing. *After McPhaden, 1999*

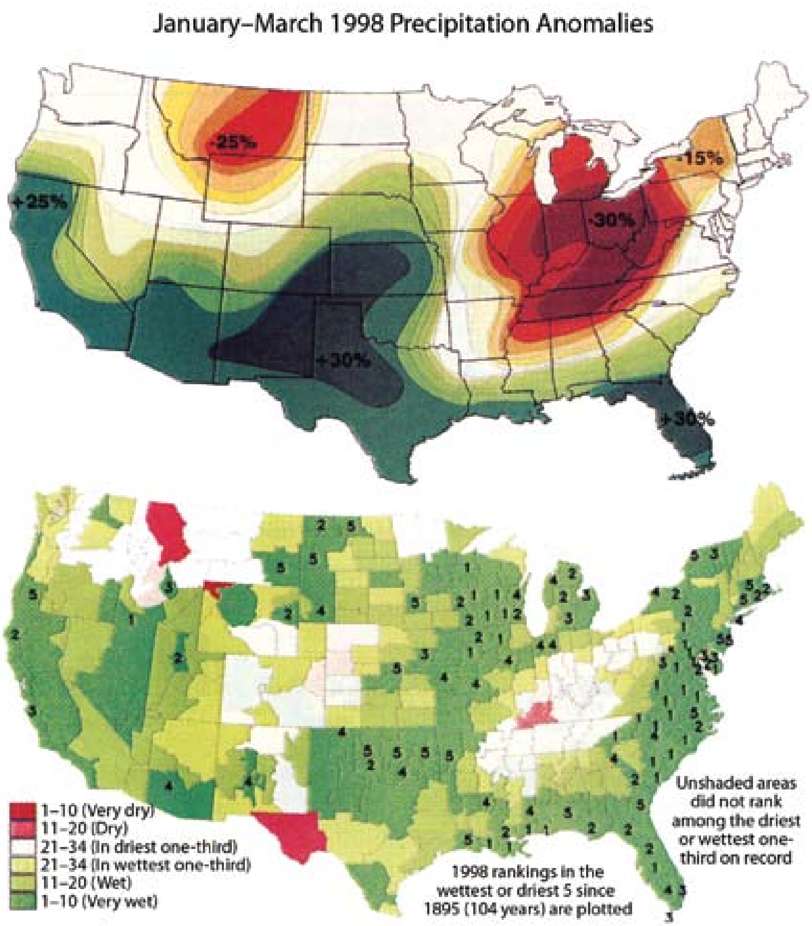

Figure 6. January–March 1998 precipitation anomalies in the continental United States forecast issued in mid December 1997 (top) and observed (bottom). The observed precipitation outcome shows ranking of individual US climate divisions with respect to the 104 years since 1895. The forecast in the top panel set a record for accuracy at NOAA's Climate Prediction Center. *After Barnston et al., 1999b*

of oceanic anomalies was mediated by wind-forced, downwelling, intraseasonal-time-scale equatorial Kelvin waves, as strikingly illustrated in both TAO data (Figure 5) and TOPEX/Poseidon altimeter data. Once underway, data from the TOGA observing system provided the observational underpinning for long-range weather forecasts in different parts of the globe that, with a few notable exceptions, proved to be surprisingly accurate (e.g., Figure 6). Among the exceptions were near-normal seasonal rainfall totals in India, Australia, and South Africa, where extreme drought had been anticipated. Forecasting successes were also tempered by the realization that there was little skill in predicting the explosive onset or sudden demise of this El Niño one to two seasons in advance (Barnston et al, 1999a).

CLIVAR AS A SUCCESSOR TO TOGA

It was clear even before TOGA ended that, despite its great successes, it would fall short of expectations in several areas (National Research Council, 1996). In the tropical Indian and Atlantic oceans, ocean-atmosphere variability had not been as thoroughly studied and ocean observing systems were not as well developed. Likewise, not all sources of predictability in the tropics on seasonal-to-interannual time scales were identified. Predictability of the higher latitudes under the influence of the tropics, though a strong motivation for TOGA, was also less fully explored than expected. In addition, there were unanswered questions with regard to the ultimate limits of ENSO predictability and what determined them.

Thus, WCRP initiated the Climate Variability and Predictability (CLIVAR) program in 1998 to carry on the work of TOGA and its sister program, the World Ocean Circulation Experiment (WOCE), which ended in 1997. Under CLIVAR, many new threads of research developed, some of which were initiated or anticipated by TOGA, and others of which were new. Themes included the decadal modulation of ENSO and ENSO predictability (Gu and Philander, 1995; Balmaseda et al., 1995); the Pacific Decadal Oscillation (Mantua et al., 1997), sometimes referred to as "ENSO-like decadal variability"; the different flavors of El Niño (i.e., eastern vs. central Pacific, or "modoki" El Niños; Larkin and Harrison, 2005; Ashok et al., 2007); paleo-ENSO (e.g., Clement et al., 1999; Tudhope et al., 2001); and the effects of anthropogenic climate change on ENSO (e.g., Guilyardi et al., 2009).

CLIVAR stimulated further efforts to define the role of heat-content variations along the equator as a precondition for El Niño and La Niña development through both theory and observation (Jin, 1997; Meinen and McPhaden, 2000; Figure 7). The mechanisms by which intraseasonal atmospheric forcing can initiate El Niño development were also more clearly identified (e.g., Kessler et al., 1995; Kessler and Kleeman, 2000). Moore and Kleeman (1999), among others, found that intraseasonal wind fluctuations, because they occur on time scales that are short compared to a season, represent stochastic forcing of the ENSO cycle and thus are a significant limitation on its predictability.

The Indian Ocean Dipole (IOD), the dynamics of which share similarities with ENSO (Murtugudde et al, 2000), was discovered during CLIVAR (Saji et al., 1999; Webster et al., 1999). Regional ocean-atmosphere interactions associated with the 1997–1998 IOD event were viewed as a possible cause for mitigating expected El Niño droughts in India, Australia, and South Africa during the 1997–1998 El Niño. Tropical Atlantic climate variability and its regional climatic impacts also emerged as an important CLIVAR research theme (Chang et al., 2006).

CLIVAR spearheaded efforts to understand the connection between ocean conditions and extreme mid-latitude droughts and pluvials (Schubert et al., 2009). Numerous studies have identified changes in atmospheric circulation associated with tropical SST anomalies, in particular those in the Pacific associated with ENSO and longer-term decadal fluctuations, as principal drivers of extended dry and wet periods over North America and elsewhere. Unusually cold SST anomalies in the eastern and central equatorial Pacific, for example, have been identified as a primary forcing for the extended US Dust Bowl drought of the 1930s and the 1998–2004 drought in the western United States (Hoerling and Kumar, 2003; Seager et al., 2005).

Potential predictability of the climate system over the next 10–30 years has also received considerable attention (Smith et al., 2007; Keenlyside et al., 2008). Decadal prediction relies on initializing the ocean, which, because of its great thermal inertia, constrains the evolution of the climate system under the influence of both anthropogenic greenhouse gas forcing and natural variability. If successful, decadal-time-scale forecasts could provide practical guidance for long-lead-time climate change mitigation and adaptation strategies (Hawkins and Sutton, 2009).

CLIVAR has also advanced TOGA and WOCE efforts to build a sustained ocean observing system for climate. The international OceanObs99 conference (Koblinsky and Smith, 2001) and OceanObs09 conference (Harrison and Legler, 2010) were milestones along the way that highlighted successes, laid new plans, and rallied community support. During this period, the Argo float array was conceived and implemented with more than 3000 floats deployed at present. The Global Drifter Program, a combined legacy of TOGA and WOCE, was completed, and is presently at 100% of target strength, with ~ 1250 drifters worldwide (Figure 8). The Prediction and Research Moored

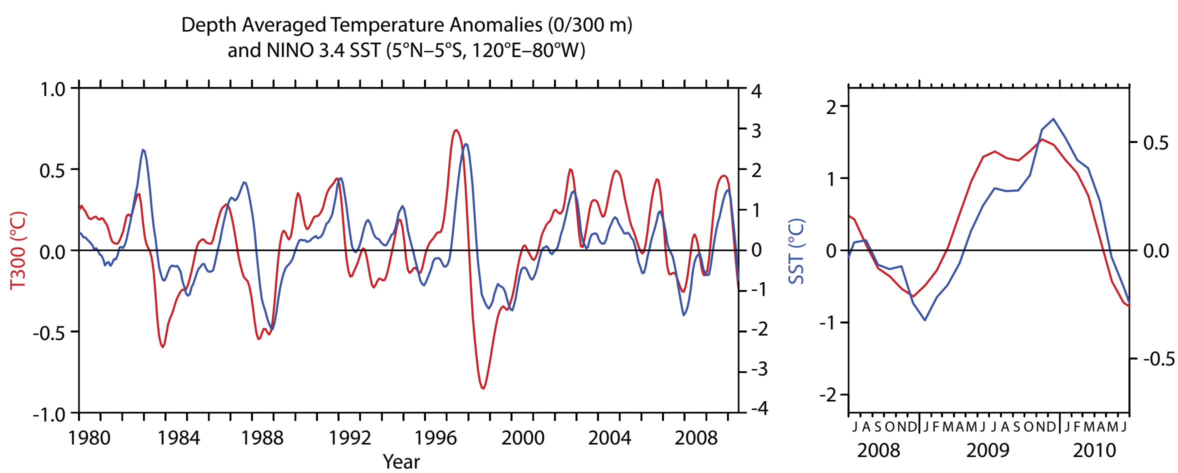

Figure 7. Heat content (as measured by the average temperature in the upper 300 m) and NINO3.4 SST anomalies for 1980 to 2010. Monthly values in the left panel have been smoothed with a five-month running mean. The right panel shows July 2008 to June 2010 (unsmoothed) to highlight the 2009–2010 El Niño. Note the different scales for heat content and NINO3.4 SST in the two panels. Heat content variations generally lead NINO3.4 SST by one to three seasons, with a build up of heat content preceding El Niño and a deficit preceding La Niña. This lead-lag relationship illustrates the role of upper ocean heat content as the source of predictability for ENSO. *After Meinen and McPhaden, 2000*

Array in the Tropical Atlantic (PIRATA) was built up beginning in 1997 (Bourles et al., 2008), and the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA), under development since 2004 in the Indian Ocean, is more than 50% complete (McPhaden et al., 2009). The Ocean Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES) program was also initiated, including moored biogeochemical measurements at key locations throughout the global ocean (Send et al., 2010).

With regard to Earth observing satellites, we now have nearly 30 years of continuous global AVHRR SST data from space. Infrared sensors cannot measure SST effectively in the presence of clouds, but microwave sensors can, albeit with coarser spatial resolution. Microwave sensors on a variety of satellites, including NASA's Tropical Rainfall Measuring Mission (TRMM) and Earth Observing System satellites, have been providing SST observations from space since the mid 1990s. SST data products derived from blending both types of measurements (e.g., Reynolds et al., 2007) have the advantage of improved accuracy for climate research and applications.

There are 17 years of high-quality, continuous altimetry measurements, thanks to the sequence of ERS, TOPEX/Poseidon, Jason, and the Ocean Surface Topography Mission (OSTM)/Jason-2 satellites. An agreement between NOAA, CNES, and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) to launch Jason-3 in 2013 assures continuity of altimetry measurements for the coming decade. The Gravity Recovery and Climate Experiment (GRACE) mission, launched in 2002 as a partnership between NASA and the German Aerospace Center, has provided an accurate definition of Earth's geoid (the surface that is perpendicular to the pull of gravity) on O(100-km) spatial scales. GRACE and altimetry data in combination allow for global mapping of absolute ocean surface geostrophic currents.

Scatterometer measurements have been continuous since 1992 from ERS and NASA missions. The NASA Quick Scatterometer (QuikSCAT), launched in 1999, provided high-accuracy surface wind stress over 90% of the globe every two days with 25-km resolution for a 10-year period until its failure in November 2009. Just before this failure, in September 2009, the Indian Space Research Organization (ISRO) launched Oceansat-2 with a scatterometer on board. Ocean color measurements from space have been continuous since 1997, most notably from NASA's Sea viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, which continue to operate.

The ESA Salinity Soil Moisture and Ocean Salinity (SMOS) mission (http://www.esa.int/esaLP/LPsmos.html) launched in November 2009 and Aquarius, a joint effort between NASA and the Space Agency of Argentina scheduled for launch in April 2011 (Lagerloef et al., 2008), will for the first time permit global sea surface salinity (SSS) measurements from space. SSS provides an important constraint on the global hydrological cycle because of large uncertainties in surface fresh water fluxes. The effects of SSS on surface density also influence the three-dimensional thermohaline

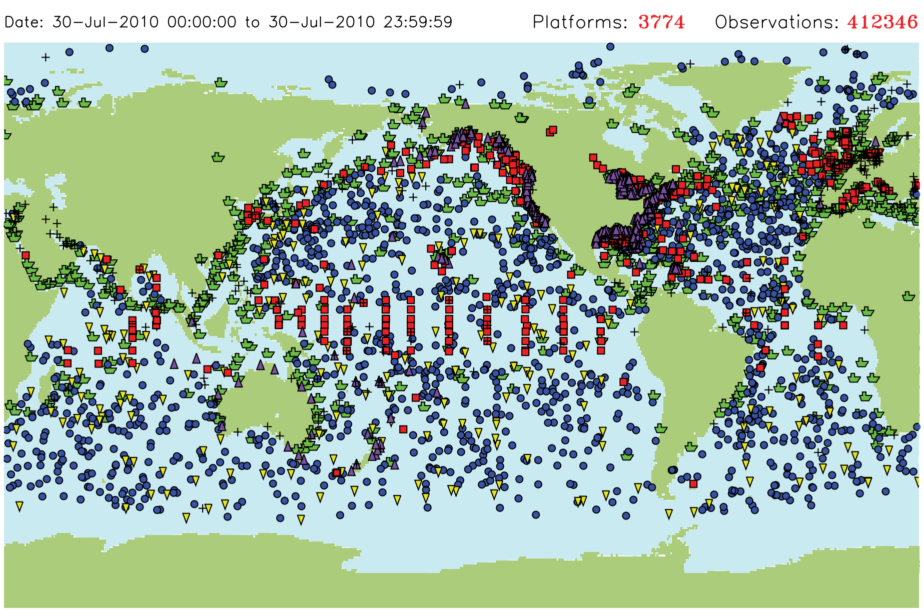

Figure 8. One day (July 30, 2010) chosen at random to illustrate real-time, in situ data transmissions from moorings (red squares), Argo floats (inverted yellow triangles), drifters (blue circles), shore stations (purple triangles), ships (green symbols), and unidentified platforms (plus symbols). The total number of platforms reporting is 3774. The deep-ocean-based networks in this figure represent to a large extent the legacy of TOGA and WOCE. *From http://www.osmc.noaa.gov*

BOX 2. THE CHALLENGE OF OBSERVING THE OCEAN FOR CLIMATE

Climate records are most valuable when they are long, continuous, and of sufficient quality to detect subtle variations in the Earth system. Sustaining existing ocean observations for continuous climate-quality records involves a fragile and precarious balance at present for both satellite and in situ systems. Many in situ climate observing systems were started by and are presently maintained by researchers. Support is typically linked to a particular principal investigator or group of investigators. Long-term, stable funding is not guaranteed for these systems, and in most cases there are no formal institutional arrangements that ensure their continuation beyond the career of a particular scientist.

As a demonstration project to address this issue, the Administrator of the US National Oceanic and Atmospheric Administration (NOAA) mandated transfer of the Tropical Atmosphere Ocean (TAO) array management from NOAA research to operations within the National Weather Service beginning in 2005. The transition, originally planned for three years, was scheduled for completion in 2007. However, NOAA underestimated the technical and financial requirements to ensure success of this transition, which is now six years behind schedule and will not be complete until 2013. In the meantime, operating costs escalated sharply and data return suffered (Lubick, 2009). Steps have recently been taken to address the most serious operational problems, but this example suggests that the challenge of sustaining ocean observations for climate may require institutional arrangements different from those that have been traditionally used to maintain networks for weather forecasting.

Establishing long, continuous climate-quality satellite data records is also a challenge. New satellite missions require decade-long lead times from concept to launch and involve development costs in the hundreds of millions to billions of dollars. Agencies involved in flying research and operational Earth-observing satellites likewise have different missions, which can significantly complicate interagency coordination (e.g., National Research Council, 2008). Long records must be pieced together from satellites that often have very different orbits, sensors, and sampling characteristics. A climate-quality data set thus requires extensive intercalibration efforts to guarantee compatibility between missions. The satellite climate record is also susceptible to data gaps from launch delays or the failure of a single critical mission, as happened for example with the NASA scatterometer (NSCAT). This satellite was originally scheduled for launch in 1989 near the midpoint of TOGA. However, construction delays resulted in a 1996 launch well after TOGA ended. The spacecraft carrying the scatterometer then failed prematurely in June 1997 after only nine months in orbit, just as the 1997–1998 El Niño was getting underway.

Transitioning mature remote-sensing technologies for the ocean from research to operations has proven to be very difficult. The National Polar Orbiting Environmental Satellite System (NPOESS), a joint effort among NOAA, the US National Aeronautics and Space Administration, and the US Department of Defense, was conceived in 1994 to integrate civilian and defense Earth-observing satellite capabilities in a cost-effective manner. Among the many sensors in the original design concept, NPOESS was intended to carry an operational altimeter. However, NPOESS experienced huge cost overruns and construction delays. The mission was eventually descoped to eliminate the altimeter in 2006 and then entirely restructured in early 2010. A more successful development has been the NOAA, French Centre National d'Etudes Spatiales, and European Organisation for the Exploitation of Meteorological Satellites partnership to launch Jason-3 in 2013 to ensure continuity of altimetry measurements for the next decade.

Observing systems for the ocean must also be enhanced because they do not yet provide the full range of data needed to advance climate science. In situ technologies are needed to systematically and cost-effectively measure in traditionally hard-to-sample regions such as the deep ocean, western boundary currents, and the ice-covered ocean. A new generation of biogeochemical sensors is required to advance interdisciplinary studies of the ocean carbon cycle, ocean acidification, oxygen minimum zones, and ecosystem dynamics. Gliders, autonomous underwater vehicles, floats that can operate at abyssal depths, and cabled observatories are examples of technologies that hold promise. Likewise, satellite missions that provide higher accuracy and greater time/space sampling of critical climate variables are needed, such as the proposed wide swath and high resolution altimeter (SWOT) for ocean surface topography (National Research Council, 2007).

circulation and the formation of salt-stratified barrier layers that trap heat in the surface mixed layer (Lukas and Lindstrom, 1991). These new space-based measurements should lead to fundamentally new insights into the workings of the climate system, particularly in the tropical Pacific where interannual variability in SSS affects both the evolution and predictability of ENSO events (Reynolds et al., 1998; Delcroix and McPhaden, 2002; Maes et al., 2005).

Ocean and atmosphere reanalysis efforts have expanded in recent years to encompass more data over longer periods of time. Compared to the first 5–15 year reanalyses undertaken during TOGA, 40–100 year ocean and atmospheric reanalyses now exist (Kalnay et al., 1996; Kistler et al., 2001; Uppala et al., 2005; Compo et al., 2006; Carton and Geise, 2008; Balmaseda et al., 2008; Wunsch et al., 2009). In addition, the latest generation of model-based analysis systems is better at extracting information from the data through refinements in assimilation techniques and through the inclusion of a more diverse set of observations.

There has also been significant progress in seasonal climate prediction since the end of TOGA. As a direct result of the research advances during TOGA, operational seasonal forecasting has been established at the major numerical weather prediction (NWP) centers around the globe, such as NCEP, ECMWF, the UK Met Office, the Japan Meteorological Agency, Météo-France, the Australian Bureau of Meteorology, and others. There have also been significant refinements in seasonal forecasting techniques, with improved model resolution, physical parameterizations, and initialization systems. Ensemble forecasting methods have been introduced to improve reliability, provide probabilistic forecasting information, and to quantify forecast uncertainties. These improvements have lead to steady improvements in ENSO forecasting skill equivalent to about a one-to-two-month increase in lead time since the mid 1990s (Anderson, 2010; Stockdale et al., in press; Figure 9).

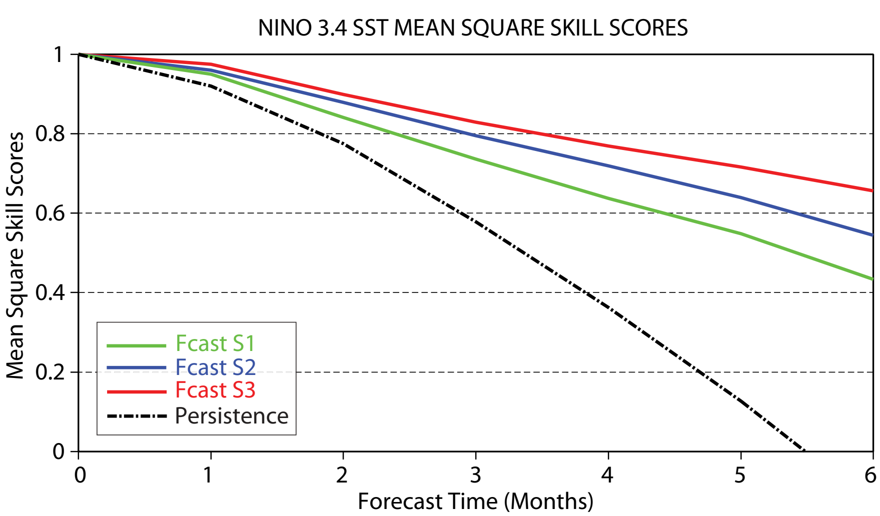

Figure 9. Forecast skill as a function of the lead time for the European Centre for Medium-Range Weather Forecasts coupled model system. The original forecast system (green) was introduced in 1997. This system was replaced in 2002 (blue). The current system (red) was introduced in 2006. These systems all out perform persistence (dot-dash) and show steady improvement in forecast skill. The improvements come from better resolution in the atmosphere and ocean, as well as advances in the way data are used for initializing the atmosphere and ocean. There has also been progress in the parameterization of subgrid-scale processes, mostly for the atmosphere. Skill, as defined here, takes into account both the time history and the amplitude of predicted anomalies relative to those observed (Stockdale et al., in press).

Development of seasonal climate forecast and analysis products of potential socio-economic value has also become more routine at national NWP centers and IRI. Regional forecasting and/or applications centers, such as the Centro Internacional para la Investigacion del Fenomeno de El Niño (CIIFEN) in Ecuador, the Asia-Pacific Climate Center for Information Services (APCC) in Korea, and the Pacific ENSO Applications Center in Hawaii, have sprouted up to take advantage of advances in climate forecasting. These centers have developed products and services to support individuals, businesses, industry, and government in making climate-sensitive decisions.

In summary, CLIVAR builds on and is advancing the findings of TOGA and related WCRP programs such as WOCE. From this solid scientific foundation, CLIVAR provides input to the WCRP crosscutting topics of anthropogenic climate change, sea level rise, and connections between atmospheric chemistry and climate. CLIVAR also coordinates climate model scenario experiments for the United Nations Intergovernmental Panel on Climate Change (IPCC) as well as providing a framework for coupled climate model development.

UNFINISHED BUSINESS

It is apparent that in the 15 years since TOGA ended, there has been great progress in our ability to observe, understand, and predict climate variability and change. In a real sense, though, TOGA's work is not complete. Except for the regular progression of the seasons, ENSO is the most predictable climate fluctuation on the planet. Yet, despite the advances in seasonal forecasting, predicting the onset, demise, and ultimate amplitude of ENSO events remains a challenge. The 2006–2007 El Niño, which started late and ended early, is typical of how important details in the evolution of the ENSO events continue to be missed by forecasters (McPhaden, 2008). Stochastic forcing related to westerly wind bursts and MJO, chaos in the climate system, model biases, and errors in initial conditions all affect ENSO forecast error growth. Model bias, in particular, is still a major problem in all climate models, many of which fail to realistically simulate the mean state, the mean seasonal cycle, and ENSO (Latif and Keenlyside, 2009).

Ongoing research may reduce bias and other errors in coupled models, extending the limits of predictability. For example, operational seasonal forecasting using dynamical models is presently based on uncoupled initialization of the oceanic and atmospheric components of coupled systems. Hence, it may be possible to improve model forecast skill through development of coupled ocean-atmosphere assimilation schemes to reduce initialization shock (e.g., Chen et al., 2004). We can also anticipate improvements from more careful use of multimodel approaches and through mining additional sources of predictability, such as land-surface processes and stratosphere-troposphere interaction (Kirtman and Pirani, 2009). Improvements in observing systems, especially in the Indian Ocean, may also help to reduce errors in initial conditions. In addition, large-scale evolving ENSO SST patterns have been shown to organize the seasonal statistics of atmospheric noise forcing (Eisenman et al, 2005) and it may be possible to exploit this feedback to improve seasonal forecasting techniques.

> "ONGOING RESEARCH MAY REDUCE BIAS AND OTHER ERRORS IN COUPLED MODELS, EXTENDING THE LIMITS OF PREDICTABILITY."

There are promising indications that climate variability in the tropical Atlantic and Indian oceans may be predictable at lead times of one to three seasons based on both external ENSO influences and ocean-atmosphere interactions internal to these basins (Barreiro et al., 2005; Wajsowicz, 2005; Luo et al., 2008). However, seasonal forecasting efforts are not as advanced and forecast skill is in general not as high for, say, the Indian Ocean Dipole or tropical Atlantic climate variability, as it is for ENSO. Compared to the Pacific, year-to-year climate variations in the other basins are weaker and shorter-lived, and therefore more difficult to predict accurately. The source of predictability in these regions appears to involve variations in upper ocean heat content and land surface processes on adjacent continents. Systematic errors in coupled ocean-atmosphere-land models and, for the Indian Ocean, an incomplete ocean observing system are among the major hurdles to improved forecast skill in these basins (Balmaseda and Anderson, 2009).

Predicting climate impacts on seasonal-to-interannual time scales is also still a challenge. For example, the unexpected drought in western South America during the 2002–2003 El Niño resulted in serious hardship for farmers and others who acted on forecasts for unusually wet conditions typical of most El Niños. The 2002–2003 El Niño, however, was a central Pacific or "modoki" El Niño that did not involve significant anomalous warming or rainfall in the eastern Pacific. Normal Indian summer monsoon rainfall in 1997 during the intense 1997–1998 El Niño was also unexpected. Drought was mitigated possibly because of the co-occurrence of an Indian Ocean Dipole that year or because of a changing relationship between ENSO and the monsoons on decadal time scales (Kumar et al, 1999). Predicting climate impacts associated with ENSO outside the tropics is likewise problematic because weather noise can obscure teleconnections from the tropics, especially for weaker El Niños and La Niñas.

One of the most pressing scientific challenges today is to understand how global warming will affect modes of

BOX 3. CLIMATE SERVICES

Confronted with the challenges of a warming planet, society is asking for credible and authoritative information on climate variability and change to inform adaptation and mitigation strategies. At present, there is no coordinated effort to provide usable information needed to understand the implications of, for example, sea level rise, shifts in patterns of temperature and precipitation, changes in the frequency and intensity of severe storms, and other climate-related phenomena across the full spectrum of temporal and spatial scales that affect society. Yet, the human-dimensions aspects of climate variability and change are profound because of impacts on agricultural production, energy generation, fresh water resources, public health, ecosystem services, economic development, national security, and many other areas of societal relevance. Climate services, as presently conceived, are meant to address these issues on seasonal-to-centennial time scales and local, regional, and global space scales.

In support of climate services, climate research, as embodied by the World Climate Research Programme, is now tasked with the great challenge of understanding Earth as a complex, nonlinear, interactive system and of assessing the impacts of anthropogenic climate change on coupled human and natural systems. In contrast to numerical weather prediction and related weather services, the need for such climate information places unique requirements on the characterization, calibration, and continuity of climate observations, the generation of multidecadal climate reanalyses, and development of coupled climate models across the atmosphere-ocean-land-cryosphere system inclusive of marine and terrestrial ecosystems. Thus, climate services are more than a simple extension of weather services to a longer time scale. Rather, they represent a unique applications enterprise founded on an evolving knowledge base that is underpinned by research into the fundamental processes governing the evolution of the climate system. That research will draw to the fullest extent on data from sustained observing systems, high-performance Earth system modeling, and predictive capability to respond to looming climate-related challenges that affect people, economies, and ecosystems across a broad range of temporal and spatial scales.

natural climate variability, especially ENSO, which is the principal driver of year-to-year climate fluctuations on a global basis. A related issue is whether background conditions in the tropical Pacific, under the influence of greenhouse gas forcing, will evolve toward permanent El Niño or La Niña-like conditions. The consensus outlook from the current generation of global climate models suggests a tendency toward a more El Niño-like background state in the tropical Pacific, but no consistent significant change in ENSO characteristics (e.g., amplitude, frequency, or duration of individual events) under various greenhouse gas emission scenarios that presume a doubling of atmospheric CO_2 from pre-industrial levels over the next 100 years (Philip and van Oldenborgh, 2006; Guilyardi et al., 2009; Collins et al., 2010). However, global climate change models have known flaws that compromise their ability to simulate ENSO in the modern climate such that the reliability of future projections in the tropical Pacific is subject to substantial uncertainty. Better ENSO representation in climate change models is imperative to gain confidence in regional-scale climate change projections, given the global reach of ENSO teleconnections on patterns of weather variability.

CLIMATE SERVICES TO ADVANCE TOGA'S LEGACY

TOGA was a tremendous success that laid the groundwork for much climate research that followed. However, in view of the pressing issues that remain unresolved and the challenges that lie ahead, we can say that, in the words of Sir Francis Drake, TOGA's "true glory" has only been partially realized. Even so, there is great potential for further progress. The way forward requires recognition that there is a continuum of climatically relevant and interacting phenomena ranging from intraseasonal to centennial time scales, and that both natural and anthropogenic forces are at work in determining the evolution of the climate system.

There is also a need for a more integrated approach to climate research and forecasting with stronger links to development of climate products and services. In the United States and most other countries, there are as yet no national climate services analogous to national weather services to provide a focal point for coordinated planning and action. Delivery of quality climate products and services, tailored to the needs of various user communities, are in the public and national interest because of their economic and strategic value. The demand created by climate products and services will in turn justify systematic, sustained ocean observations and greater efforts to improve climate-forecasting capabilities. Climate services can likewise provide a nexus for engagement of the physical climate community with the marine biogeochemistry and living resources communities to address pressing issues such as the influence of warming and acidifying oceans on marine ecosystems and fisheries.

Recently, the third World Climate Conference, held in Geneva, Switzerland, in September 2009, called for the establishment of a global framework for climate services, including the ocean observations that support those services (http://www.wmo.int/wcc3). NOAA has also recently proposed a new NOAA Climate Service (http://www.noaa.gov/climate.html) as part of a coordinated US national effort. These initiatives reflect a growing awareness that climate services have a strategic role to play in the sustainability of the planet.

In TOGA, IOC and its partners ICSU and WMO brought together nations in common cause to advance understanding of the ocean's role in climate for the benefit of society. That work continues today as part of a foundation that broadly supports research in WCRP and IPCC assessments. The next great leap forward to ensure TOGA's legacy will be the development of a comprehensive framework for end-to-end climate services at both national and international levels. It is through the widespread application of climate information for practical purposes that sustained ocean observations, climate research, and climate forecasting will achieve their "true glory."

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