US CLIVAR
Climate Variability & Predictability

VARIATIONS

Winter 2015 • Vol. 13, No. 1

ENSO: Observing System, Predictability, and Predictions

Guest Editors:
Arun Kumar and Yan Xue
NOAA Climate Prediction Center

In 1982-83, the unobserved El Niño caught the community by surprise and led to the establishment of the Tropical Ocean Global Atmosphere (TOGA) program. The crowning achievement of TOGA was deploying the Tropical Atmosphere Ocean (TAO) array in the equatorial Pacific to provide real-time ocean and atmosphere observations for improving ENSO predictions. The completion of the TOGA program in 1994 saw ENSO prediction efforts reaching an operational status. Since then, however, further improvements in skill of ENSO predictions have proven to be slow. There is some evidence that since the year 2000, ENSO prediction skill has declined. Furthermore, sustaining the Tropical Pacific observing system (TPOS) has proven to be a difficult endeavor and surprises, like changes in the characteristics of ENSO variability, have also emerged.

Following TOGA, the focus of community efforts largely have shifted to understanding ENSO variability on longer time scales. However, a realization of the difficulties in improving ENSO prediction skill – and a lack of understanding of ENSO predictability – calls for a renewed

ENSO observing system: Past, present, and future

William S. Kessler[1], Arun Kumar[2], and Neville R. Smith[3]

[1]NOAA Pacific Marine Environmental Laboratory

[2]NOAA Climate Prediction Center

[3]Co-Chair, Tropical Pacific Observing System Steering Committee, Australia

El Niño – Southern Oscillation (ENSO) is the largest signal of interannual climate variability. Sea surface temperature (SST) variations associated with ENSO, by influencing tropical precipitation and associated diabatic heating in the tropical atmosphere, affect weather patterns and climate across the globe. The global influence of ENSO on seasonal climate variability can be easily discerned as atmospheric teleconnection patterns (Horel and Wallace 1981; Trenberth et al. 1998). Different phases of ENSO - El Niño and La Niña – result in shifts in the probability of droughts, floods, heat waves, and extreme weather around the globe, which provides the societal motivation for developing skillful prediction of ENSO and has prompted a strong emphasis on ENSO research in the last 30 years.

The unpredicted and mostly unobserved El Niño event of 1982-83 focused community attention on the phenomenon and provided the underpinnings for the establishment of Tropical Ocean/ Global Atmosphere (TOGA) experiment of 1985-94. The goals of TOGA were to:

- Gain a description of the tropical oceans and the global atmosphere as a time-dependent system in order to determine the extent to which the system is predictable on time scales of months to years and to understand the mechanisms and processes underlying its predictability;
- Study the feasibility of modeling the coupled ocean-atmosphere system for the purpose of predicting its variation on time scales of months to years; and
- Provide the scientific background for designing an observing and data dissemination system to support operational ENSO predication by coupled ocean-atmosphere models.

IN THIS ISSUE

focus on better understanding and predicting of ENSO variability on seasonal time scales. Recent developments in ocean observing technologies are also challenging us to rethink the future design of TPOS. Kessler et al. provide a summary of the past, present, and future of TPOS. One of the key aspects of ENSO predictions is converting ocean observations into analysis to provide initial conditions for coupled forecasts. Rosati et al. review the status of the ocean data assimilation systems and the progress being made towards operation. Kirtman provides an assessment of ENSO prediction skill, and potential remote triggers for ENSO variability is discussed by Yu and Paek. Capotondi et al. discuss the issue of biases in the coupled model that affect both the skill of ENSO predictions and assimilation of ocean observations. Recent changes in the characteristics of ENSO variability have generated considerable interest in understanding possible sources, and are the focus of Wittenberg's discussion.

US CLIVAR is fostering discussion on future research priorities to improve observations, understanding, and prediction of ENSO. The next US CLIVAR Summit will include a special science session to explore these issues and identify pathways for addressing them.

US CLIVAR VARIATIONS

Editors: Mike Patterson and Kristan Uhlenbrock
US CLIVAR Project Office
1201 New York Ave NW, Suite 400
Washington, DC 20005
202-787-1682 www.usclivar.org

A part of the TOGA program was implementation of a tropical observing system, with a major focus being the Pacific Ocean. The oceanic components of the observing system included a network of drifters, tide gauges, and ships of opportunity eXpendable BathyThermograph (XBT) lines, and were complemented with atmospheric measurements. The central component of the observing system, however, was the Tropical Atmosphere Ocean (TAO) moored array, and was largely completed by 1994 (Figure 1). The TAO included nearly 70 moorings with data available in real-time. In 2000, the array, with the support of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), was extended westward and became the TAO/TRITON array.

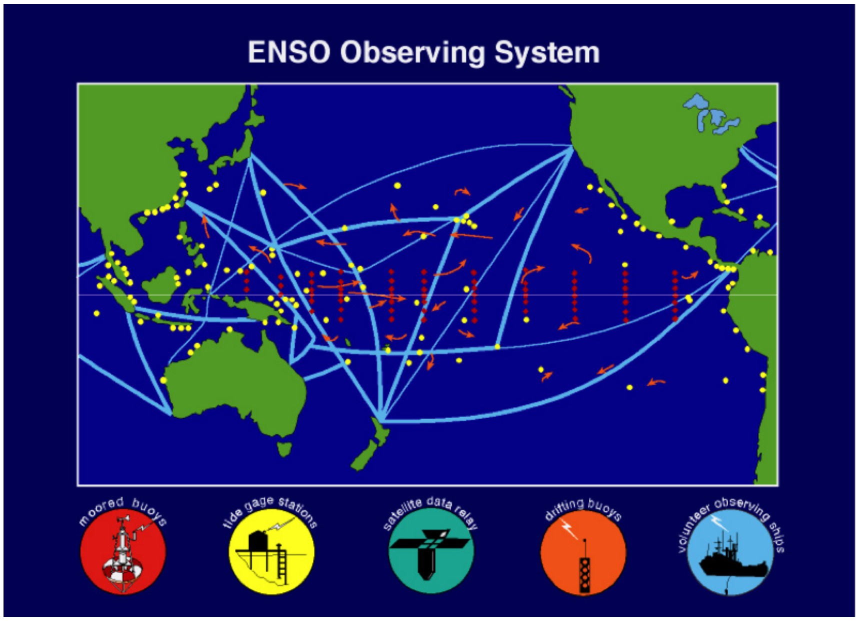

Figure 1: Oceanic component of ENSO observing system following the completion of the TOGA program in 1994. The location of the TAO/TRITON moored array is shown in red dots.

The completion of TOGA in 1994 and the associated ENSO observing system resulted in the availability of real-time data for monitoring and prediction of ENSO and revolutionized the understanding of ENSO dynamics. TOGA also concluded with the successful implementation of operational seasonal forecasts (Cane et al. 1986, Ji et al. 1994). Achievements of the TOGA program were summarized as a collection of papers in a special issue of *Journal of Geophysical Research – Oceans* (Anderson et al. 1998).

Advances in ENSO understanding and prediction continue to be made and largely rely on the availability of ongoing, in situ ocean observations - from what is known as the Tropical Pacific Observing System (TPOS) - and improvements in ocean data assimilation and coupled models. The physical basis of the success and acceptance of seasonal predictions stems from the way slow changes in ocean heat content - related to sub-surface ocean temperature and thermocline depth anomalies - precondition the system for warm and cold ENSO events to occur months and seasons later. At present, ENSO prediction is the mainstay of seasonal forecasts in many regions. Seasonal ENSO forecasts can be skillful at up to six to nine month lead times, although the skill is uneven and appears to depend on the decadal climate regime (Barnston et al. 2012). The continued success of seasonal forecast enterprises depends crucially on the sustained availability of ocean observations – temperature, surface winds, sea surface heights - in the tropical Pacific. These observations are used both for the real-time monitoring of the ENSO system and for constraining the state of the ocean in the ocean data assimilation system; the latter providing the estimate of the ocean conditions for initializing coupled ENSO forecast systems.

Over the years the implementation of TPOS, and in particular TAO/TRITON array, has made significant contributions to our understanding of ENSO processes and mechanisms. The coincident ocean and atmosphere observations provided by this array have improved our understanding of the coupled atmosphere-ocean ENSO phenomenon, in particular, the role of westerly wind bursts and ocean temperature gradients in the onset and persistence of El Niño and the role of equatorial Kelvin waves in setting the timescales of variability (also known as the delayed oscillator theory; Suarez and Schopf 1988). Observations have also confirmed that a build-up of excess heat along the Equator is a precondition to an ENSO event (Wyrtki 1975). ENSO research further suggested that the heat is discharged to higher latitudes during and after El Niño events, and the time between El Niños is determined by the time taken to recharge the equatorial heat content following a La Niña event, a paradigm that has come to be known as the recharge oscillator theory (Jin 1997).

Besides a large cache of documented improvement in ENSO understanding and its prediction skill on seasonal time scales, passing years have also exposed various limitations. It has now being realized that:

- There are facets of ENSO variability that are still not well understood or were not even recognized when the TPOS was originally designed;
- The current generation of coupled models and data assimilation systems still have considerable biases that not only influence the skill of seasonal predictions, but also restrict effective use of ocean observations; and
- The sustainability of the TAO/TRITON array in open oceans has also come under question. At the same time advances in ocean observation technologies, for example altimetry, satellite salinity, and global deployment of the Argo float array, have begun to provide additional sources of information.

Recognition of gaps in our knowledge of ENSO variability and predictions, and emergence of new ocean technologies, behoove us to revisit the strategy for observing the tropical Pacific Ocean and further provides a context for the future of the TPOS. Some of these aspects are discussed below.

Understanding the gaps and challenges

Despite the emergence of operational seasonal prediction systems, and skill in ENSO prediction that has been realized subsequent to TOGA, further improvements in skill of ENSO predictions have proved to be stubbornly slow (Kirtman and Pirani 2009). Present ENSO forecast models, despite their vast advances in complexity and approach, exhibit comparable predictive skills, which seem to have plateaued at moderate levels (Wang et al. 2010; Barnston et al. 2012; Xue et al. 2014). It remains to be seen whether these slow advances in prediction skill are due to inherent predictability limits of ENSO, inadequately-observed processes, or inadequacies and biases in the prediction systems.

Consistent with the recent plateau in ENSO prediction skill, we have seen a succession of surprises related to the characteristics of ENSO variability. After the year 2000, warm ENSO events tended to have largest amplitude in the central Pacific – the so called Central Pacific (CP) El Niño – that did not fit the previously accepted picture of eastern Pacific-focused El Niño events; this initiated a considerable discussion about the diversity of ENSO (Capotandi et al. 2015). Longer observations and coupled model simulations also highlighted considerable low-frequency variability in ENSO with some epochs having stronger or weaker, more or less frequent ENSO signals than others (Wittenberg 2009). It is not clear what aspects of the background conditions produce this spectrum of behavior, or indeed, whether these are quasi-random. Underlying much of the debate about the diversity of ENSO is continued uncertainty as to whether ENSO is a self-sustained, quasi-cyclic oscillation, with irregularity due to "weather noise" (or internal nonlinearities), or if El Niño is a damped event-like phenomenon that requires external forcing as an essential trigger.

Although modeling of the tropical Pacific and seasonal forecasting using coupled atmosphere-ocean models has improved since the end of the TOGA experiment, much remains to be done as models continue to be plagued by large biases. Model biases influence prediction skill of ENSO and use of observational data in multiple ways. For example, optimal and efficient use of observational data is lacking because in the presence of large model biases much of the “information content” of available observations is needed for correcting model biases, rather than describing/initializing variability.

Our continued quest (a) to understand the limits of ENSO predictability, (b) to describe the low-frequency variability in ENSO characteristics, and (c) to reduce model biases to improve utilization of observational data and improve skill of seasonal predictions, leads to questions about the underlying oceanic, atmospheric, and coupled processes of the system. This then naturally leads to the observational requirements of TPOS to provide an accurate depiction of physical processes that are judged to be responsible. Kessler et al. (2014) provides an exhaustive summary of possible physical processes and mechanisms that may play a crucial role in determining the characteristics of ENSO variability and model biases (due to their inadequate or missing representation). The processes include:

- Equatorial upwelling and role of rapid ocean-atmospheric interactions on small spatial scales in the eastern Pacific;
- Mechanisms by which subsurface ocean dynamics is manifested as surface SST variability;
- Atmospheric boundary layer processes;
- Large scale feedbacks (e.g., zonal, thermocline, Ekman feedback) and their role in determining and constraining ENSO variability;
- Diurnal cycle and penetration of surface fluxes into the ocean;
- Pathways for recharge and discharge to the subtropics; and
- Tropical instability waves.

Such processes, and related atmospheric process associated with clouds, deep convection, etc., will need observations beyond the tropical Pacific, such as in the global atmosphere, maritime continent, and adjacent ocean basins.

A path forward

Recognition of the evolution of ENSO-related observational requirements for TPOS - subsequent to TOGA - recently converged with challenges in maintaining the current state of TPOS that has relied heavily on the TAO array. After 2012, observations from TAO saw a steep decline (Figure 2), which was primarily related to the lack of ship time available to service moorings across the vast Pacific. The resulting reduction in oceanic observations in the tropical Pacific raised concerns whether the array can and/or should be maintained at its full complement of moorings designed and implemented as part of the TOGA. There is also recognition of other observational technologies (e.g., Argo and satellites), which can complement oceanic observations from TAO moorings.

A confluence of several of these separate factors initiated a desire to reevaluate the requirements and appropriate system design for the future of TPOS, principally, but not exclusively, in the context of ENSO monitoring and prediction. Following this recognition, the National Oceanic and Atmospheric Administration (NOAA) and JAMSTEC organized a review of TPOS, with the purpose to revisit the research and operational requirements for tropical Pacific observations and to consider how the sustainable observing system could evolve most usefully. A TPOS workshop was held January 27-30, 2014, at the Scripps Institution of Oceanography (report available online). The workshop had 65 invitees from 13 countries and 35 institutes. The outcome of the workshop recognized the requirement of observations for ENSO research, modeling, and forecasting, and proposed to establish a TPOS project (TPOS 2020). It was proposed that the TPOS 2020 project will oversee the transition of the current TPOS to a more resilient and integrated observing system to meet the identified gaps as well as future needs to improve skill of ENSO predictions. The TPOS 2020 project has the following scientific objectives:

- To redesign and refine TPOS to observe ENSO and advance scientific understanding of its causes;
- To determine the most efficient and effective observational solutions to support prediction systems for ocean, weather, and climate services; and
- To advance understanding of tropical Pacific physical and biogeochemical variability and predictability.

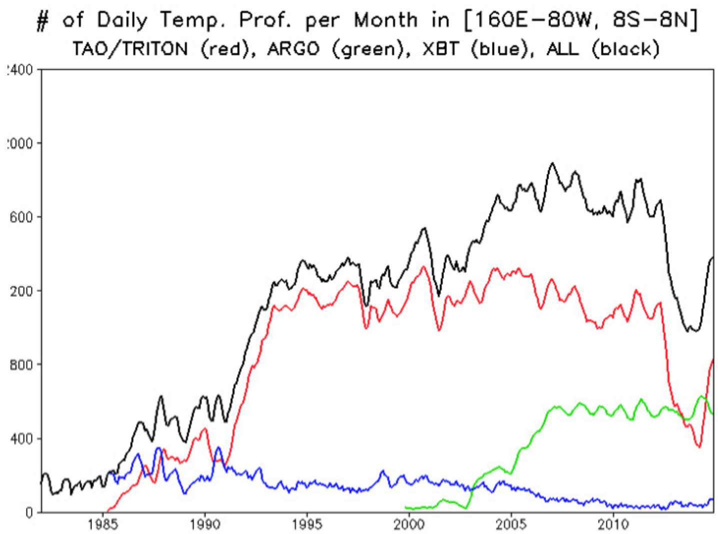

Figure 2. Time evolution of number of temperature profiles per month in the equatorial Pacific from 1980 to 2014. Different lines correspond to different observing systems: XBT (blue line); TAO/TRITON (red line); Argo (green line); and total (black line). Figure courtesy of Yan Xue and David Behringer, NOAA Climate Prediction Center.

TPOS 2020 aims to achieve a significant change in all elements that contribute to TPOS, including greater and continued efficiency, greater effectiveness, enhanced robustness and sustainability, and improved governance, coordination, and supporting arrangements. As we look to the next decade and beyond, the future TPOS should be a robust observing system that is ready to detect and diagnose surprises related to ENSO variability, and support and enable measurements that are key to understanding physical process. Further, the future TPOS should provide observations enabling us to advance understanding of ENSO variability and predictability on various time scales and reduce model biases.

References

Anderson, D. L. T., E. S. Sarachik, P. J. Webster, and L. M. Rothstein, Eds., 1998: The TOGA Decade: Reviewing the progress of El Niño research and prediction. *J. Geophys. Res. Oceans*, **103**, 14,167-14,510, http://onlinelibrary.wiley.com/10.1002/%28ISSN%292156-2202c/specialsection/TOGA1.

Barnston, A. G., M. K. Tippett, M. L. L'Heureux, S. Li, and David G. DeWitt, 2012: Skill of real-time seasonal ENSO model predictions during 2002–11: Is our capability increasing? *Bull. Amer. Meteor. Soc.*, **93**, 631–651, doi:10.1175/BAMS-D-11-00111.1.

Cane, M. A., S. E. Zebiak, and S. C. Dolan, 1986: Experimental forecasts of El Niño. *Nature*, **321**, 827-832, doi:10.1038/321827a0.

Capotondi, A., A. T. Wittenberg, M. Newman, E. Di Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B. Dewitte, B. Ciese, E. Guilyardi, F.F. Jim, K. Karnauskas, B. Kirtman, T. Lee, N. Schneider, Y. Xue, and S.-W. Yeh, 2015: Understanding ENSO diversity. *Bull. Amer. Meteor. Soc.,* in press, doi:10.1175/BAMS-D-13-00117.1.

Horel, J. D., and J. M. Wallace, 1981: Planetary-scale atmospheric phenomenon associated with the southern oscillation. *Mon. Wea. Rev.*, **109**, 2080-2092, doi:10.1175/1520-0493(1981)109<0813:PSAPAW>2.0.CO;2.

Ji, M., A. Kumar, and A. Leetmaa, 1994: A multiseason climate forecast system at the National Meteorological Center. *Bull. Amer. Meteor. Soc.*, **75**, 569-577.

Jin, F.-F., 1997: An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. *J. Atmos. Sci.*, **54**, 811-829, doi:10.1175/1520-0469(1997)054<0811:AEORPF>2.0.CO;2.

Kessler, W. S., T. Lee, M. Collins, E. Guilyardi, D. Chen, A. T. Wittenberg, G. Vecchi, W G. Large, and D. Anderson, 2014: ENSO research: The overarching science drivers and requirements for observations. Tropical Pacific Observing System White Paper #3, http://tpos2020.org/wp-content/uploads/WP03_ENSO_research_Final.pdf

Kirtman, B. and A. Pirani, 2009: The state of the art of seasonal prediction: Outcomes and recommendations from the first World Climate Research Program workshop on seasonal prediction. *Bull. Amer. Meteor. Soc.*, **90**, 455–458, doi:10.1175/2008BAMS2707.1.

Suarez, M. J., and P. S. Schopf, 1988: A delayed action oscillator for ENSO. *J. Atmos. Sci.,* **45,** 3283-3287, doi:10.1175/1520-0469(1988)045<3283:ADAOFE>2.0.CO;2.

Trenberth, E. K., G. W. Branstrator, D. Karoly, A. Kumar, N.-C. Lau, and C. Ropelewski, 1998: Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *J. Geophys. Res. Oceans*, **107**, C7, 14291-14324, doi:10.1029/97JC01444.

Wang, W., M. Chen, and A. Kumar, 2010: An assessment of the CFS real-time seasonal forecasts. *Weather and Forecasting*, **25**, 950-969.

Wittenberg, A. T., 2009: Are historical records sufficient to constrain ENSO simulations? *Geophys. Res. Lett.*, **36**, L12702, doi:10.1029/2009GL038710.

Wyrtki, K., 1975: El Niño-the dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *J. Phys. Oceanogr.*, **5**, 572-584, doi:10.1175/1520-0485(1975)005<0572:ENTDRO>2.0.CO;2.

Xue. Y., M. Chen, A. Kumar, Z.-Z. Hu, and W. Wang, 2013: Prediction skill and bias of tropical Pacific sea surface temperature in the NCEP Climate Forecast System Version 2 *J. Climate*, **26**, 5358-5378, doi:10.1175/JCLI-D-12-00600.1.

Upcoming Meetings

ENSO Extremes and Diversity: Dynamics, Teleconnection, and Impacts Workshop | Sydney, Australia	February 4-6, 2015
Third International Symposium: Effects of Climate Change on World's Oceans | Santos City, Brazil	March 24-27, 2015
EGU General Assembly 2015 | Vienna, Austria	April 12-17, 2015
California Drought: Causes, Impacts, and Policy | Irvine, California	April 20-22, 2015
7th International Symposium on Gas Transfer at Water Surfaces | Seattle, Washington	May 18-21, 2015
The Width of the Tropics: Climate Variations and Their Impacts | Santa Fe, New Mexico	July 26-31, 2015

Click to view the full calendar of events

Ocean data assimilation for ENSO prediction

Anthony Rosati[1], Oscar Alves[2], Magdalena Balmaseda[3], Xiaosong Yang[1], and Yan Xue[4]

[1]NOAA Geophysical Fluid Dynamics Laboratory

[2]Bureau of Meteorology, Australia

[3]European Center for Medium-Range Weather Forecasts, United Kingdom

[4]NOAA Climate Prediction Center

Operational ocean reanalyses (ORAs) are now routinely used at national climate centers for El Niño–Southern Oscillation (ENSO) monitoring and prediction efforts. Since seasonal forecasts became operational, their skill has been slowly but steadily increasing. The improvement in skill is equally attributed to better initialization of the ocean and atmosphere as well as improved coupled models (Stockdale et al. 2011). Improved initialization is due to the advances in data assimilation schemes, improvements in ocean models, increased model resolutions, and dramatic improvements in the global ocean observing system (Behringer and Xue 2004; Zhang et al. 2007; Balmaseda and Anderson 2009; Yin et al. 2011; Fujii et al. 2015b).

Ocean data assimilation (ODA) systems are an essential component of seasonal-interannual prediction systems, both for the coupled forecast model and the ORAs. Of particular value for the forecasts is state estimation of the tropical Pacific by the ODA, since the predictability of seasonal-interannual forecasts is realized primarily from ENSO. Operational centers use ODA for monitoring equatorial wave activity, warm water volume, equatorial thermocline variability, salinity variability, and other important aspects of ENSO development.

Impact of tropical Pacific observing systems

The quality of the ocean state estimation or initialization is only as good as the components that make up the analysis. The delicate amalgamation of three components is dependent on each of the component's credibility. The observations must have the spatial and temporal resolution, as well as accuracy, to capture the modes of ENSO variability. The model must be of a resolution and minimum bias to simulate ENSO (Jin et al. 2008). The method of data assimilation may be the least important, especially in the extremes of data rich and data poor regions. Formally, data assimilation should not have correlated errors, and yet one of main functions of data assimilation is correcting model systematic errors.

Following Xue et al. (2012) the ensemble spread of monthly heat content (HC) in the upper 300 m from ten ocean reanalyses is used to show the roles of ocean observing systems on reducing uncertainties among ocean reanalyses. To see how observations influence the spatial distribution of uncertainties (spread) in the HC300, Figure 1 shows the ensemble spread of HC300 analyses and the corresponding data counts, during the period (a) prior to the full Tropical Atmosphere-Ocean (TAO) array (1980 to 1993), (b) prior to Argo (1994 to 2003), and (c) following the full deployment of TAO and Argo (2004 to 2009). Since the topic here is ENSO, only the tropical Pacific is considered. There is a clear reduction in the

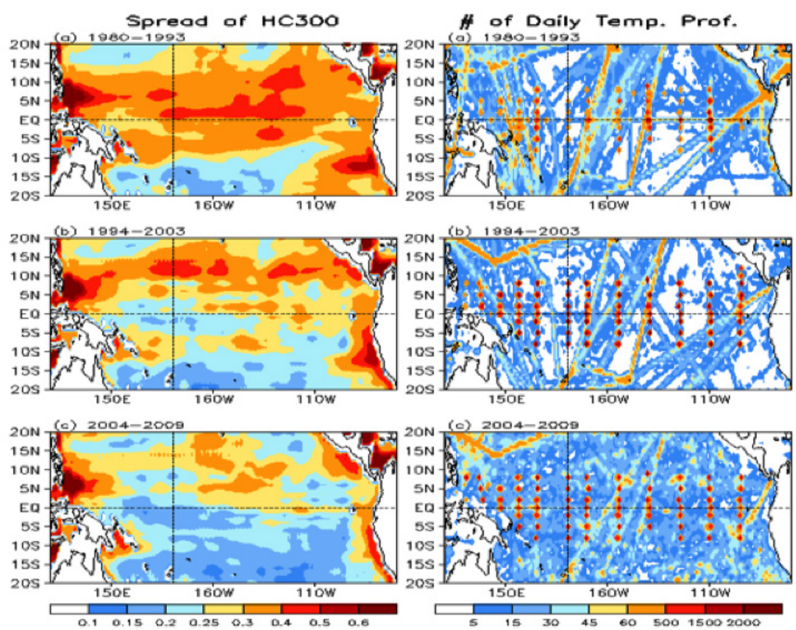

Figure 1. The spread of the analyses of upper 300 m average temperature HC300 (OC) among 10 ocean reanalyses (a) from 1980 to 1993, (b) from 1994 to 2003, and (c) from 2004 to 2009 (left). Number of daily temperature profiles corresponding to each of the three periods (right). Adapted from Xue et al. (2012).

ensemble spread from (a) to (b) and from (b) to (c), corresponding to the increase in data counts. The introduction of TAO in the early 1990s and Argo in the early 2000s significantly increases convergence among the ten analyses, with the Intertropical Convergence Zone (ITCZ) region having the largest spread in all three data periods.

Recent years saw a rapid decline of the TAO/Triangle trans-Ocean buoy Network (TRITON) array, and the data return rate decreased to 40% of its target value in 2013. The National Oceanic and Atmospheric Administration (NOAA) and Japan Agency for Marine-Earth Science and Technology (JAMSTEC) requested a review of the tropical Pacific observing system (TPOS) to revisit the scientific and forecast requirements for the TPOS and to consider how the sustainable observing system could evolve. It was recommended to establish a TPOS 2020 project that would oversee the transition to a more resilient and integrated observing system to meet the identified gaps as well as future needs (see article by Kessler et al., this issue, for more information). Of particular relevance for this article are two white papers and their references that stemmed from the TPOS 2020 workshop held in January 2014; one on operational forecasting systems (Balmaseda et al., 2014) and the other on the current status and achievements of ODA systems and their requirements for TPOS (Fujii et al. 2015a).

A project motivated by the TPOS 2020 workshop is the Real Time Ocean Reanalysis Intercomparison Project (RTORA-IP), which can be viewed as a real-time extension of the Ocean Reanalyses Intercomparison Project (ORA-IP) sponsored by the Global Synthesis and Observations Panel (GSOP) and the Global Ocean Data Assimilation Experiment (GODAE) Ocean View (Balmaseda et al. 2015). A pilot website has been developed by the NOAA Climate Prediction Center.

Considering there was a substantial data decline from the TAO/TRITON array since summer 2012, it is critical to know how much of the data loss has impacted the quality of ocean reanalyses that are routinely produced at operational centers around the world. The tropical Pacific subsurface temperature analysis has been routinely used in monitoring the thermal structure of ENSO in support of official ENSO predictions at operational centers. When there is a large data gap in the TAO/TRITON array, subsurface temperature analyses from various ocean data assimilation systems likely diverge, and the spread of ocean reanalyses may be as large as the signal. The goal of RTORA-IP is to monitor the spread of subsurface temperature analyses - particularly along the equatorial belt - with an aim for ENSO monitoring and to provide this information in real time, so that forecasters can have an informed knowledge of the quality of ocean reanalyses. Figure 2 is an example of one of the routine figures published monthly on the RTORA-IP website. What is shown is ensemble mean anomalous temperature along the equator from six routinely produced ocean analyses along with the ensemble spread and signal to noise ratio (S/N) contrasting two time periods. When S/N is larger than 1, the signal is larger than the noise and more confidence can be placed in the ensemble mean as an estimate of the climate signal. The left panel is from September 2013, during the period when the TAO array exhibited a precipitous decline in the number of daily temperature profiles. The right panel is from a recent month, December 2014, when the TAO array returned to its target value. The S/N ratio in the right panel shows that the signal is large in the upper 100 m, indicating good agreement among the ORAs, largely due to the assimilation of the TAO array. Whereas in the left panel noise dominates the central and eastern basin, showing the large spread among the ORAs due to the ocean models being less constrained by the TAO data.

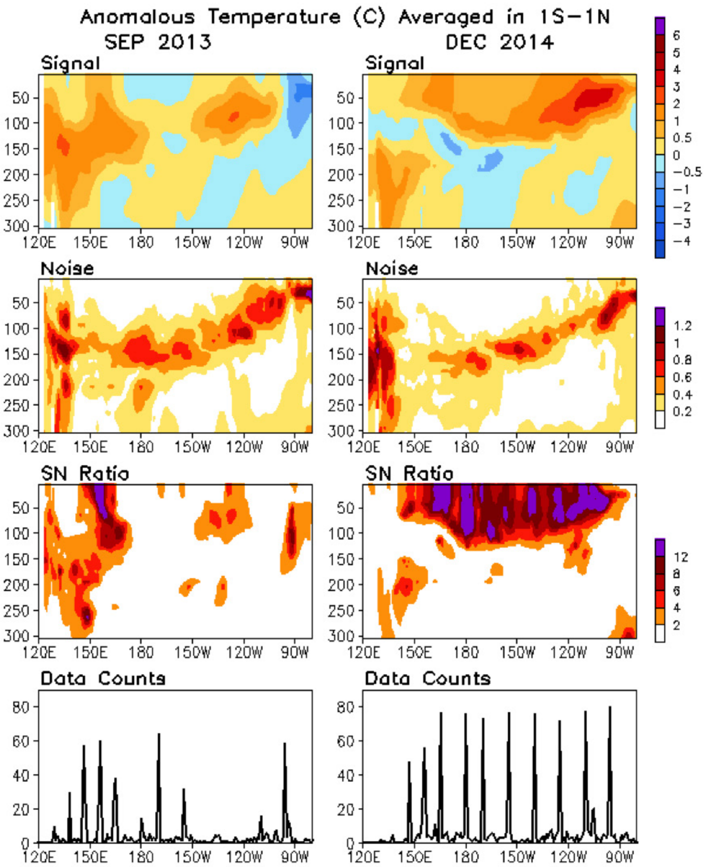

Figure 2. Longitude by depth (m) sections of anomalous temperature (°C) averaged for 1°N-1°S for the ensemble mean, spread, and signal to noise ratio for six ocean analyses for September 2013 (left) and December 2014 (right). The data counts (bottom) are the number of temperature profiles in 3°S-3°N by longitude. Based on analyses from the NOAA CPC's Real Time Ocean Reanalysis Intercomparison Project.

Coupled modal data assimilation

Coupled model data assimilation (CDA) is an emerging field among many operational and research centers, with the expectation that it will improve forecasts at various time ranges (from medium range out to seasonal and decadal). Phenomena that involve a direct interaction between the ocean and atmosphere, such as ENSO, Madden-Julian Oscillation, and tropical cyclones will most obviously benefit. Oceanic phenomena such as the Meridional Overturning Circulation, western boundary currents, tropical instability waves, and eddy dynamics will also benefit. ENSO is an example of strongly coupled ocean-atmosphere modes at longer time scales, suggesting that the strength of the correlation between errors in the prior ocean forecast and the prior atmospheric forecast are strongly flow-dependent. Therefore, when the ocean analysis and atmosphere analysis are not calculated simultaneously, as they would be in CDA, and are used as initial conditions for the coupled model, there is an inconsistency that may lead to "initialization shock" that can lead to degradation in the forecast skill. One of the most challenging aspects of CDA is the formulation of the error covariance between the variables that interact between the ocean and atmosphere. Balanced relationships are needed between variations in the upper ocean and in the atmospheric boundary layer. These can be obtained from model integrations, but verification data are also needed. Ultimately the extent to which "initialization shock" is an issue will depend on the properties of an individual system and will need further investigation.

Observations of the air-sea interface are crucial to better understand the important coupled processes that should be represented in the CDA systems. Observations in the boundary layers of both the atmosphere and ocean can help to constrain these coupled processes. Fujii et al. (2009) demonstrate that distribution and variability of precipitation in the tropics are improved in their weakly CDA run, in which ocean observation data alone is assimilated into a coupled model, compared to an atmosphere model intercomparison project (AMIP) run (i.e., a free simulation of the atmospheric model using the observed sea surface temperature (SST) as boundary forcings). They find that the negative feedback between the change of SST and atmospheric convective activity is not properly represented in the AMIP run due to the prescribed SST, but it is recovered in the CDA run. They also show that the negative feedback improves the precipitation fields and atmospheric circulations.

A noteworthy international workshop held in September 2012 at the University of Reading, consisted of scientific presentations reviewing the current status of the science of coupled data assimilation and the current research and development plans at the different centers represented. Three working groups, formed at the workshop, were each asked to discuss, in detail, a specific scientific aspect of the coupled data assimilation problem, with the aim of producing a set of recommendations for future research. The following topics were allocated to the working groups:

- Working Group 1: Dealing with different time and space scales
- Working Group 2: Better use of near-surface observations
- Working Group3: Model errors and biases

A comprehensive summary report from the working groups, and the presentations and references, may be found on the website.

An example from the workshop of an operational, weakly coupled assimilation system is PECDAS (Predictive Ocean Atmosphere Model for Australia (POAMA) Ensemble Coupled Data Assimilation System). PECDAS has been developed at the Australian Bureau of Meteorology for seasonal prediction applications and is based on the pseudo-ensemble Kalman filter for ocean assimilation called PEODAS (POAMA Ensemble Ocean Data Assimilation System; Yin et al. 2011). PECDAS is an approximate form of the ensemble Kalman filter, based on a multivariate ensemble optimum interpolation system of Oke et al. (2005), but uses covariances from a time evolving model ensemble. Only temperature and salinity ocean observations are assimilated into PECDAS once per day. At the same time the atmospheric prognostic variables are nudged towards the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA)-interim dataset. SST is also relaxed to an observed analysis with

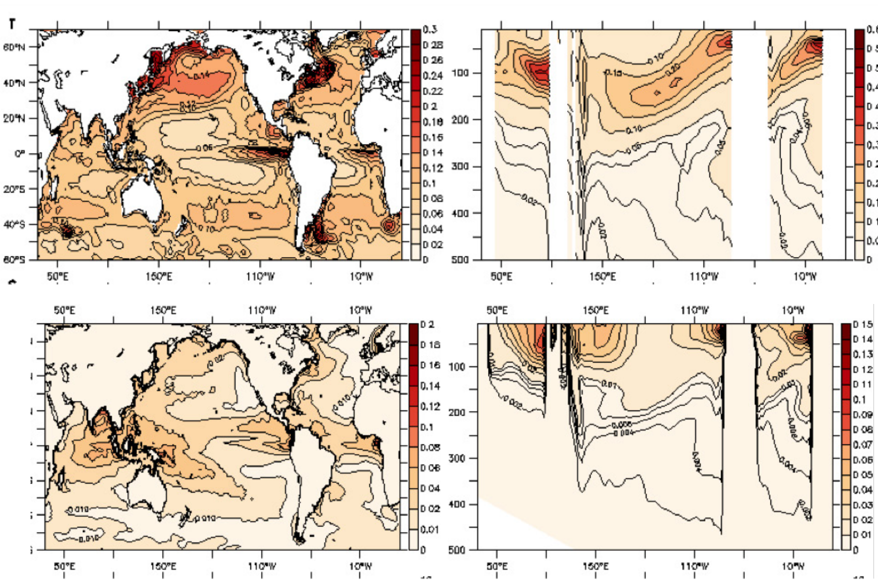

Figure 3. (top) Ensemble spread in temperature (°C) simulations by PECDAS at the surface (left) and in the vertical along the equator (m; right), averaged over the period 1980-2006. (bottom) Same as (top) but for salinity (PSU).

a one-day relaxation timescale. PECDAS provides an ensemble of coupled states that are used to perturb coupled forecasts.

The spread in temperature in the PECDAS ensemble is shown in Figure 3 (top; previous page) as an average over the whole reanalysis period. Spread in SST is concentrated in areas of strong SST variability, such as the eastern Pacific, eastern Atlantic, and western boundary currents. Along the equator the largest spread is along the equatorial thermocline, where vertical gradients in temperature are largest and where variability is strongly driven by surface wind variability. The spread in salinity in the PECDAS ensemble is shown in Figure 3 (bottom) as an average over the whole reanalysis period. The spread in sea surface salinity is largest in areas of strong rainfall in the tropics, particularly in the western Pacific, the ITCZ, and the South Pacific convergence zone. Along the equator, maximum spread is at the surface, again mainly because it is being driven by rainfall variability. The weak coupled assimilation approach adopted in PECDAS has been used to initialize coupled model forecasts. The performance of the forecasts is similar to those using uncoupled assimilation.

Summary

Here we showed a brief assessment of ODA for ENSO prediction by emphasizing two components. The first was the important role of the tropical observing system on the quality of the analysis used for initializing the prediction system. The TPOS 2020 project along with its workshop was introduced as the path forward for a sustained TPOS to support prediction systems. The second component was the recent focus on the development of coupled model data assimilation, which holds the promise of improving forecasts by having balanced relationships between the ocean and atmosphere.

References

Balmaseda, M., and Anderson, D., 2009: Impact of initialization strategies and observations on seasonal forecast skill. *Geophys. Res. Lett*., **36**, L01701, doi:10.1029/2008GL035561.

Balmaseda, M., F. Hernandez, A. Storto, M. Palmer, L. Shi, G. Smith, T. Toyoda, M. Valdivieso, O. Alves, B. Barnier, T. Boyer, Y.-S. Chang, G. A. Chepurin, N. Ferry, G. Forget, Y. Fujii, S. Good, S. Guinehut, K. Haines, Y. Ishikawa, S. Keeley, A. Köhl, T. Lee , M. Martin, S. Masina, S. Masuda, B. Meyssignac, K. Mogensen, L. Parent, D. Peterson, Y. Yin, G. Vernieres, X. Wang, J. Waters, R. Wedd, O. Wang, Y. Xue, M. Chevallier, J-F. Lemieux, F. Dupont, T. Kuragano, M. Kamachi, T. Awaji, A. Cantalbiano, K. Wilmer-Becker, and F. Gaillard, 2015 The Ocean Reanalyses Intercomparison Project (ORA-IP). *J. Oper. Oceanogr.,* submitted.

Behringer, D., and Xue, Y., 2004: Evaluation of the global ocean data assimilation system at NCEP: The Pacific Ocean. *Eighth Symposium on Integrated Observing and Assimilation System for Atmosphere, Ocean, and Land Surface*, Seattle, WA, Amer. Meteor. Soc. 2.3. Available online at: https://ams.confex.com/ams/84Annual/webprogram/Paper70720.html.

Fujii, Y., Nakaegawa, T., Matsumoto, S., Yasuda, T., Yamanaka, G., and M. Kamachi 2009: Coupled climate simulation by constraining ocean fields in a coupled model with ocean data. *J. Climate*, **22**, 5541-5557, doi:10.1175/2009JCLI2814.1.

Fujii. Y., J. Cummings, Y. Xue, A. Schiller, T. Lee, M. A. Balmaseda, E. Remy, S. Masuda, G. Brassington, O. Alves, B. Cornuelle, M. Martin, P. Oke, G. Smith, and X. Yang, 2015a: Evaluation of tropical Pacific observing system from the ocean data assimilation perspective. *Quart. J. Roy. Meteor. Soc.,* submitted.

Fujii, Y., Ogamwa, K., Ando, K., Yasuda, T., and Kuragano, T., 2015b: Evaluating the impacts of the tropical Pacific observing system on the ocean analysis fields in the global ocean data assimilation system for operational seasonal forecasts in JMA. *J. Oper. Oceanogr*., submitted.

Jin, E. K., J. L. Kinter, B. Wang, C.-K. Park, I.-S. Kang, B. P. Kirtman, J.-S. Kug, A. Kumar, J.-J. Luo, J. Schemm, J. Shukla, and T. Yamagata, 2008: Current status of ENSO prediction skill in coupled ocean-atmosphere models. *Climate Dyn*., **31**, 647–664, doi:10.1007/s00382-008-0397-3.

Oke, P. R., G. B. Brassington, D. A. Griffin, and A. Schiller, 2008: The Bluelink ocean data assimilation system (BODAS). *J. Ocean Model.,* **20**, 46-70, doi:10.1016/j.ocemod.2007.11.002.

Stockdale, T. N., D. Anderson, M. Balmaseda, F. Doblas-Reyes, L. Ferranti, K. Mogensen, F. Molteni, and F. Vitart, 2011: ECMWF Seasonal Forecast System 3 and its prediction of sea surface temperature. *Climate Dyn*., **37**, 455–471, doi:10.1007/s00382-010-0947-3.

Yin, Y., O. Alves, and P. Oke, 2011: An Ensemble Ocean Data Assimilation System for Seasonal Prediction. *Mon. Wea. Rev*., **139**, 786-808, doi:10.1175/2010MWR3419.1.

Zhang, S., M. J. Harrison, A. Rosati, and A. Wittenberg, 2007: System design and evaluation of coupled ensemble data assimilation for global oceanic climate studies. *Mon. Wea. Rev.*,**135**, 3541-3564, doi:10.1175/MWR3466.1.

Xue, Y., M. A. Balmaseda, T. Boyer, N. Ferry, S. Good, I. Ishikawa, A. Kumar, M. Rienecker, T. Rosati, and Y. Yin, 2012: A comparative analysis of upper ocean heat content variability from an ensemble of operational ocean reanalyses, *J. Climate*, **25**, 6905-6929, doi:10.1175/JCLI-D-11-00542.1.

Current status of ENSO prediction and predictability

Ben Kirtman

University of Miami

The largest source of seasonal-to-interannual predictability is the so-called El Niño phenomenon, which is due to coupled ocean-atmosphere interactions in the tropical Pacific. El Niño grows through positive feedbacks between sea surface temperature (SST) and winds – a weakening of the easterly trade winds produces a positive SST anomaly in the eastern tropical Pacific which in turn alters the atmospheric zonal (Walker) circulation to further reduce the easterly winds and then produces even stronger SST anomalies. El Niño influences seasonal climate almost everywhere, either by directly altering the tropical Walker circulation, or through teleconnections associated with Rossby wave trains that propagate information to remote regions, substantially modifying local weather patterns. The time between El Niño events is typically about two to seven years, but the mechanisms controlling the initiation or onset, the strength, the duration, the spatial structural details, or the reversal to the La Niña phase are not completely understood.

Current ENSO prediction capabilities

The ability to predict seasonal variations of tropical climate developed in the late 1980s. This development was primarily due to enhanced observing systems in the tropical Pacific (NOAA Tropical Atmosphere Ocean, TAO, array of tethered buoys; providing essential observations of the ocean's sub-surface behavior), the advancement of a theoretical understanding of the coupled air-sea interactions that lead to El Niño predictability and its remote teleconnections, and a steady improvement in our modeling systems. This improvement led to considerable optimism regarding our ability to predict seasonal climate variations in general and El Niño/Southern Oscillation (ENSO) events in particular. Indeed, seasonal prediction is now routine at many operational meteorological services around the globe, and there is considerable demand for seasonal prediction information for risk assessment and decision support.

More recently, the production of routine ENSO predictions, continued predictability research, and the use of predictions for decision support have lead to the recognition that the inclusion of quantitative information regarding uncertainty (i.e., probabilistic prediction) in the forecasts and probabilistic measures of forecast quality in the verifications are essential (e.g., Palmer et al. 2000; Goddard et al. 2001; Kirtman 2003; Palmer et al. 2004; DeWitt 2005; Hagedorn et al. 2005; Doblas-Reyes et al. 2005; Saha et al. 2006). One approach that is ad-hoc, but still resolves substantial forecast uncertainty, is the use of multiple prediction systems (Palmer et al. 2004; Hagedorn et al. 2005; Doblas-Reyes 2005; Palmer et al. 2008; Kirtman et al. 2014). Other techniques such as perturbed physics ensembles (currently in use at the UK Met Office for their operational system) or stochastic physics (e.g., Berner et al. 2008) have also been developed.

The need to account for model uncertainty in seasonal prediction is the core motivation of the newly developed North American Multi-Model Ensemble (NMME; website) experiment. One of the most important aspects of the NMME experiment is to document how model diversity affects forecast quality. Essentially, we ask where and when does the NMME improve the forecast quality compared to CFSv2, which is the NCEP operational dynamic model. To address the issue of model diversity versus ensemble size, we present one brief calculation here. Note that this is a non-exhaustive presentation of the NMME results and simply highlights the utility of the multi-model approach in improving seasonal prediction skill scores. The calculation uses the "Sign Test" applied to the mean squared error (MSE) that shows regions where the full NMME significantly outperforms CFSv2 (DelSole and Tippet 2014). The basis for the approach is simple: if two forecasts have equal skill, then one forecast is just as likely to beat the other and vice-versa. More formally, the null hypothesis is that NMME will outperform CFSv2 with 50% probability, which can be tested for statistical significance. The results of this sign test are summarized in Figure 1 (next page), which shows results for July starts verifying in DJF (December-January-February) for global sea surface temperature anomalies (SSTA), North American 2-m temperature (T2m), and North American precipitation. In terms of SSTA, particularly in the tropics, the NMME significantly reduces the MSE. This is also true for North American rainfall forecasts, but CFSv2 in terms of T2m is hard to beat. This North American T2m result also holds when simply considering correlation metrics.

The practical utility of the multi-model approach is readily apparent when considering the most recent SST evolution in the tropical Pacific. For example, in spring and early summer of

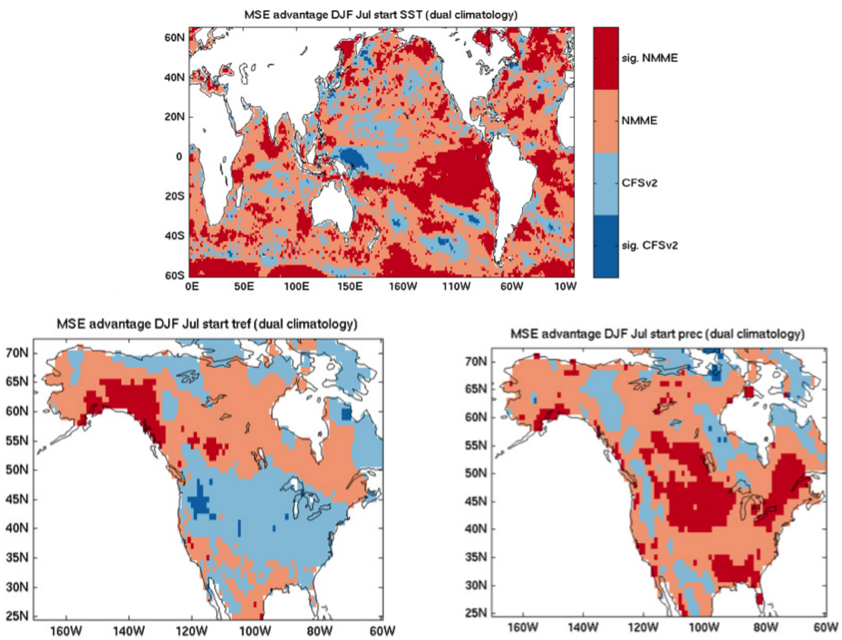

Figure 1: Sign Test applied to the difference between the squared error of NMME and CFSv2 hindcasts for (top) SSTA, (bottom left) T2m, and (bottom right) precipitation. Dark blue shading represents regions where CFSv2 has significantly lower squared error than NMME. Light blue shading represents regions where CFSv2 has lower squared error, but not significantly. Pink shading indicates regions where CFSv2 has higher squared error than NMME, but not significantly. Red shading indicates regions where CFSv2 has significantly higher squared error than NMME. All panel show results for forecasts initialized in July verifying in the following DJF.

2014 media reports were calling for a rather large El Niño, and in fact the April 2014 NMME ensemble predicted just shy of a 50% chance that December 2014 Niño3.4 SST anomalies would exceed two standard deviations (see Figure 2, bottom, next page). However, a more detailed examination of the forecast plume indicates that there were significant probabilities predicted for much more modest anomalies (Figure 2, top left), which where born out in later forecasts, the most recent forecast (Figure 2, top right), and the actual evolution. This experience exemplifies how probabilistic forecasts provide so much more information than a single deterministic forecast.

Need for improved understanding – Impact of subseasonal variability

Despite the development and improvement noted above, basic questions regarding our ability to model the physical processes in the tropical Pacific remain open challenges in the forecast community. For instance, it is unclear how the Madden-Julian Oscillation (MJO), Westerly Wind Bursts (WWBs), intra-seasonal variability, or atmospheric weather noise influence the predictability of ENSO (e.g., Thompson and Battisti 2001; Kleeman et al. 2003; Flugel et al. 2004; Kirtman et al. 2005) or how to represent these processes in current models. It has been suggested that enhanced MJO and WWB activity was related to the rapid onset and the large amplitude of the 1997-98 event (e.g., Slingo et al. 1999; Vecchi and Harrison 2000; Eisenman et al. 2005). However, more research is needed to fully understand the scale interactions between ENSO and the MJO and the degree that MJO/WWB representation is needed in ENSO prediction models to better resolve the range of possibilities for the evolution of ENSO (Lengaigne et al. 2004; Wittenberg et al. 2006).

Lopez et al. (2012) introduced a semi-stochastic parameterization of WWBs and Lopez and Kirtman (2014) used this to examine the effect on ENSO predictability and prediction. To summarize Lopez and Kirtman (2014), WWBs significantly limit El Niño predictability in spring. However, this drop in predictability is even more notable when the prediction system fails to produce WWBs. The real prediction experiments mimic the predictability results such that there is a pronounced drop in skill during spring and that this drop is more dramatic when there are no WWBs in the prediction system. The overall implication is that part of the spring prediction barrier is due to the presence of WWBs in nature. So, the barrier is, at least in part, a fundamental property of the climate system, and prospects for predicting through this barrier are limited by how well WWBs are predicted.

There are other possible ENSO triggers. For example, although modeling and observational studies have highlighted a robust relationship between the Pacific Meridional Mode (PMM) and El Niño – namely that the PMM is often a precursor to El Niño events it remains unclear if this relationship has any real predictive use. Bridging the gap between theory and practical application is essential because the potential use of the PMM precursor, as a supplemental tool for ENSO prediction, has been implied but not yet implemented into a realistic forecast setting. In Larson and Kirtman (2014), a suite of sea surface temperature hindcasts are utilized from the NMME prediction experiment between 1982 and 2010. The goal is to first assess the NMME's ability to forecast the PMM precursor, and second, examine the relationship between PMM and ENSO within a forecast framework. In terms of model performance, results are optimistic in that not only is PMM variability captured well by the multi-model ensemble mean, but it also appears as a precursor to ENSO events in the NMME. In

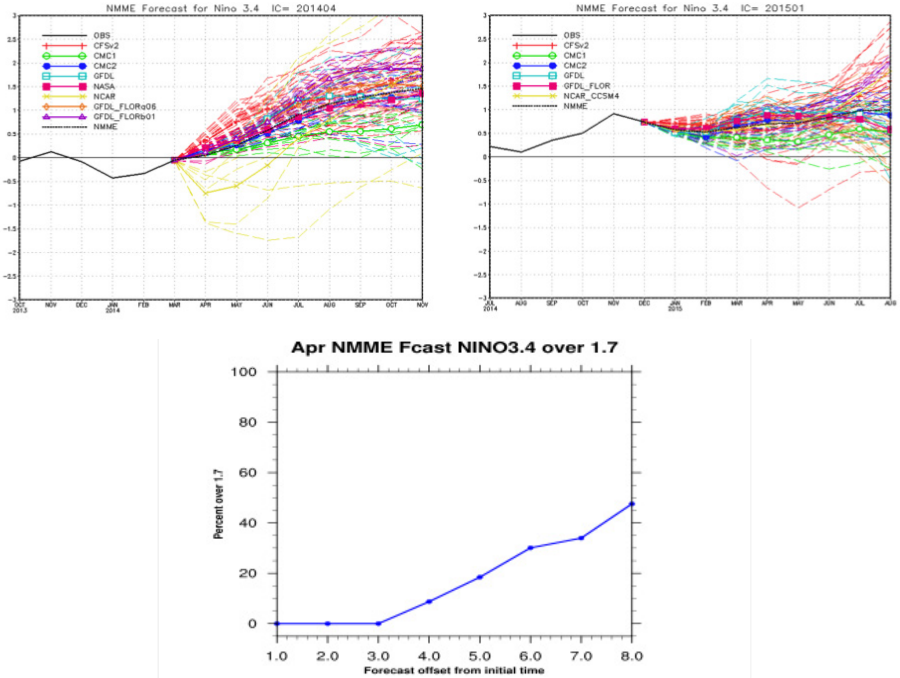

Figure 2: NMME Niño3.4 forecast plume (°C) for forecasts initialized in (top left) April 2014 and (top right) January 2015. (Bottom) Percentage of ensemble members in the April 2014 forecasts that exceed 1.7°C as a function of lead-time.

forecast mode, positive PMM events predict eastern Pacific El Niño events in both observations and model forecasts with some skill, yet with less skill for central Pacific El Niño events. Conversely, negative PMM events poorly predict La Niña events in observations, yet the model forecasts fail to capture this observed representation. There proves to be considerable opportunity for improvement of the PMM/ENSO relationship in the forecast models, and accordingly, the predictive use of PMM for certain types of ENSO events may also see improvement.

Need for improved understanding – Differences among El Niño events

The longitudinal position of the center of maximum SSTA associated with El Niño has significant variability from event to event, and even over the coarse of a single event. While there is an ongoing debate as to whether there is a fundamental difference in the physics leading to these variations, or whether this is simply a manifestation of noisiness in the climate system (Capotondi et al. 2015), capturing these differences is important because of the apparent effect on teleconnections (Kim et al. 2012). Kirtman et al. (2013) show that the NMME forecasts arguably capture some aspects of this diversity in the SSTA, but the predictions are lacking in much of the details of the structural diversity and produce relatively too much warming in the eastern Pacific. Capturing the rainfall anomalies and associated teleconnections, however, is potentially easier given the non-linear response of rainfall with SST. Infanti and Kirtman (2015) probe this possibility in the NMME forecast by looking how the structural differences and intensity in the tropical rainfall anomalies affect the uncertainty in North American teleconnections.

Lopez and Kirtman (2013) hypothesize that since WWBs are preferentially excited in the western Pacific, they can be connected to variability in the longitudinal position of the SSTA maximum. They investigate this possibility by analyzing the diversity of warm events, namely eastern Pacific (EP) and central Pacific (CP) warm events in simulations of CCSM3 and CCSM4 that include a state-dependent parameterization of WWBs. They find that parameterized WWBs tend to enhance EP variability more relatively to CP variability. This enhancement, in the case of state-dependent WWBs forcing, is due to an increase in the so-called thermocline feedback as opposed to the so-called zonal advective feedback. The model results suggest that there are three different ENSO regimes. Regime (i) is characterized by strong EP and weak CP warm events. Regime (ii) includes moderate EP and moderate CP warm events – this is referred to as basin-wide (BW) events. Regime (iii) includes those events with strong CP and relatively weak EP warm events. The inclusion of WWBs enhances the contrast among these regimes – again suggesting the importance of including at least the statistical effect of these wind events in prediction systems.

Need for model improvements

Chronic biases in the mean state of climate models and their intrinsic ENSO modes remain. It is suspected that these biases have a deleterious effect on El Niño/La Niña forecast quality and the associated teleconnections. Some of these errors are extremely well known throughout the coupled modeling community. Three classic examples, which are likely interdependent, are 1) the so-called double ITCZ problem, 2) the excessively strong equatorial cold tongue typical to most models, and 3) the sub-tropical eastern Pacific and Atlantic warm biases endemic to all models. Such biases may limit our ability to predict seasonal-to-interannual climate fluctuations, and could be indicative of errors in the model formulations. Resolution may be one cause of some of these errors (Luo et al 2005). Studies with models that employ higher resolution in both the atmosphere and ocean have demonstrated significant

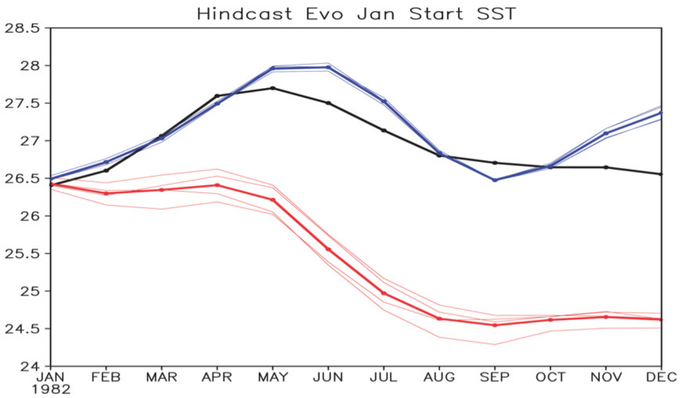

Figure 3: Niño3.4 systematic error for forecast initialized in January for CCSM3 (red) and CCSM4 (blue). The thin curves are the individual ensemble members and the thick curves are the ensemble mean. The black curve corresponds to observational estimates. Y-axis is sea surface temperature in Celsius.

improvements in the mean state of the tropical Pacific and the simulation of El Niño and its teleconnections (Shaffrey et al. 2009; Jia et al. 2014).

Despite the persistent problems noted above, there have been notable model improvements. For example, there has been a concerted effort to improve the ENSO simulation in the NCAR family of models (Neale et al. 2008). Figures 3 and 4 help examine how these improvements affect ENSO forecasts following the NMME protocol. The impact on the systematic forecast error is shown in Figure 3 where the improvement with CCSM4 is easily detected. The fact that the forecast skill is also improved is indicated in Figure 4, which shows the difference (CCSM4 minus CCSM3) in SSTA anomaly correlation measured by Fisher's r-to-z transform. Shading indicates transformed difference, and stippling indicates where correlations are significantly different at 0.05 level of significance. In most locations CCSM4 has larger correlations. The notable exception is the deep tropical Pacific where CCSM3 is larger, but this does not pass this particular significance test. For T2m (not shown) the correlation is generally larger for CCSM4, particularly over North America. In terms of the precipitation correlation (not shown), the results are noisy but generally positive with some notable regions where the CCSM4 has significantly larger correlation.

Clearly there has been substantial progress in improved understanding of ENSO predictability and prediction. However, it is also clear that there are many unanswered questions. For example, a complete understanding of what determines the amplitude, timing, and spatial structure of events remains elusive, and there is no consensus regarding the asymmetry between warm and cold events. Moreover, we do not fully understand the relative roles of ENSO triggers, atmospheric noise, or subsurface ocean preconditioning, which limits our ability to quantify the limit of predictability. In terms of prediction, model error remains a daunting challenge, and we have only scratched the surface in terms of developing initialization strategies that emphasize improving forecast quality.

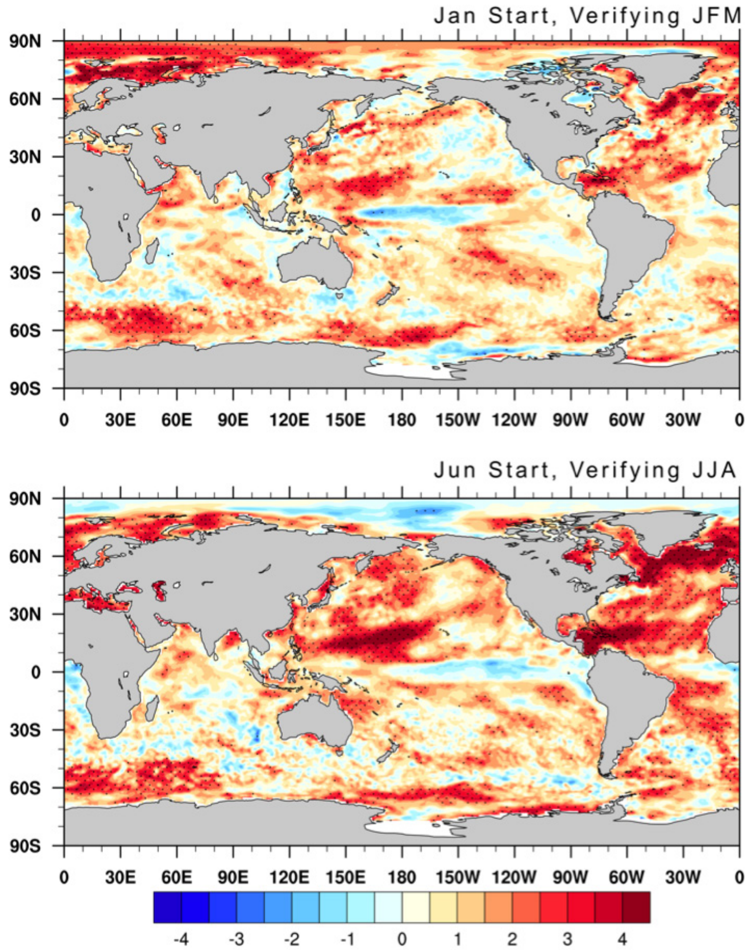

Figure 4: Difference in anomaly correlation for CCSM4 SSTA minus CCSM3 SSTA measured by Fishers r-to-z transform. Anomaly correlation is calculated versus observed SSTA where the forecasts are initialized during 1982-2010. Shading indicates transform difference; stippling indicates where correlations are significantly different at 0.05 level of significance. Red (blue) shading indicates CCSM4 anomaly correlation higher (lower) than CCSM3. January start hindcasts verifying in JFM, or a 1.5 season lead is shown in the top panel. June start hindcasts verifying in JJA (1.5 season lead) shown in the bottom panel.

References

Berner, J., F. J. Doblas-Reyes, T. N. Palmer, G. Shutts, and A. Weisheimer, 2008: Impact of a quasi-stochastic cellular automaton backscatter scheme on the systematic error and seasonal prediction skill of a global climate model. *Phil. Trans. R. Soc.* A, **366**, 2561–2579, doi:10.1098/rsta.2008.0033.

Capotondi, A., A. T. Wittenberg, M. Newman, E. Di Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B. Dewitte, B. Giese, E. Guilyardi, F.-F. Jin, K. Karnauskas, B. Kirtman, T. Lee, N. Schneider, Y. Xue, and S.-W. Yeh, 2015: Understanding ENSO diversity. *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-D-13-00117.1.

DelSole, T., and M. K. Tippett, 2014: Comparing forecast skill. *Mon. Wea. Rev.,* **142**, 4658-4678, doi:10.1175/MWR-D-14-00045.1.

DeWitt, D. G., 2005: Retrospective forecasts of interannual sea surface temperature anomalies from 1982 to present using a directly coupled atmosphere–ocean general circulation model. *Mon. Wea. Rev*., **133**, 2972-2995, doi:10.1175/MWR3016.1.

Doblas-Reyes, F. J., R. Hagedorn, and T. N. Palmer, 2005: The rationale behind the success of multi-model ensembles in seasonal forecasting - II. Calibration and combination. *Tellus A,* **57**, 234–252, doi:10.1111/j.1600-0870.2005.00104.

Eisenman, I., L. Yu, and E. Tziperman, 2005: Westerly wind bursts: ENSO's tail rather than the dog? *J. Climate,* **18,** 5224-5238, doi:10.1175/JCLI3588.1

Flugel, M., P. Chang, and C. Penland, 2004: The role of stochastic forcing in modulating ENSO predictability. *J. Climate,* **17,** 3125–3140, doi:10.1175/1520-0442(2004)017<3125:TROSFI>2.0.CO;2.

Goddard, L., S. J. Mason, S. E. Zebiak, C. F. Ropelewski, R. Basher, and M. A. Cane, 2001: Current approaches to seasonal-to-interannual climate predictions. *Int. J. Climatol.,* **21,** 1111–1152, doi:10.1002/joc.636.

Hagedorn, R. F., J. Doblas-Reyes, and T. N. Palmer, 2005: The rationale behind the success of multi-model ensembles in seasonal forecasting - I. Basic concept. *Tellus A*, **57**, 219–233, doi:10.1111/j.1600-0870.2005.00103.x.

Infanti, J. M., and B. P. Kirtman, 2015: Forecast uncertainty of the North American rainfall and temperature response to the diversity of ENSO. *Climate Dyn.,* submitted.

Jia, L., X. Yang, G. A. Vecchi, R. G. Gudgel, T. L. Delworth, A. Rosati, W. F. Stern, A. T. Wittenberg, L. Krishnamurthy, S. Zhang, R. Msadek, S. Kapnick, S. Underwood, F. Zeng, W. G. Anderson, V. Balaji, and K. Dixon, 2014: Improved seasonal prediction skill of land temperature and precipitation in a GFDL high-resolution climate model. *J. Climate,* doi:10.1175/JCLI-D-14-00112.1.

Kim, S. T., J.-Y. Yu, A. Kumar, and H. Wang, 2012: Examination of the two types of ENSO in the NCEP CFS model and its extratropical associations. *Mon. Weather Rev.*, **140,** 1908–1923, doi:10.1175/MWR-D-11-00300.1.

Kirtman, B. P., 2003: The COLA anomaly coupled model: Ensemble ENSO prediction. *Mon. Wea. Rev*., **131**, 2324-2341, doi:10.1175/1520-0493%282003%29131<2324%3ATCACME>2.0.CO%3B2.

Kirtman, B. P., K. Pegion, and S. Kinter, 2005: Internal atmospheric dynamics and climate variability. *J. Atmos. Sci.,* **62**, 2220-2233, doi:10.1175/JAS3449.1.

Kirtman, B. P., J. M. Infanti, and S. M. Larson, 2013: The diversity of El Niño in the North American multi-model prediction system. US CLIVAR Variations, 11-2, http://www.usclivar.org/sites/default/files/USCLIVAR_VARIATIONS_11_2_Summer2013.pdf.

Kirtman, B. P., D. Min, J. M. Infanti, J. L. Kinter, D. A. Paolino, Q. Zhang, H. van den Dool, S. Saha, M. P. Mendex, E. Becker, P. Peng, P. Tripp, J. Huang, D. G. DeWitt, M. K. Tipett, A. G. Barnston, S. Li, A. Rosati, S. Schubert, M. Rienecker, M. Suarex, A. E. Li, J. Marshak, Y.-K. Lim, J. Tribbia, K. Pegion, W. J. Merryfield, B. Denis, and E. R. Wood, 2014: The North American Multi-Model Ensemble (NMME): Phase-1 seasonal-to-interannual prediction, Phase-2 toward developing intra-seasonal prediction. *Bull. Amer. Meteor. Soc*., **95,** 585-601, doi:10.1175/BAMS-D-12-00050.1.

Kleeman, R., Y. Tang, and A. M. Moore, 2003: The calculation of climatically relevant singular vectors in the presence of weather noise as applied to the ENSO problem. *J. Atmos. Sci.*, **60**, 2856–2868, doi:10.1175/1520-0469(2003)060<2856:TCOCRS>2.0.CO;2.

Larson, S. M., and B. P. Kirtman, 2014: The Pacific Meridional Mode as an ENSO precursor and predictor in the North American Multi-Model Ensemble. *J. Climate* **27,** 7018-7032, doi:10.1175/JCLI-D-14-00055.1.

Lengaigne, M. E., E. Guilyardi, J-P. Boulanger, C. Menkes, P. M. Inness, P. Delecluse, J. Cole, and J. M. Slingo, 2004: Triggering of El Niño by westerly wind events in a coupled general circulation model. *Climate Dyn.*, **23**, 6, doi:10.1007/s00382-004-0457-2.

Lopez, H., B. P. Kirtman, E. Tziperman, and G. Gebbe, 2012: Impact of interactive westerly wind bursts on CCSM3. *Dyn. Atmos. Oceans*, **59,** 24-51, doi:10.1016/j.jynamtmoce.2012.11.001.

Lopez, H., and B. P. Kirtman, 2013: Westerly wind bursts and the diversity of ENSO in CCSM3 and CCSM4. *Geophys. Res. Lett*., **40**, 4722–4727, doi:10.1002/grl.50913.

Lopez, H., and B. P. Kirtman, 2014: WWBs, ENSO predictability, the spring barrier and extreme events. *J. Geophys. Res. Atmos*., **119,** 10,114-10,138**,** doi:10.1002/2014JD021908.

Luo, J.-J., T. Yamagata, E. Roeckner, G. Madec, and T. Yamagata, 2005: Reducing climatology bias in an ocean–atmosphere CGCM with improved coupling physics. *J. Climate*, **18**, 2344–2360, doi:10.1175/JCLI3404.1.

Neale, R., J. H. Richter, and M. Jochum, 2008: The Impact of convection on ENSO: From a delayed oscillator to a series of events. *J. Climate*, **21**, 5904–5924, doi:10.1175/2008JCLI2244.1.

Palmer, T. N., C . Brankovic, and D. S. Richardson, 2000: A probability and decision-model analysis of PROVOST seasonal multimodel ensemble integrations. *Quart. J. Roy. Meteor. Soc.,* **126,** 2013–2034, doi:10.1002/qj.49712656703.

Palmer, T. N., F. J. Doblas-Reyes, R. Hagedorn, A. Alessandri, S. Gualdi, U. Andersen, G. Feddersen, P. Cantelaube, J.-M. Terres, M. Davey, R. Graham, P. Delecluse, A. Lazar, M. Deque, J.-F. Gueremy, E. Diez, B. Orfila, M. Hoshen, A. P. Morse, N. Keenlyside, M. Latif, E. Maisonnave, P. Rogel, B. Marletto, and M. C. Thomson, 2004: Development of a European multi-model ensemble system for seasonal-to-interannual prediction (DEMETER). *Bull. Amer. Meteor. Soc.*, **85,** 853-872, doi:10.1175/BAMS-85-6-853.

Palmer T. N., F. Doblas-Reyes, A. Weisheimer, and M. Rodwell, 2008: Toward seamless prediction. Calibration of climate change projections using seasonal forecasts. *Bull. Amer. Meteor. Soc.*, **89,** 459-470, doi:10.1175/BAMS-89-4-459.

Saha, S., S. Nadiga, C. Thiaw, J. Wang, W. Wang, Q. Zhang, H. M. Van den Dool, H.-L. Pan, S. Moorthi, D. Behringer, D. Stokes, M. Peña, S. Lord, G. White, W. Ebisuzaki, P. Peng, and P. Xie, 2006: The NCEP Climate Forecast System. *J. Climate*, **19,** 3483–3517, doi:10.1175/JCLI3812.1.

Shaffrey, L., I. Stevens, W. Norton, M. Roberts, P. L. Vidale, J. Harle, A. Jrrar, D. Stevens, M. Woodage, M-E. Demory, J. Donners, D. Clark, A. Clayton, J. Cole, S. Wilson, W. Connolley, T. Davies, A. Iwi, T. Johns, J. King, A. New, J. M. Slingo, A. Slingo, L. Steenman-Clark and G. Martin, 2009: UK-HiGEM: The new UK High Resolution Global Environment Model. Model description and basic evaluation. *J. Climate,* **22**, 1861-1896, doi:10.1175/2008JCLI2508.1.

Slingo, J. M., D. P. Rowell, K. R. Sperber, and F. Nortley, 1999: On the predictability of the interannual behaviour of the Madden-Julian Oscillation and its relationship with El Niño. *Quar. J. Roy. Meteor. Soc.*, **125**, 583-609, doi:10.1002/qj.49712555411.

Thompson, C. J., and D. S. Battisti, 2001: A linear stochastic dynamical model of ENSO. Part II: Analysis. *J. Climate,* **14,** 445–466, doi:10.1175/1520-0442(2001)014<0445:ALSDMO>2.0.CO;2.

Vecchi, G. A., and D. E. Harrison, 2000: Tropical Pacific sea surface temperature anomalies, El Niño, and equatorial westerly wind events. *J. Climate*, **13**, 1814–1830, doi:10.1175/1520-0442(2000)013<1814:TPSSTA>2.0.CO;2.

Wittenberg, A. T., A. Rosati, N.-C. Lau, and J. J. Ploshay, 2006: GFDL's CM2 global coupled climate models. Part III: Tropical Pacific climate and ENSO. *J. Climate*, **19**, 698–722, doi:10.1175/JCLI3631.1.

Precursors of ENSO beyond the tropical Pacific

Jin-Yi Yu and Houk Paek

University of California, Irvine

Precursors of the El Niño-Southern Oscillation (ENSO) are atmospheric or oceanic phenomena that often occur before the onset of ENSO events and offer the potential to predict ENSO events with significant lead times. Most of the well-known ENSO precursors identified, so far, occur within the tropical Pacific, such as the build-up of subsurface ocean heat content anomalies in the tropical western Pacific (e.g., Wyrtki 1985; Meinen and McPhaden 2000) and the appearance of westerly wind bursts in the tropical western-to-central Pacific (e.g., McPhaden 1999; Vecchi and Harrison 2000; Zhang and Gottschalk 2002). These precursors have been suggested to affect ENSO onset through fluctuations in thermocline depths in the equatorial Pacific, which are recognized as a central element of the ENSO generation mechanism. Precursors outside the tropical Pacific have also been shown to exist, including wind and sea surface temperature (SST) variations in the subtropical or extratropical Pacific as well as in the Indian Ocean (e.g., Clarke and van Gorder 2003) and Atlantic Ocean (e.g., Rodriguez-Fonseca et al. 2009). The increasing interest in different flavors of ENSO in recent years has begun to place more emphasis on ENSO precursors outside the tropical Pacific, particularly those in the subtropical Pacific. The US CLIVAR working group on ENSO diversity summarized recent ENSO diversity studies in Capotondi et al. (2015). One view emerging from these studies is that there may exist two different flavors or types of ENSO, which are often referred to as the Eastern Pacific (EP) ENSO and Central Pacific (CP) ENSO (Yu and Kao 2007; Kao and Yu 2009), and that subtropical Pacific precursors may be particularly important to the CP ENSO. As CP ENSO events have occurred more frequently in recent decades (e.g., Ashok et al. 2007; Kao and Yu 2009; Yu et al. 2010; Lee and McPhaden 2010; Yu et al. 2015), the subtropical

Pacific precursors may become more important for predicting ENSO events in the coming decades. This article intends to describe the major features of these precursors, their connections with the two types of ENSO, and a possible reason why they have become more important in recent decades.

Subtropical Pacific precursors and ENSO

Subtropical Pacific precursors for ENSO are most prominent in the northeastern Pacific as a band of SST anomalies extending typically from Baja California toward the equatorial central Pacific. Taking the 1986, 1994, 1997, and 2004 El Niño events as examples (Figure 1), positive SST anomalies appeared off Baja California several months before the onset of these El Niño events in the equatorial Pacific. The SST anomalies then persisted in the subtropical Pacific for several months and at the same time extended southwestward. As the subtropical SST anomalies approached the equatorial Pacific, the El Niño events developed and began to grow. The thought is that the initial warming outside Baja California is forced by atmospheric fluctuations via surface heat fluxes, particularly those associated with the North Pacific Oscillation (NPO; Walker and Bliss 1932; Rogers 1981; Linkin and Nigam 2008) as suggested by several recent studies (e.g., Vimont et al. 2003; Anderson 2004; Yu and Kim 2011). These initial SST anomalies then feedback to modify near surface winds via convection. The wind anomalies induced by the convection tend to be located to the southwest of the initial subtropical SST anomalies (Xie and Philander 1994), where new positive SST anomalies can be formed through a reduction in evaporation. The atmosphere then continues to respond to the new SST anomalies by producing wind anomalies further southwestward. Through this wind-evaporation-SST (WES) feedback (Xie and Philander 1994), the SST anomalies initially induced by the extratropical atmosphere off Baja California can extend southwestward into the deep tropics. This series of subtropical Pacific coupling processes are referred to as the seasonal footprinting mechanism (Vimont et al., 2001, 2003, 2009). This mechanism also offers a way to explain how the subtropical SST anomalies can be sustained from boreal winter, when the extratropical atmospheric variability (e.g., the NPO) is the most active, to the following spring or summer to excite El Niño events.

The SST anomaly pattern of the subtropical precursor strongly resembles the so-called Pacific Meridional Mode (PMM; Chiang and Vimont 2004), which has been shown to be the leading coupled variability mode of the subtropical Pacific. A strong association between the spring PMM index and the following winter ENSO index was demonstrated in Chang et al. (2007). They found that a majority of El Niño events over the past four decades were preceded by SST and surface wind anomalies similar to the PMM.

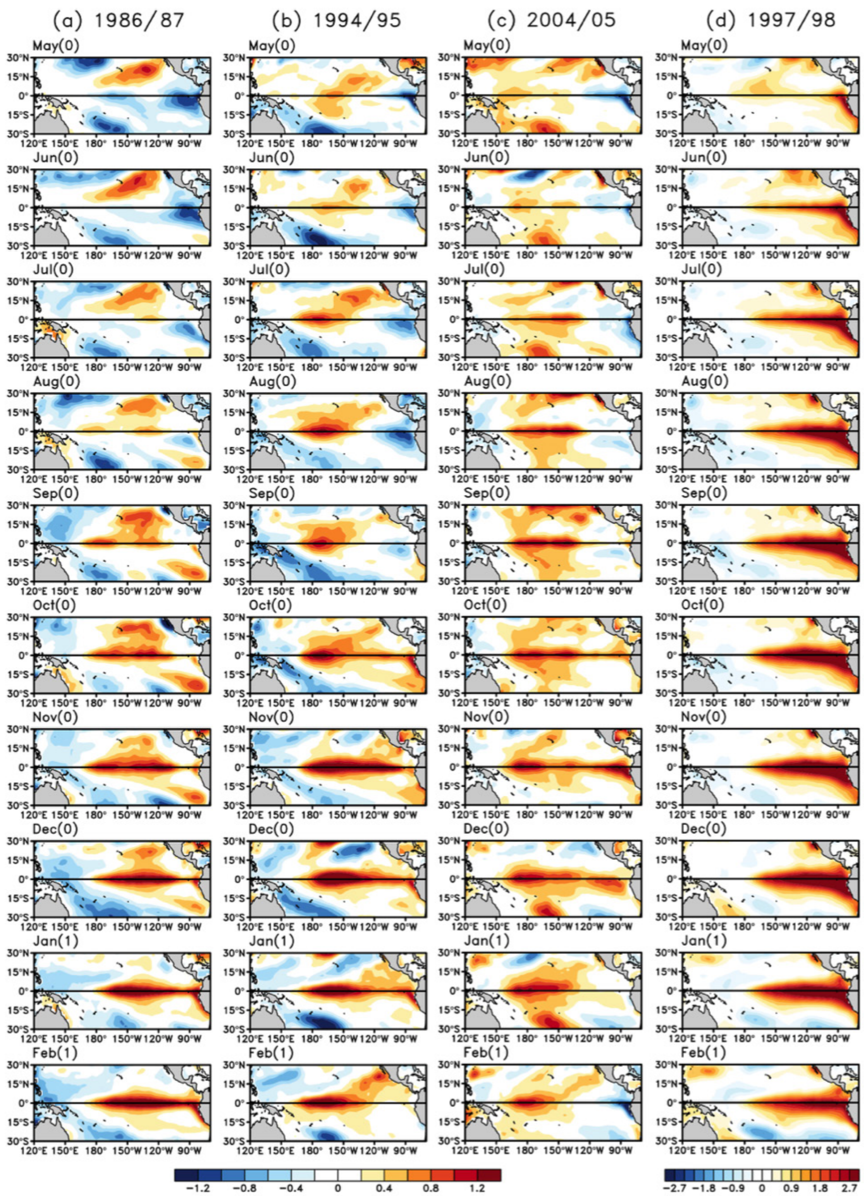

Figure 1. Monthly sea surface temperature anomalies (°C) observed in the developing (0) and peak (1) years of the (a) 1986/87 El Niño event, (b) 1994/95 El Niño event, (c) 2004/05 El Niño event, and (d) 1997/98 El Niño event.

There are a few different ways to explain how the PMM anomalies can generate ENSO events in the equatorial Pacific. One explanation is that the surface wind anomalies associated with the subtropical precursors can directly or indirectly (through the reflection of off-equatorial Rossby wave at the western Pacific) excite downwelling Kelvin waves along the equatorial thermocline that propagate eastward to trigger El Niño events in the eastern Pacific (e.g., Alexander et al. 2010). The subtropical precursors have also been suggested to be capable of directly increasing the ocean heat content in the equatorial Pacific via modulations in the strength of the trade winds, which then creates a charged state for ENSO in the equatorial Pacific (Anderson 2004; Anderson and Maloney 2006; Anderson et al. 2013). The SST and wind anomalies associated with the subtropical precursors also resemble the optimal structures identified by liner inverse models that are capable of growing into large ENSO events (Penland and Sardeshmukh 1995; Xue et al. 1997).

These earlier studies on the relationship between the subtropical precursors and ENSO did not consider the existence of different types of ENSO. In Figure 1, the subtropical precursors in three of the four examples (i.e., the 1986, 1994, and 2004 events) were followed by an El Niño event in the central Pacific (i.e., the CP El Niño). The subtropical precursors seem to be particularly important to the generation of the CP ENSO. The SST anomaly pattern associated with the CP ENSO are characterized by positive anomalies extending from the equatorial central Pacific to the northeastern subtropical Pacific (see Figure 3b of Kao and Yu 2009, for example), which is similar to the SST anomaly pattern of the subtropical Pacific precursors (or the PMM). No such subtropical extension is found in the SST anomaly pattern associated with the EP ENSO. A lead-lagged regression of the Pacific SST anomalies to a CP ENSO index shows that the CP ENSO is preceded by positive SST anomalies off Baja California during the previous winter (Yu et al. 2010), while a lead-lagged regression of the Pacific SST anomalies to a NPO index shows that the CP ENSO pattern peaks in the equatorial Pacific 12 months after the peak in NPO events (Yu and Kim 2011). These studies offer evidence that there exists a close relationship between the subtropical Pacific precursors and the CP ENSO. It is argued that the arrival of the subtropical Pacific precursor in the equatorial central Pacific could trigger local air-sea interactions that intensify local SST anomalies into a CP El Niño event via surface heat fluxes (Yu et al. 2010) or the wind-induced surface ocean advection (Kug et al. 2009; Yu et al. 2010). The earlier view, which links the precursors to ENSO onsets via the eastward propagation of precursor-induced ocean waves along the thermocline, appears more related to the onset of EP ENSO events. Therefore, when the subtropical precursor reaches the equatorial Pacific, it may locally force a CP ENSO event by interacting with the local ocean mixed layer. In this view, the SST and surface wind anomalies in the subtropical Pacific are not just precursors to the ENSO but an essential element of the CP ENSO dynamics.

Figure 2 illustrates our view on the underlying dynamics of the two types of ENSO and how they may be related to the subtropical Pacific precursors. In this perspective, the generation of the CP ENSO is more related to the ocean mixed layer dynamics. Dommenget (2010) and Clement et al. (2011) have demonstrated that ENSO-like events can be produced in coupled models where the ocean component consists of a mixed layer only without any thermocline dynamics. The generation of the EP ENSO is considered more related to the thermocline dynamics depicted by the delayed-oscillator (Suarez and Schopf 1988; Battisti and Hirst 1989) and charge-recharged oscillator theories (e.g., Wyrtki 1975; Zebiak 1989; Jin 1997).

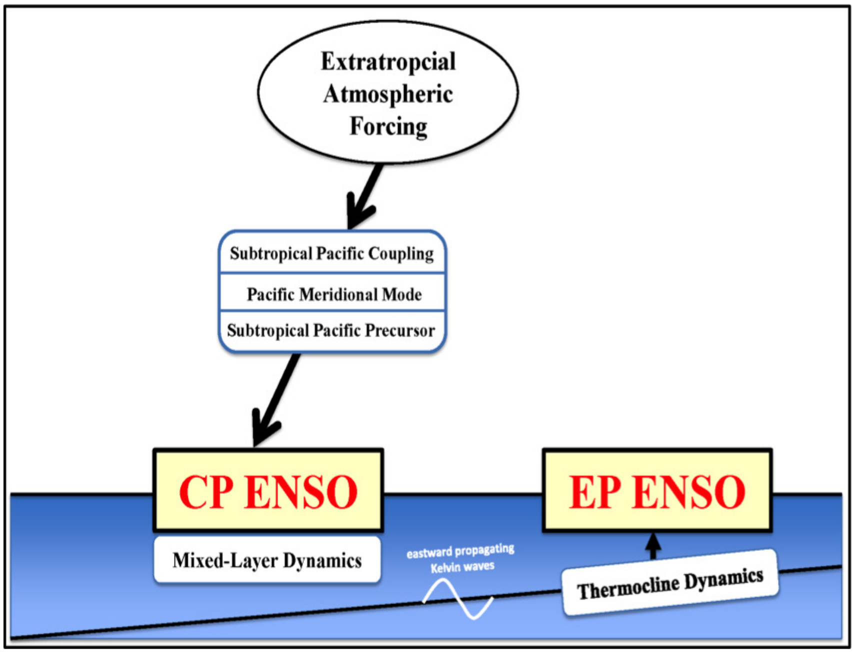

Figure 2. A schematic to illustrate the possible relationships between the subtropical Pacific precursors and the two types of ENSO (CP and EP).

The early-1990s climate shift and the increasing importance of the subtropical Pacific precursors

In order for the subtropical precursors to be able to influence the ENSO events several months later in the tropics, they must rely on subtropical Pacific ocean-atmosphere coupling (i.e., the WES feedback mechanism). The strength of the subtropical Pacific coupling, therefore, plays a key role in determining how efficiently the subtropical Pacific precursors are in generating ENSO events, particularly CP ENSO events. In decades when the subtropical Pacific coupling is strong, more subtropical precursors can penetrate deeper into the equatorial central Pacific to excite CP ENSO events.

The exact time of the recent ENSO shift from the EP type to the CP type has been suggested to be between the 1980s (Ashok et al. 2007) and the beginning of the 21st century (Lee and McPhaden 2010). Yu et al. (2012) showed that the SST variations in the equatorial central Pacific (i.e., the Niño4 index) are more closely related to the SST variability in the equatorial eastern Pacific (i.e., the Niño3 index) before the early-1990s, but more related to sea level pressure variations associated with the NPO (i.e., the NPO index) afterward. Their study suggests that the change of ENSO from the EP type to the CP type to be during the early-1990s.

Yu et al. (2015) further analyzed the subtropical Pacific coupling strength during the past few decades by examining the correlation coefficient between the SST and surface wind stress anomalies associated with the PMM (Figure 3). They find that the coupling strength is indeed stronger after the early-1990s. They argued that the stronger subtropical Pacific coupling makes it easier for the subtropical precursors to influence the deep tropics, and, as a result, the occurrence of CP ENSO events increases. Yu et al. (2015) also noticed that the early-1990s is close to the time that the Atlantic Multi-decadal Oscillation (AMO) changed from a negative phase to a positive phase. They conducted observational analyses and coupled AGCM-slab ocean model experiments to suggest that the recent emergence of the CP El Niño can at least partly be attributed to this AMO phase change via the following chain of events: a switch in the AMO to its positive phase in the early 1990s led to an intensification of the Pacific Subtropical High. The intensified High resulted in stronger-than-average background trade winds that enhanced the WES feedback mechanism, strengthening the subtropical Pacific coupling between the atmosphere and ocean, making the subtropical Pacific precursors more capable of penetrating into the deep tropics, and ultimately leading to increased occurrence of the CP ENSO events. The study of Yu et al. (2015) suggests that an early-1990s climate shift occurred in the Pacific, after which the subtropical Pacific precursors became more important for the generation of ENSO events.

Successful prediction and modeling of the ENSO in the recent and coming decades may depend more on a better understanding and improved skill in the modeling of the subtropical Pacific precursors and their underlying generation mechanisms. Prediction systems based on this framework would be different from the prediction and modeling systems the climate research community has

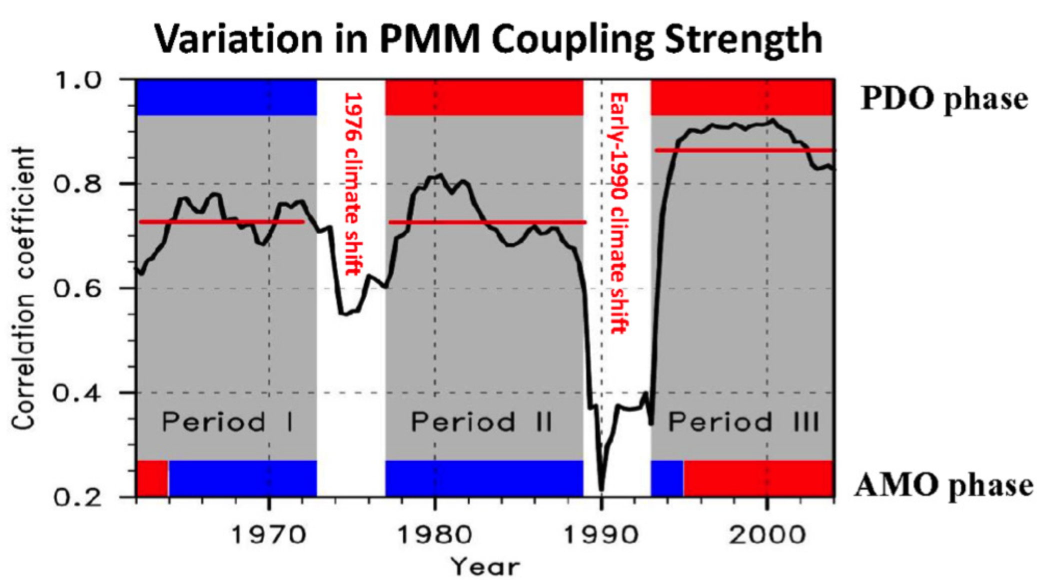

Figure 3. The 10-year running correlation coefficients between the PMM-SST and PMM-wind indices in boreal spring (MAM). NCAR/NCEP reanalysis data is used in the calculation. The red line indicates a mean of the correlation coefficients during each period. The shadings at the top and bottom are the positive/negative (red/blue) phases of the 10-year low-pass filtered PDO and AMO, respectively. (Modified from Yu et al. 2015)

developed in the 1980s and 90s for the conventional ENSO, which emphasize subsurface ocean dynamics in the equatorial Pacific.

Larson and Kirtmann (2014) have reported some skill in using the PMM to forecast ENSO events with the North American Multimodel Ensemble (NMME) Experiments. In order to utilize the subtropical precursors, particularly the PMM, to forecast ENSO events, coupled atmosphere-ocean models have to be able to realistically simulate the precursor events. Lin et al. (2014) examined twenty-three CMIP5 models to conclude that the PMM structure can be reasonably simulated in most of the coupled models. However, the so-called seasonal footprinting mechanism that sustains an equatorward extension of the PMM is not well simulated in a majority of the CMIP5 models. Therefore, it is necessary to improve the subtropical Pacific coupling in coupled models in order for these models to be applied successfully for forecasts of ENSO occurrence.

The views presented in this article assume the existence of the two distinct types of ENSO with different generation mechanisms. It should be noted that there is still an ongoing debate concerning this assumption as reported in Capotondi et al. (2015). Nevertheless, it is generally agreed in the ENSO research community that the characteristics of ENSO seem to be changing in recent decades, including a westward shift in the central location of the ENSO SST anomalies. This shift has motivated efforts to revisit traditional views of ENSO dynamics and its global teleconnections (Wang et al. 2015; Capotondi et al. 2015). The increasing emphasis on the ENSO precursors outside the tropical Pacific is one component of these efforts. This article focuses only on the northeastern subtropical Pacific ENSO precursors. Other regions outside the tropical Pacific have also been emphasized in several recent studies for ENSO precursors, such as the western North Pacific (Wang et al. 2012) and the southeastern subtropical Pacific (Zhang et al. 2014).

Acknowledgments

This work was supported by the National Science Foundation’s Climate and Large Scale Dynamics Program through grant AGS-1233542 and by National Oceanic and Atmospheric Administration's Modeling, Analysis, Predictions, and Projections Program through grant NA11OAR4310102.

References

Alexander, M. A., D. J. Vimont, P. Chang, and J. D. Scott, 2010: The impact of extratropical atmospheric variability on ENSO: Testing the seasonal footprinting mechanism using coupled model experiments. *J. Climate*, **23**, 2885-2901, doi:10.1175/2010JCLI3205.1.

Anderson, B. T., 2004: Investigation of a large-scale mode of ocean atmosphere variability and its relation to tropical Pacific sea surface temperature anomalies. *J. Climate*, **17**, 1089–4098, doi: 10.1175/1520-0442(2004)017<4089:IOALMO>2.0.CO;2.

Anderson, B. T., and E. Maloney, 2006: Interannual tropical Pacific sea surface temperatures and their relation to preceding sea level pressures in the NCAR CCSM2. *J. Climate*, **19**, 998–1012. doi:10.1175/JCLI3674.1.

Anderson, B. T., R. C. Perez, and A. Karspeck, 2013: Triggering of El Niño onset through trade wind–induced charging of the equatorial Pacific. *Geophy. Res. Lett.s*, **40**, 1212-1216, doi:10.1002/grl.50200.

Ashok, K., S. K. Behera, S. A. Rao, H. Weng, and T. Yamagata, 2007: El Niño Modoki and its possible teleconnection. *J. Geophy. Res*., **112**, C11007, doi:10.1029/2006JC003798.

Battisti, D. S. and A. C. Hirst, 1989: Interannual variability in the tropical atmosphere-ocean model: influence of the basic state, ocean geometry and nonlinearity. J. *Atmos. Sci*., **45**, 1687-1712, doi:10.1175/1520-0469%281989%29046<1687%3AIVIATA>2.0.CO%3B2.

Capotondi, A., A. T. Wittenberg, M. Newman, E. Di Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B. Dewitte, B. Giese, E. Guilyardi, F.-F. Jin, K. Karnauskas, B. Kirtman, T. Lee, N. Schneider, Y. Xue, and S.-W. Yeh, 2015: Understanding ENSO diversity. *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-D-13-00117.1.

Chang, P., L. Zhang, R. Saravanan, D. J. Vimont, J. C. H. Chiang, L. Ji, H. Seidel, and M. K. Tippett, 2007: Pacific meridional mode and El Niño-Southern Oscillation. *Geophys. Res. Lett.*, **34**, L16608, doi:10.1029/2007GL030302.

Chiang, J. C. H., and D. J. Vimont, 2004: Analogous Pacific and Atlantic meridional modes of tropical atmosphere-ocean variability. *J. Climate*, **17**, 4143– 4158, doi:10.1175/JCLI4953.1.

Clarke, A. J., and S. van Gorder, 2003: Improving El Niño prediction using a space–time integration of Indo-Pacific winds and equatorial Pacific upper ocean heat content. *Geophys. Res. Lett.*, **30**, 1399, doi:10.1029/2002GL016673.

Clement, A., P. DiNezio, and C. Deser, 2011: Rethinking the ocean's role in the Southern Oscillation. *J. Climate*, **24**, 4056-4072, doi:10.1175/2011JCLI3973.1.

Dommenget, D., 2010: The slab ocean El Niño. *Geophys Res Lett*, **37**. L20701, doi:10.1029/2010/GL044888.

Jin, F.-F., 1997: An equatorial recharge paradigm for ENSO, I. Conceptual model. *J. Atmos. Sci.*, **54**, 811-829, doi:10.1175/1520-0469%281997%29054<0811%3AAEORPF>2.0.CO%3B2.

Kao, H. Y., and J. Y. Yu, 2009: Contrasting Eastern-Pacific and Central-Pacific types of ENSO. *J. Climate*, **22**, 615-632, doi:10.1175/2008JCLI2309.1.

Kug, J.-S., F.-F. Jin, and S.-I. An, 2009: Two types of El Niño events: Cold tongue El Niño and warm pool El Niño. *J. Climate*, **22**, 1499–1515, doi:10.1175/2008JCLI2624.1.

Larson, S., and B. P. Kirtman, 2014: The Pacific meridional mode as an ENSO precursor and predictor in the North American multimodel ensemble. *J. Climate*, **27**, 7018–7032, doi:10.1175/JCLI-D-14-00055.1.

Lee, T., and M. J. McPhaden, 2010: Increasing intensity of El Niño in the central-equatorial Pacific. *Geophys. Res. Lett.*, **37**, L14603, doi:10.1029/2010GL044007.

Lin, C.-Y., J.-Y. Yu, and H. H. Hsu, 2014: CMIP5 model simulations of the Pacific Meridional Mode and its connection to the two types of ENSO, *Int. J. Climatol.*, doi:10.1002/joc.4130.

Linkin, M. E., and S. Nigam, 2008: The North Pacific Oscillation-West Pacific teleconnection pattern: Mature-phase structure and winter impacts. *J. Climate*, **21**, 1979-1997, doi:10.1175/2007JCLI2048.1.

Meinen, C. S., and M. J. McPhaden, 2000: Observations of warm water volume changes in the equatorial Pacific and their relationship to El Niño and La Niña. *J. Climate*, **13**, 3551-3559, doi:10.1175/1520-0442%282000%29013<3551%3AOOWWVC>2.0.CO%3B2.

McPhaden, M. J., 1999: Genesis and evolution of the 1997–1998 El Niño. *Science*, **283**, 950–954, doi:10.1126/science.283.5404.950.

Penland, C., and P. D. Sardeshmukh, 1995: The optimal growth of tropical sea surface temperature anomalies. *J. Climate*, **8**, 1999-2024, doi:10.1175/1520-0442%281995%29008<1999%3ATOGOTS>2.0.CO%3B2.

Rodriguez-Fonseca, B., I. Polo, J. Garcia-Serrano, T. Losada, E. Mohino, C. R. Mechoso, and F. Kucharski, 2009: Are Atlantic Niños enhancing Pacific ENSO events in recentdecades?, *Geophys. Res. Lett.*, **36**, L20705, doi:10.1029/2009GL040048.

Rogers, J. C., 1981: The North Pacific Oscillation. *Int. J. Climatol*., **1**, 39–57, doi:10.1002/joc.3370010106.

Suarez, M. J., and P. S. Schopf, 1988: A delayed action oscillator for ENSO. *J. Atmos. Sci.*, **45**, 3283-3287, doi:10.1175/1520-0469%281988%29045<3283%3AADAOFE>2.0.CO%3B2.

Vecchi, G. A., and D. E. Harrison, 2000: Tropical Pacific sea surface temprature anomalies, El Niño and equatorial westerly events. *J. Climate*, **13**, 1814–1830, doi:10.1175/1520-0442%282000%29013<1814%3ATPSSTA>2.0.CO%3B2.

Vimont, D. J., D. S. Battisti, and A. C. Hirst, 2001: Footprinting: A seasonal connection between the tropics and mid-latitudes. *Geophys. Res. Lett.* **28**, 3923-3926, doi:10.1029/2001GL013435.

Vimont, D. J., J. M. Wallace, and D. S. Battisti, 2003: The seasonal footprinting mechanism in the Pacific: Implications for ENSO. *J. Climate,* **16**, 2668–2675, doi:10.1175/1520-0442%282003%29016<2668%3ATSFMIT>2.0.CO%3B2.

Vimont, D. J., M. Alexander, and A. Fontaine, 2009: Midlatitude excitation of tropical variability in the Pacific: The role of thermodynamic coupling and seasonality*. *J. Climate*, **22**(3), 518-534, doi:10.1175/2008JCLI2220.1.

Walker, G. T., and E. W. Bliss, 1932: World Weather V Mem. *R. Meteorol. Soc.*, **4**, 53–84, http://www.rmets.org/sites/default/files/ww5.pdf.

Wang, S.-Y., M. L'Heureux, and H.-H. Chia, 2012: ENSO prediction one year in advance using Western North Pacific sea surface temperatures. *Geophys. Res. Lett.,* **39**, L05702, doi:10.1029/2012GL050909.

Wang, C., C. Deser, J.-Y. Yu, P. DiNezio, and A. Clement, 2015: El Niño-Southern Oscillation (ENSO): A review. *Coral Reefs of the Eastern Pacific*, P. Glymn, D. Manzello, and I. Enochs, Eds., Springer Science Publisher, in press.

Wyrtki, K., 1975: El Niño—The dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *J. Phys. Oceanogr.*, **5**, 572–584, doi:10.1175/1520-0485%281975%29005<0572%3AENTDRO>2.0.CO%3B2.

Wyrtki, K., 1985: Water displacements in the Pacific and the genesis of El Niño cycles. *J. Geophy. Res.: Oceans (1978–2012)*, **90**, 7129-7132, doi:10.1029/JC090iC04p07129.

Xie, S.-P. and S. G. H. Philander, 1994: A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific. *Tellus*, **46A**, 340-350, doi:10.1034/j.1600-0870.1994.t01-1-00001.x.

Xue, Y., M. A. Cane, and S. E. Zebiak, 1997: Predictability of a coupled model of ENSO using singular vector analysis. Part I: Optimal growth in seasonal background and ENSO cycles. *Mon. Wea. Rev.*, **125**, 2043-2056, doi:10.1175/1520-0493%281997%29125<2043%3APOACMO>2.0.CO%3B2.

Yu, J.-Y. and H.-Y. Kao, 2007: Decadal changes of ENSO persistence barrier in SST and ocean heat content indices: 1958-2001. *J. Geophys. Res.*, **112**, D13106, doi:10.1029/2006JD007654.

Yu, J.-Y., H.-Y. Kao, and T. Lee, 2010: Subtropics-related interannual sea surface temperature variability in the equatorial central Pacific. *J. Climate*, **23**, 2869-2884, doi:10.1175/2010JCLI3171.1.

Yu, J.-Y., and S. T. Kim, 2011: Relationships between extratropical sea level pressure variations and the Central-Pacific and Eastern-Pacific types of ENSO, *J. Climate*, **24**, 708-720, doi:10.1175/2010JCLI3688.1.

Yu, J.-Y., M.-M. Lu, and S. T. Kim, 2012: A change in the relationship between tropical central Pacific SST variability and the extratropical atmosphere around 1990. *Enviro. Res. Lett.*, **7**, 034025, doi:10.1088/1748-9326/7/3/034025.

Yu, J.-Y., P. –K. Kao, H. Paek, H. –H. Hsu, C. –W. Hung, M. –M. Lu and S. –I. An, 2015: Linking emergence of the Central-Pacific El Niño to the Atlantic Multi-decadal Oscillation. *J. Climate*, 28, 651-662, doi:10.1175/JCLI-D-14-00347.1.

Zebiak, S. E., 1989: Ocean heat content variability and El Niño cycles. *J. Phys. Oceanogr.*, **19**, 475–486, doi:10.1175/1520-0485%281989%29019<0475%3AOHCVAE>2.0.CO%3B2.

Zhang, Q., and J. Gottschalk, 2002: SST anomalies of ENSO and the Madden–Julian oscillation in the equatorial Pacific. *J. Climate,* **15**, 2429–2445, doi:10.1175/1520-0442%282002%29015<2429%3ASAOEAT>2.0.CO%3B2.

Zhang, H., A. Clement, and P. Di Nezio, 2014: The South Pacific Meridional Mode: A mechanism for ENSO-like variability. *J. Climate*, **27**, 769–783, doi:10.1175/JCLI-D-13-00082.1.

Climate model biases and El Niño Southern Oscillation (ENSO) simulation

Antonietta Capotondi[1,2], Yoo-Geun Ham[3], Andrew Wittenberg[4], and Jong-Seong Kug[5]

[1]University of Colorado, Boulder

[2]NOAA Earth System Research Laboratory

[3]Chonnam National University, Gwangju, South Korea

[4]NOAA Geophysical Fluid Dynamics Laboratory

[5]Pohang University of Science and Technology, South Korea

Over the last two decades the representation of ENSO in climate models has significantly improved, as documented by the extensive literature describing ENSO simulations in the Climate Model Intercomparison Project versions 3 and 5 (CMIP3 and CMIP5). Several aspects of ENSO, however, are still not satisfactorily represented in the current generation of climate models (Bellenger et al. 2014). In addition, as our understanding of ENSO and its complex coupled feedbacks deepens, we want any "realistic" ENSO simulations to be achieved as a result of a correct representation of those feedbacks, and not from compensating errors.

Part of the problem is that it is not always clear what is meant by "realistic". ENSO behavior is strongly modulated in time, in both observations and climate models (see article by Wittenberg, this issue). The relatively short observational record means that the ENSO target for modelers is somewhat murky, and may not be fully representative of the full range of ENSO behavior that is achieved in nature (Wittenberg 2009). On the other hand, the tropical Pacific mean state is better resolved by the observational record, and several biases are clear and shared by most of the present generation of models: an equatorial cold tongue that is too intense and too far west; a "double" or "alternating" Intertropical Convergence Zone (ITCZ) in the eastern Pacific; and warm sea surface temperature (SST) biases near the coast of South America (Guilyardi et al. 2009, 2012a).

Figure 1 shows the time evolution of the Niño3.4 index, the area averaged SST over the region 5°S-5°N, 170°W-120°W, over the last century for one observational data set (HadISST, Rayner et al. 2003) and three models from the CMIP5 archive (GFDL-ESM2M, NCAR-CCSM4, MRI-CGCM3) - illustrating inter-model differences in ENSO character. The figure shows some similarities between the observations and the models. The ENSO evolution is quite "irregular" in all the models, as in the observational time series, so that ENSO can be more adequately described as a series

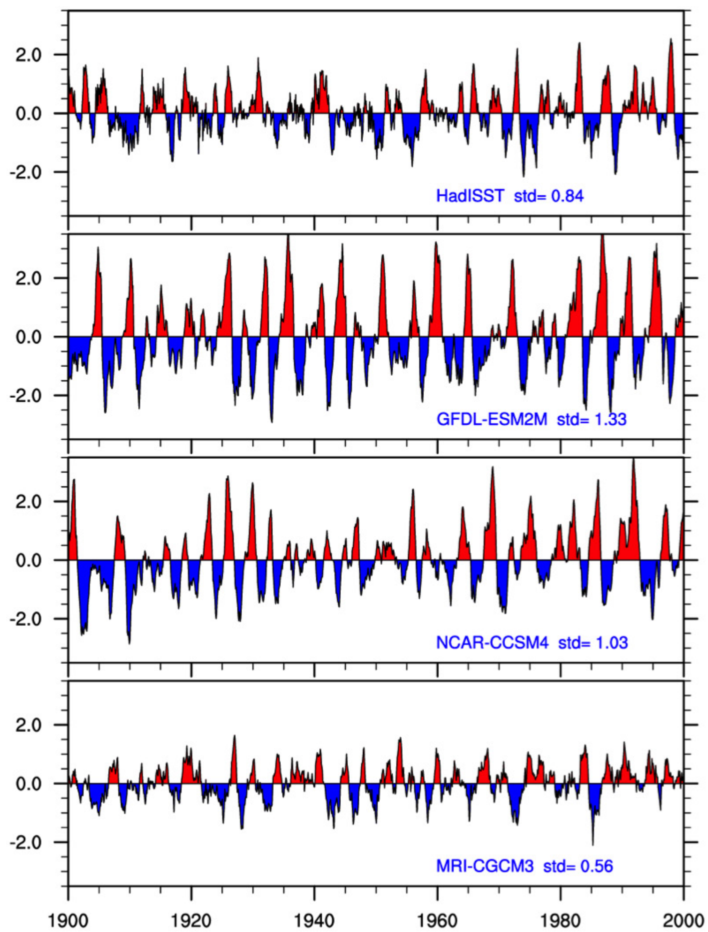

Figure 1. Evolution of the Niño3.4 index (area averaged interannual SSTAs over the region 5°S-5°N, 170°W-120°W) over the period 1900-2000 for HadISST (top panel) and 20th-century climate simulations (only one ensemble member of which is shown) from the CMIP5 archive: GFDL-ESM2M, NCAR-CCSM4, MRI-CGCM3. The time series standard deviation, computed over the period 1950-2000, is also indicated in each panel as a measure of the ENSO amplitude. Vertical axis units are °C.

of events rather than a regular oscillation. This represents a big improvement relative to the ENSO simulation in some of the CMIP3 models for which the ENSO evolution was quite periodic. Both GFDL-ESM2M and NCAR-CCSM4 also show some degree of asymmetry between the positive and negative events. Large El Niño events tend to be stronger than large La Niña events, as also seen in the observational time series, indicating that the models may capture some of the observed ENSO nonlinearities – though it remains a challenge in many models (An et al. 2005; Choi et al. 2013; Dommenget et al. 2013; Zhang and Sun, 2014). Despite these "realistic" features, which indicate improvement relative to previous model generations, the models shown in Figure 1 either overestimate or underestimate the ENSO amplitude (as quantified by the standard deviation of the Niño3.4 index). Though the amplitude can vary from one ensemble member to the next in a given model, generally both GFDL-ESM2M and NCAR-CCSM4 have a stronger ENSO than HadISST, while MRI-CGCM3 has weaker variations. An examination of the whole CMIP5 and CMIP3 archives shows that the spread in ENSO amplitudes is significantly reduced in the CMIP5 relative to the CMIP3, but still relatively large (Bellenger et al. 2014).

Some aspects of the model mean state may be important in influencing the characteristics of interannual variability (Guilyardi et al. 2012a). For example, the intensity of the equatorial cold tongue, which helps set the strength of the zonal and meridional SST gradients near the equator, is key for determining how readily atmospheric deep convection spreads into the equatorial eastern Pacific during El Niño. The convection responds to the pattern of total, not anomalous, SST - so to get the warmest total SST on the equator in the east Pacific, an overly intense cold tongue requires an overly intense warm event. Thus models with stronger cold tongue biases tend to shift the ENSO-related atmospheric response farther to the west (Ham and Kug 2015). The westward extension of the cold tongue is also important, since it determines the position of the maximum zonal SST gradient. If the cold tongue extends too far west, the ENSO sea surface temperature anomaly (SSTA) pattern can take on an unrealistic "double-peaked" structure in which SSTAs driven by zonal advection in the west are displaced too far west of SSTAs driven by vertical advection in the east (Graham et al. 2015).

The structure of the time-mean tropical ocean thermocline can also be expected to affect ENSO amplitude in the eastern equatorial Pacific, where vertical temperature advection is one of the leading terms in the heat budget of interannual SSTAs. Sensitivity experiments with an earlier version of the NCAR climate model showed that stronger near-surface vertical temperature gradients, due to a sharper and/or shallower thermocline, resulted in larger SSTAs (Meehl et al. 2001). Similar results were found in GFDL experiments that indirectly perturbed the climatological equatorial thermocline, via changes in the depth of penetration of off-equatorial solar radiation (Anderson et al. 2009). The implication is that vertical mixing and thermal stratification, which affect the equatorial thermocline intensity, can play a very important role in determining the ENSO amplitude.

The magnitude and spatial distribution of the mean surface wind stress also appear to influence some of the ENSO properties - in particular its amplitude - due to the control of the surface zonal wind stress upon the mean upwelling and zonal SST gradient (Wang and An 2002). A tendency for weaker ENSO amplitudes with increasing zonal wind stress in the Niño4 (5°S-5°N, 160°E-150°W) region is detected in the CMIP3 archive (Guilyardi 2006). ENSO events tend to peak during boreal winter (December-January-February), an indication of a phase locking with the annual cycle, and can be viewed as a disruption of the annual cycle. As such, the ENSO amplitude can be expected to be somewhat related to the amplitude of the annual cycle, and indeed an inverse relationship between the ENSO amplitude and the relative strength of the annual cycle is found in the CMIP3 models (Guilyardi 2006; An et al. 2010).

Just as model biases in the climatology can affect ENSO, biases in ENSO can affect the mean state. For example, strong ENSO variability enhances the long-term rainfall in the equatorial central Pacific and also assists with vertical and lateral diffusion of heat by undulating the equatorial thermocline and cold tongue (Watanabe & Wittenberg 2012; Watanabe et al. 2012; Ogata et al. 2013). This two-way feedback between ENSO and the mean state suggests that biases in one aspect could easily affect the other.

The ENSO time evolution is another challenge for the models to reproduce correctly. The spatial pattern of the anomalous zonal wind stress during El Niño - in particular its meridional width and longitudinal position - helps to set the ENSO period by controlling the ocean adjustment timescale. A multiple regression analysis performed on a subset of the CMIP3 models shows a statistically significant relationship between the ENSO period and meridional width/longitudinal position of anomalous zonal wind stress (Capotondi et al. 2006). And many of ENSO's temporal asymmetries – with warm events being shorter, more intense, and more likely to transition to the opposite phase than cold events – also depend on the nonlinearity of the anomalous wind stress response to SSTAs (Choi et al. 2013). But what determines the spatiotemporal patterns of that wind response? Changes in atmospheric parameterizations, in particular of convective momentum transport, have considerably improved the wind stress responses in some GCMs - resulting in a dominant timescale of about four years (similar to observed) and a much broader spectral width, albeit with too large of an amplitude (Wittenberg et al. 2006; Kim et al. 2008; Neale et al. 2008).

An aspect of ENSO that has received much attention over the last decade is the large diversity in spatial patterns among different events (see Capotondi et al. 2015 for a review). Warm events, for instance, range from strong cases - like the 1997-1998 El Niño - with the largest anomalies close to the South American coast, to weaker events that exhibit the largest amplitude in the central equatorial Pacific - like the 2002-2003 El Niño. Since the atmospheric response to SSTAs is very sensitive to the details of those anomalies, a realistic simulation of the full range of ENSO diversity is very important to ensure correct atmospheric teleconnections. However, models seem to have difficulty in reproducing ENSO diversity, as most models, to different degrees, simulate SSTAs that extend too far west relative to observations.

To characterize diversity, ENSO events have often been divided into two groups, with SSTAs peaking in the equatorial eastern or central Pacific. Different criteria have been used to identify these two groups of events, and, accordingly, different definitions have been introduced for them as summarized in Capotondi et al. (2015). Figure 2 compares the composite equatorial profiles of warm ENSO events with maximum anomalies in the eastern and central Pacific for observations and 20 CMIP5 models. While some models (NCAR-CCSM4, CMRM-CM5, GFDL-CM3, GFDL-ESM2M) show distinct zonal maxima for the two groups of events, somewhat similar to the observations, other models (e.g., HadGEM2-CC, HadGEM2-ES, INM_CM4, MIROC-ESM, MRI-CGCM3) display longitudinal evolutions for the two groups that are strongly overlapping. Ham and Kug (2011) and Kug et al. (2012) have related the models' inability to simulate diversity to the severity of the models' cold tongue and precipitation biases, since the confinement of the ENSO-related atmospheric response to the western Pacific may result in a limited range of precipitation and SSTA patterns.

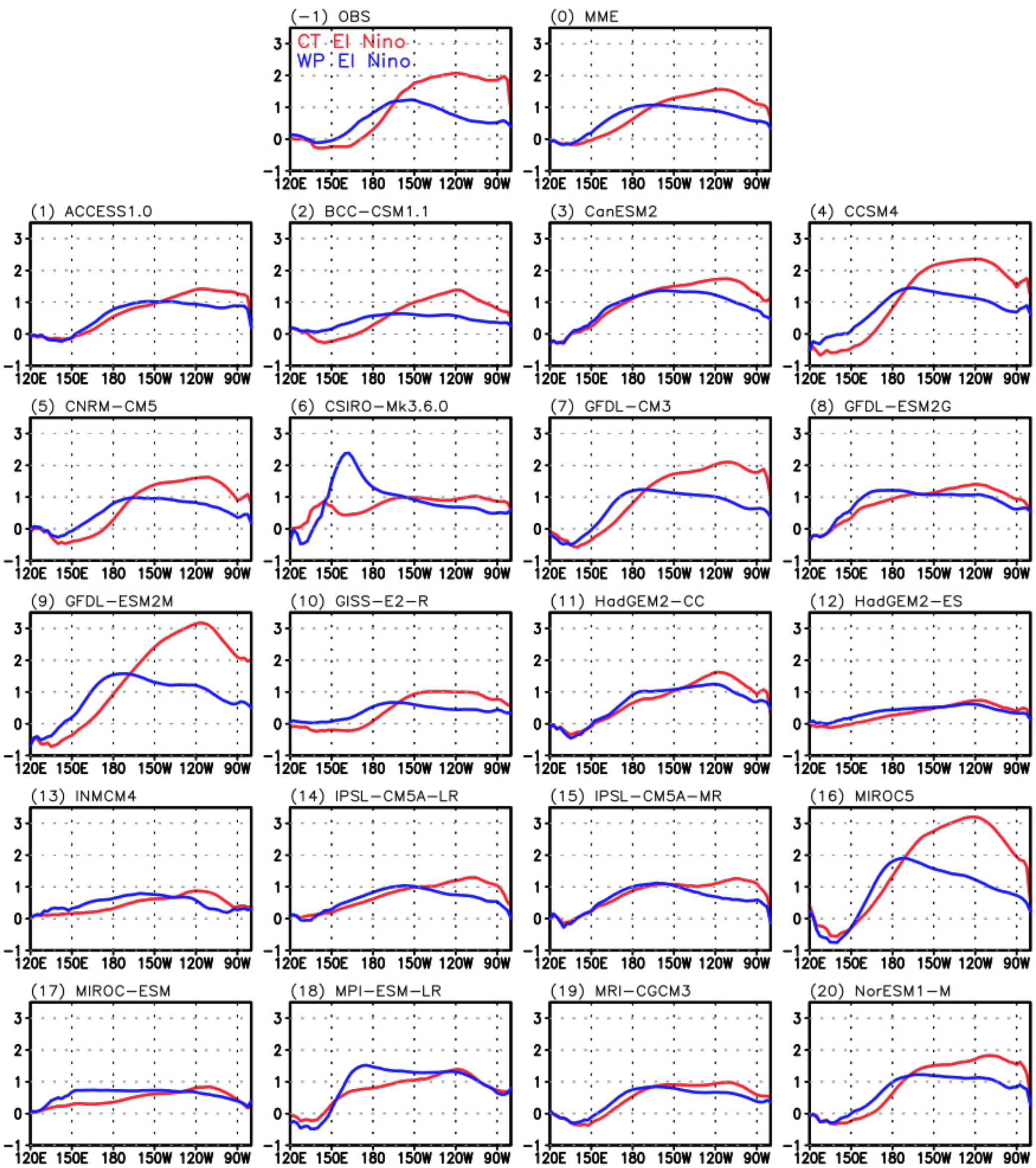

Figure 2. Equatorial average (5°S-5°N) SSTAs for composite "cold tongue" (CT) events (red line) and "warm pool" (WP) events (blue line) for observations (ERSST V2, Smith and Reynolds 2004; panel -1), the multi-model ensemble mean (panel 0) and 20 models from the CMIP5 archive (panels 1-20). CT and WP events are identified using the normalized Niño3 (area averaged SSTAs over 5°S-5°N, 150°W-90°W) and Niño4 (area averaged SSTAs over 5°S-5°N, 160°E-150°W) indices, respectively. CT events are characterized by a value of the Niño3 index greater than one, and greater than the value of the Niño4 index, and vice versa for the WP events. Equatorial profiles are shown as a function of longitude. Vertical axis units are °C.

As computer power increases, there are promising signs that increased model resolution may begin to alleviate some of the longstanding model biases in the mean state, with improvements in ENSO patterns, teleconnections, synchronization to the seasonal cycle, and forecast skill (Delworth et al. 2012; Vecchi et al. 2014; Jia et al. 2015; Krishnamurthy et al. 2015; Yang et al. 2015).

Going forward, a key question is what impact model biases may have on ENSO's sensitivity to external forcings (Vecchi & Wittenberg 2010; Collins et al. 2010). Are models simulating the proper level of intrinsic variability? What about the right sensitivities to natural forcings like volcanoes and anthropogenic emissions of CO2 and aerosols? More tests are needed to evaluate the response of simulated ENSOs to past climates - such as the mid-Holocene, Last Glacial Maximum, and Pliocene - and improved paleo reconstructions are needed to benchmark their performance. Improved observational reconstructions are also needed for the instrumental epoch, especially for dynamical constraints on ENSO feedbacks – including the surface fluxes of heat, water, and momentum, and subsurface advection and mixing. Improved physical diagnostics and metrics are also needed to constrain the dynamics of ENSO (Guilyardi et al. 2012b).

References

An, S.-I., Y.-G. Ham, J.-S. Kug, F.-F. Jin, and I.-S. Kang, 2005: El Niño-La Niña asymmetry in the Coupled Model Intercomparison Project simulations. *J. Climate*, **18**, 2617-2627, doi:10.1175/JCLI3433.1.

An, S-I, Y.-G. Ham, J.-S. Kug, A. Timmermann, J. Choi, and I.-S. Kang, 2010: The inverse effect of annual-mean state and annual-cycle changes on ENSO. *J. Climate*, **23**, 1095–1110, doi:10.1175/2009JCLI2895.1.

Anderson, W., A. Gnanadesikan, and A. Wittenberg, 2009: Regional impacts of ocean color on tropical Pacific variability. *Ocean Sci*., **5**, 313-327, doi:10.5194/os-5-313-2009.

Bellenger, H., E. Guilyardi, J. Leloup, M. Lengaigne, and J. Vialard, 2014: ENSO representation in climate models: from CMIP3 to CMIP5. *Climate Dyn*., **42**, 1999-2018, doi:10.1007/s00382-013-1783-z.

Capotondi, A., A. T. Wittenberg, M. Newman, E. Di Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B. Dewitte, B. Ciese, E. Guilyardi, F.F. Jim, K. Karnauskas, B. Kirtman, T. Lee, N. Schneider, Y. Xue, and S.-W. Yeh, 2015: Understanding ENSO diversity. *Bull. Amer. Meteor. Soc*., in press, doi:10.1175/BAMS-D-13-00117.1.

Capotondi, A., A. Wittenberg, and S. Masina, 2006: Spatial and temporal structure of tropical Pacific interannual variability in 20th century coupled simulations. *Ocean Model*., **15**, 274-298, doi:10.1016/j.ocemod.2006.02.004.

Choi, K.-Y., G. A. Vecchi, and A. T. Wittenberg, 2013: ENSO transition, duration and amplitude asymmetries: Role of the nonlinear wind stress coupling in a conceptual model. *J. Climate*, **26**, 9462-9476, doi:10.1175/JCLI-D-13-00045.1.

Collins, M., S.-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F.-F. Jin, M. Jochum, M. Lengaigne, S. Power, A. Timmermann, G. Vecchi, and A. Wittenberg, 2010: The impact of global warming on the tropical Pacific and El Niño. *Nat. Geosci.*, **3**, 391-397, doi:10.1038/ngeo868.

Delworth, T. L., A. Rosati, W. Anderson, A. J. Adcroft, V. Balaji, R. Benson, K. Dixon, S. M Griffies, H.-C. Lee, R. C. Pacanowski, G. A. Vecchi, A. T. Wittenberg, F. Zend, and R. Zhang, 2012: Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model. *J. Climate*, **25**, 2755-2781, doi:10.1175/JCLI-D-11-00316.1.

Dommenget, D., T. Bayr, and C. Frauen, 2013: Analysis of the non-linearity in the pattern and time evolution of El Niño Southern Oscillation. *Climate Dyn*., **40**, 2825-2847, doi:10.1007/s00382-012-1475-0.

Graham, F. S., et al., 2015: How coupled models alter El Niño ocean dynamics: A case study using the ACCESS coupled model. *Climate Dyn.,* submitted.

Guilyardi, E., 2006: El Niño-mean state-seasonal cycle interactions in a multi-model ensemble. *Climate Dyn*., **26,** 329-348, doi:10.1007/s00382-005-0084-6.

Guilyardi, E., A. Wittenberg, A. Fedorov, M. Collins, C. Wang, A. Capotondi, G. Jan van Oldenborgh, and T. Stockdale, 2009: Understanding El Niño in ocean-atmosphere general circulation models: Progress and challenges. *Bull. Amer. Meteor. Soc*., **90**, 325-340, doi:10.1175/2008BAMS2387.1.

Guilyardi, E., H. Bellenger, M. Collins, S. Ferrett, W. Cai, and A. Wittenberg, 2012a: A first look at ENSO in CMIP5. *CLIVAR Exchanges*, 58, 29-32, ISSN:1026-0471.

Guilyardi, E., W. Cai, M. Collins, A. Fedorov, F.-F. Jin, A. Kumar, D.-Z. Sun, and A. Wittenberg, 2012b: New strategies for evaluating ENSO processes in climate models. *Bull. Amer. Meteor. Soc*., **93**, 235-238. doi:10.1175/BAM S-D-11-00106.1.

Ham, Y.-G., and J.-S. Kug, 2011: How well do current climate models simulate two types of El Niño? *Climate Dyn*., **39**, 383-398, doi:10.1007/s00382-011-1157-3.

Ham, Y.-G., and J.-S. Kug, 2015: Improvement of ENSO simulation based on inter-model diversity. *J. Climate*, doi:10.1175/JCLI-D-14-00376.1.

Jia, L., X. Yang, G. A. Vecchi, R. Gudgel, T. Delworth, A. Rosati, W. F. Stern, A. Wittenberg, L. Krishnamurthy, S. Ahang, R. Msadek, S. Kapnick, S. Underwood, F. Zeng, W. G. Anderson, V. Balaji, and K. Dixon, 2015: Improved seasonal prediction of temperature and precipitation over land in a high-resolution GFDL climate model. *J. Climate*, in press, doi:10.1175/JCLI-D-14-00112.1.

Kim, D., J.-S. Kug, I.-S. Kang, F.-F. Jin, and T. Wittenberg, 2008: Tropical Pacific impacts of convective momentum transport in the SNU coupled GCM. *Climate Dyn*., **31**, 213-226, doi:10.1007/s00382-007-0348-4.

Krishnamurthy, L., G. A. Vecchi, R. Msadek, A. Wittenberg, T. Delworth, and F. Zeng, 2015: The seasonality of the Great Plains Low-Level Jet and ENSO relationship. *J. Climate,* submitted.

Kug, J.-S., Y.-G. Ham, J.-Y. Lee, and F.-F. Jin, 2012: Improved simulation of two types of El Niño in CMIP5 models. *Environ. Res. Lett*., **7**, doi:10.1088/1748-9326/3/034002.

Meehl, G. A., P. R. Gent, J. M. Arblaster, B. L. Otto-Bliesner, E. C. Brady, and A. Craig, 2001: Factors that affect the amplitude of El Niño in global coupled climate models. *Climate Dyn*., **17**, 515-526, doi:10.1007/PL00007929.

Neale, R. B., J. H. Richter, and M. Jochum, 2008: The impact of convection on ENSO: From a delayed oscillator to a series of events. *J. Climate*, **21**, 5904-5924, doi:10.1175/2008JCLI2244.

Ogata, T., S.-P. Xie, A. Wittenberg, and D.-Z. Sun, 2013: Interdecadal amplitude modulation of El Niño/Southern Oscillation and its impacts on tropical Pacific decadal variability. *J. Climate*, **26**, 7280-7297, doi:10.1175/JCLI-D-12-00415.1.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K . Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res*., **108**, 4407, doi:10.1029/2002JD002670.

Smith, T. M., and R. W. Reynolds, 2004: Improved extended reconstruction of SST (1854-1997*), J. Climate*, **17**, 2466-2477, doi:10.1175/1520-0442(2004)017<2466:IEROS>2.0.CO;2.

Vecchi, G. A., T. Delworth, R. Gudgel, S. Kapnick, A. Rosati, A. T. Wittenberg, F. Zeng, W. Anderson, V. Balaji, K. Dixon, L. Jia, H.-S. Kim, L. Krishnamurthy R. Msadek, W. F. Stern S. D. Underwood, G. Villarini, X. Yang, and S. Zhang, 2014: On the seasonal forecasting of regional tropical cyclone activity, *J. Climate*, **27**, 7994-8016, doi:10.1175/JCLI-D-14-00158.1.

Vecchi, G. A., and A. T. Wittenberg, 2010: El Niño and our future climate: Where do we stand? *Wiley Interdiscip. Rev.: Climate Change*, **1**, 260-270, doi:10.1002/wcc.33.

Wang, B., and S.-I. An, 2002: A mechanism for decadal changes of ENSO behavior: Roles of background wind changes. *Climate Dyn*., **18**, 475-486, doi:10.1007/s00382-001-0189-5.

Watanabe, M., and A. T. Wittenberg, 2012: A method for disentangling El Niño-mean state interaction. *Geophys. Res. Lett*., **39**, L14702, doi:10.1029/2012GL052013.

Watanabe, M., J.-S. Kung, F.-F. Jin, M. Collins, M. Ohba, and A. T. Wittenberg, 2012: Uncertainty in the ENSO amplitude change from the past to the future. *Geophys. Res. Lett*., **39**, L20703, doi:10.1029/2012GL053305.

Wittenberg, A. T., 2009: Are historical records sufficient to constrain ENSO simulations? *Geophys. Res. Lett*., **36**, L12702, doi:10.1029/2009GL038710.

Wittenberg, A. T., A. Rosati, N.-C. Lau, and J. J. Ploshay, 2006: GFDL's CM2 global coupled climate models, Part III: Tropical Pacific climate and ENSO. *J. Climate*, **19**, 698-722, doi:10.1175/JCLI3631.1.

Yang, X., et al., 2015: Seasonal predictability of extratropical storm tracks in GFDL's high-resolution climate prediction model. *J. Climate*, submitted.

Zhang, T., and D.-Z. Sun, 2014: ENSO Asymmetry in CMIP5 Models. *J. Climate*, **27**, 4070–4093, doi:10.1175/JCLI-D-13-00454.1.

Low-frequency variations of ENSO

Andrew T. Wittenberg

NOAA Geophysical Fluid Dynamics Laboratory

Clues from the past

Historical reconstructions of ENSO, like that in Figure 1, indicate that its behavior varies from decade to decade. During the 1960s and 1970s, the equatorial Pacific sea surface temperature anomaly (SSTA) variability was weak, with a biennial and westward-propagating character. The 1980s and 1990s were more active, with El Niños every five years - including two exceptional events that produced intense SSTAs in the far eastern Pacific, and a distinct eastward propagation of SSTAs as they transitioned into La Niñas. And since 1999, the SSTAs have weakened and shifted farther west.

Farther back in time, direct temperature measurements become sparse, and historical reconstructions become more sensitive to the methods used to impute missing data. This is especially true prior to 1880. For example, the exceptional El Niño of 1877-78 - whose impacts are well documented (Davis 2001; Aceituno et al. 2009) - is prominent in Figure 1, but was practically missing from the previous version of this reconstruction (Huang et al. 2015).

To augment the instrumental record, researchers have turned to paleoclimatic proxy records from corals, tree rings, lake sediments, and ice cores, which over the instrumental epoch show varying degrees of correlation with ENSO. Different proxies respond to different aspects of ENSO – but together they tell an intriguing story – that ENSO has existed in some form for over 100,000 years (Tudhope et al. 2001) and has evolved in response to changes in orbital parameters, CO_2, the strength of the Atlantic Meridional Overturning Circulation, and other forcings (Liu et al. 2014, An and Choi 2014a). In particular, ENSO appears to have strengthened over the past 6,000 years, due to a gradual shift of Earth's perihelion from late September towards early January.

Proxy reconstructions also suggest that ENSO's variance has waxed and waned over the last few centuries (McGregor et al. 2013; Li et al. 2013). Figure 2 shows a multi-proxy synthesis based on 14 previous studies, which suggests that ENSO's SSTAs during 1979-2009 were significantly stronger than anytime during 1590-1880. In the broader context of the past 7,000 years, ENSO's recent variance does not appear to have been unusual (Cobb et al. 2013; Carré et al. 2014). Uncertainties remain due to the indirectness of the paleoproxy/ENSO relationship – which could evolve in time

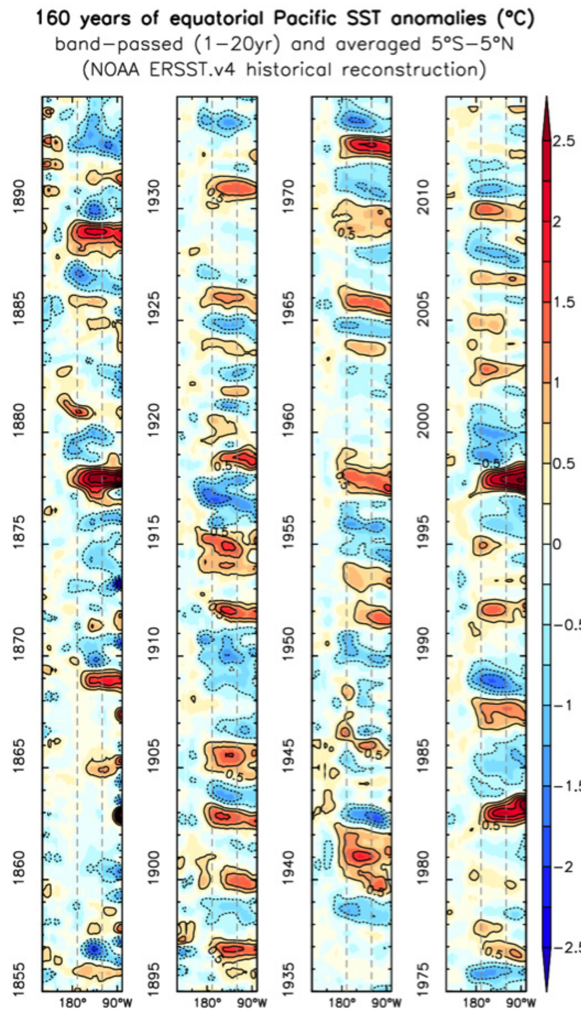

Figure 1. Longitude-time plot of equatorial Pacific ENSO SSTAs (°C, averaged 5°S-5°N) during 1855-2014 (presented as four consecutive 40-year chunks), based on the NOAA ERSST historical reconstruction version 4 (Huang et al. 2015). Contour interval is 0.5°C (zero contour omitted), and shading increments every half-contour. Gray dashed lines bracket the NINO3.4 region (170°W-120°W, 5°S-5°N). SSTAs are computed from monthly total SSTs by subtracting a 1981-2010 monthly climatology. The resulting SSTA time series is end-padded with zeros and then band-pass filtered, by first removing a convolution with a 211-month triangle, and then convolving with a 9-month triangle. The filter transmits >50% amplitude at spectral periods between 1-20yr; >90% between 2.4-12yr; and <10% outside 0.6-50yr.

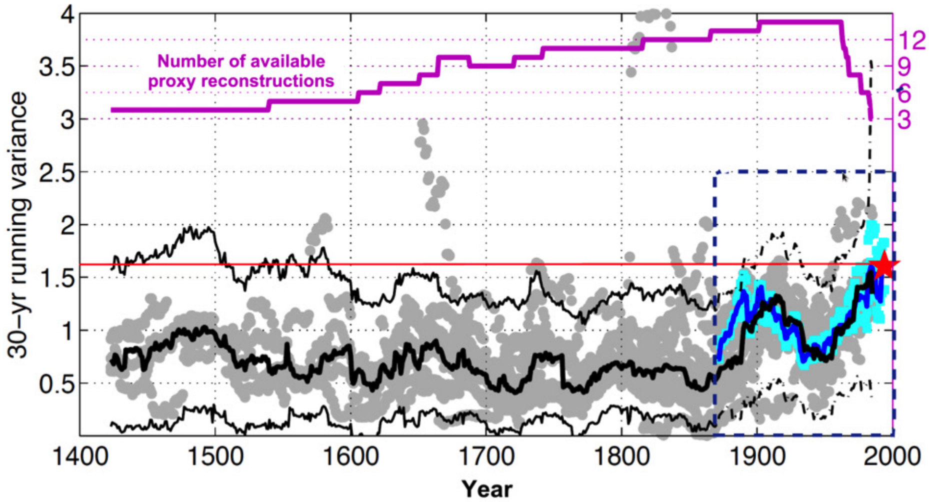

Figure 2. Proxy-reconstructed central Pacific ENSO SSTA variance over the past 600 years. Cyan squares indicate the 30-year running variance (left axis) of annual-mean (July-June) SSTAs averaged over the NINO3.4 region (170°W-120°W, 5°S-5°N), from 4 different instrumental reconstructions; blue line is their median. Magenta line indicates the number of available proxy reconstructions (right axis) based on corals, tree rings, and lake sediments. Gray dots show the 30-year running variance of the individual proxy reconstructions, each adjusted to match the instrumental variance (blue line) during 1900-1977; the thick black line is their median. Thin black lines give a proxy-based 90%-confidence band for the true running variance. Red line and star indicate the observed variance during 1979-2009. Adapted from Figure 7 of McGregor et al. (2013).

and might be poorly constrained from short instrumental records (Coats et al. 2013; Stevenson et al. 2013; Russon et al. 2015). For example, Emile-Geay et al. (2013) found that the particular choice of 20th-century instrumental dataset, used to calibrate proxy records to SSTs, exerted substantial leverage on reconstructions of the last millennium. Improved instrumental records, then, could improve understanding of ENSO not only for the instrumental era, but also farther back into the past.

An intrinsic component of ENSO modulation

General circulation model (GCM) studies have shown that multi-decadal fluctuations in ENSO behavior can occur even with no change in external forcings (Wittenberg 2009; Stevenson et al. 2012; Borlace et al. 2013). These fluctuations can then affect global climate on multi-decadal scales (Vimont 2005; DiLorenzo et al. 2010; Ogata et al. 2013). Some studies have attributed ENSO's modulation to changes in ENSO stability, driven by decadal-scale variations in the background state of the tropical Pacific and elsewhere (An & Wang 2000; Kravtsov 2012; Kang et al. 2014; Xie et al. 2014; Lübbecke and McPhaden 2014). Others have even posited a coupled feedback loop between ENSO and decadal-scale climate modes (Ogata et al. 2013; Choi et al. 2012, 2013a).

It is easily demonstrated that spontaneous multidecadal modulation can arise even from an unforced, purely memoryless process with an interannual time scale (Wittenberg 2009). Stripped-down models of ENSO, which explicitly omit interactions with external decadal modes, have also displayed intrinsic modulation that resembles observations in many respects (Cane et al. 1995; Timmermann et al. 2003; Newman et al. 2011a,b; Choi et al. 2013b). Wittenberg et al. (2014) recently showed that epochs of extreme ENSO behavior in a GCM control run could be completely disrupted by a tiny perturbation – suggesting that the intrinsic component of ENSO modulation, despite any influence it might feel from interaction with the decadal background state, is essentially chaotic and unpredictable. It remains an open question whether the ENSO modulation in models is inherently more or less predictable than in the real world (Karamperidou et al. 2014; Eade et al. 2014).

Impacts of increasing CO_2

Numerous studies have demonstrated that both natural and anthropogenic forcings can alter ENSO, in a manner detectable with sufficiently long records or large ensembles (Cane 2005; Vecchi and Wittenberg 2010; Collins et al. 2010; Li et al. 2013). But nature will provide just one realization of ENSO over the coming decades. So what will be the dominant drivers of near-term changes in ENSO behavior, and how long must we wait to detect anthropogenic impacts?

Figure 3 (next page) shows that the answer may depend on the variable and location of interest. In panel (a) for the western equatorial Pacific, each blue dot corresponds to a single 30-year chunk from a preindustrial (1860) control run of a coupled GCM. The vertical axis is the mean SST in that 30-year chunk relative to the longer-term mean of the 1860 run, while the horizontal axis is the percent amplification of ENSO SSTAs in that chunk relative to the long-term average amplitude. The horizontal spread of the blue dots represents the unforced, intrinsic modulation of ENSO amplitude among the 30-year chunks - which spans roughly a factor of two. The western equatorial Pacific cools slightly during intrinsically-generated, active-ENSO epochs, and the linearity of this relationship suggests that much of the multidecadal variability in this region is linked to ENSO modulation.

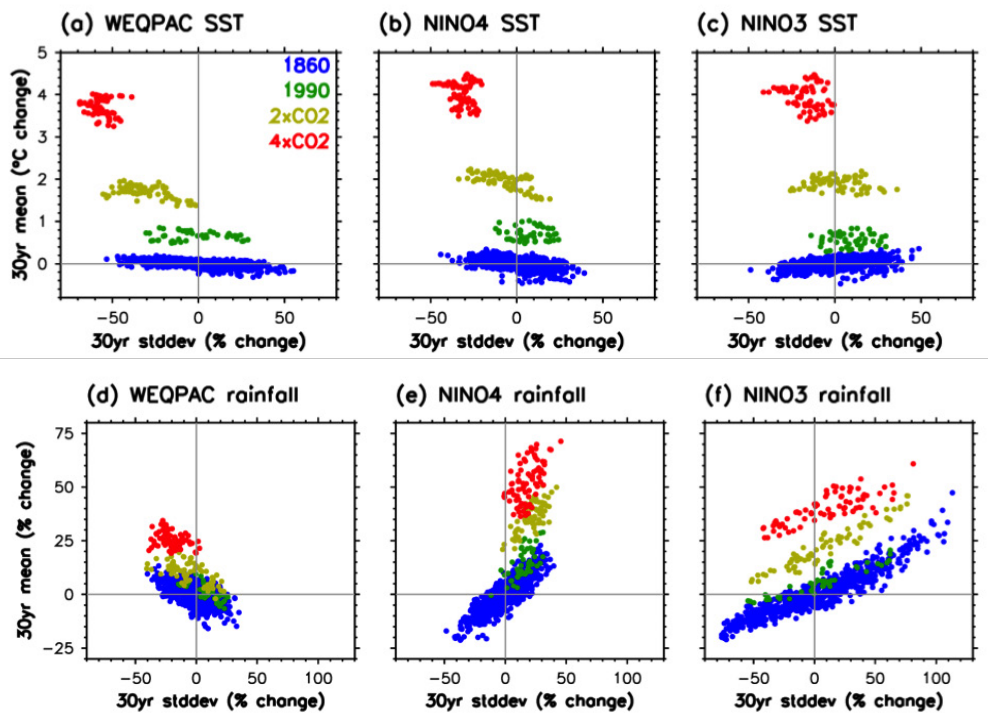

Figure 3. Scatterplots of local climate change versus local ENSO amplification, for equatorial Pacific SST and rainfall simulated by the GFDL CM2.1 global coupled GCM. Panel titles indicate averaging regions: WEQPAC (120°E-160°E, 5°S-5°N), NINO4 (160°E-150°W, 5°S-5°N), and NINO3 (150°W-90°W, 5°S-5°N). Dots indicate statistics for sliding 30-year windows sampled at 5-year intervals. Blue dots are from a 4000-year control run with solar irradiance, land cover, and atmospheric composition held fixed at pre-industrial (1860) values, and CO_2 at 286 ppmv. Green dots are from a 300-year control run with modern (1990) forcings, and CO_2 at 353 ppmv. Yellow (red) dots are from the last 400 years of a 600-year run in which all forcings are as in the pre-industrial run, except for CO_2 which increases 1% per year until doubling (quadrupling), after which CO_2 is held fixed at 572 (1144) ppmv. Abscissa indicates the percent departure of local ENSO amplitude (30-year standard deviation of running annual means) from the pre-industrial 4000-year mean amplitude. Ordinate indicates the departure of the local 30-year mean climate from the pre-industrial 4000-year mean, expressed as (a,b,c) °C of SST, or (d,e,f) percent of rainfall.

As CO_2 increases to 1990 conditions (green), then doubles (yellow) or quadruples (red) relative to 1860, the west Pacific SSTs in this model warm to previously unprecedented levels on the vertical axis - far outside the range of intrinsic variations (blue). The mean warming at this location could thus easily be detected within just 30 years, against the backdrop of intrinsic (mostly ENSO-driven) multidecadal variability in the 1860 run. Also as CO_2 increases, the ENSO SSTAs weaken (shift to the left). Given the horizontal overlap between the yellow and blue dots, the weaker ENSO at doubled CO_2 could take many decades to detect against the backdrop of ENSO modulation; but eventually the reduction in active-ENSO epochs, and the decreased interdecadal modulation (horizontal spread) of ENSO amplitude, would become obvious. At quadrupled CO_2, these ENSO changes might well be detected with just 30 years of data.

The eastern equatorial Pacific (Figure 3c) tells a different story. The blue dots indicate that east Pacific mean SSTs tend to *warm* slightly during active-ENSO epochs, the opposite of the western Pacific. This is consistent with recent studies (Ogata et al. 2013; Sun et al. 2014; An and Choi 2014b). Then as CO_2 increases, ENSO SSTAs at first strengthen up to present-day values of CO_2, then weaken at even higher CO_2. This suggests that there might be an "optimal climate" for ENSO SSTAs in the eastern/central Pacific - perhaps around present-day values of CO_2. If so, then the future of ENSO would depend not only on spatial location, but also on how close the tropical Pacific was to that climate optimum, and which side it was currently on. Taking Figure 2 at face value, one might be tempted to suggest that the increased activity during 1979-2009 evidenced an anthropogenic boost in ENSO; but Figure 3c cautions that many decades might be needed to reliably detect such a signal in the east Pacific, and that ENSO's fortunes could even reverse at still higher CO_2.

The story is even more interesting for rainfall. Looking in the central and eastern Pacific (Figure 3e,f) at the blue dots, we see that strong-ENSO epochs are associated with much wetter mean conditions (Watanabe and Wittenberg 2012; Watanabe et al. 2012). The tight relationship again suggests that most of the intrinsic decadal-scale variability in those regions could arise from chaotic ENSO modulation. The relationship also holds at higher values of CO_2, though at a much warmer and wetter level. The opposite holds in the west Pacific (Figure 3d), with drier mean conditions during active-ENSO epochs.

In the eastern equatorial Pacific (Figure 3f), the CO_2-induced changes in time-mean rainfall along the vertical axis would be obscured in short records, due to the (largely ENSO-driven) intrinsic multidecadal variations in rainfall, which causes overlap of the red and blue dots in the vertical. Similarly, changes in the amplitude of ENSO rainfall anomalies might take centuries to detect, though the decrease in amplitude modulation would eventually become apparent. But note that the yellow and red dots *do not* overlap the blue in two dimensions - thus for a *known* ENSO amplitude in a single 30-year record, it would actually be quite easy to detect a CO_2-induced enhancement of mean rainfall.

Farther west (Figure 3d,e), increased CO_2 in this simulation boosts the time-mean rainfall to unprecedented levels along the vertical axis. At the same time, the ENSO rainfall variability shifts eastward along the equator, with less variance in the west and more in the central Pacific. For the central equatorial Pacific then, increased CO_2 could *enhance* ENSO rainfall variability, despite *weakened* SSTAs (rightward shift of red dots in Figure 3e, leftward shift of red dots in Figure 3b). Most model studies suggest that in the Pacific of the future, the time-mean warming at the equator will exceed that off-equator (Liu et al. 2005; Xie et al. 2010). This could make near-equatorial rainfall more sensitive to equatorial SSTAs, especially in the central Pacific; indeed this appears to be a robust response among most climate models (Power et al. 2013; Cai et al. 2014; Watanabe et al. 2014).

Thus changes in ENSO may vary regionally, and affect different stakeholders in different ways. For a given level of CO_2, some regions could see robust increases or decreases in variability of SST or rainfall within only a few decades, while other regions might not detect ENSO changes for much longer. However, it is clear from Figure 3 that at each location, changes in CO_2 greatly alter the *likelihood* of hitherto "extreme" epochs (the fringes of the blue dots). Thus for these regions we would expect not only unprecedented increases in the *mean* SST and rainfall, but also big changes in the likelihood of epochs of strong and weak ENSO variability.

Results from CMIP projections

The Coupled Model Intercomparison Project phases 3 and 5 (CMIP3, CMIP5) tell a rather murky story about the future of ENSO - with projections ranging from strengthening, to weakening, to a change in spatial pattern, to no significant change (Vecchi and Wittenberg 2010; Collins et al. 2010; Stevenson et al. 2012; Watanabe et al. 2012; Guilyardi et al. 2012; Taschetto et al. 2014; Capotondi et al. 2015). Models at least project that ENSO will neither vanish nor explode over the coming century, with the IPCC Fifth Assessment concluding that *"there is high confidence that ENSO very likely remains as the dominant mode of interannual variability in the future… However, natural modulations of the variance and spatial pattern of ENSO are so large in models that confidence in any specific projected change in its variability in the 21st century remains low"* (Christensen et al. 2013).

Based on an analysis of CMIP3 projections, DiNezio et al. (2012) found that a competition of changes in ocean-atmosphere feedbacks tempers ENSO's response to anthropogenic forcings. A projected future weakening of the Pacific Walker Circulation (Vecchi et al. 2006) would tend to weaken equatorial oceanic upwelling – attenuating ENSO by weakening the influence of thermocline depth fluctuations on SSTs. On the other hand, CO_2-induced intensification of oceanic thermal stratification would boost subsurface zonal and vertical temperature contrasts along the equator – amplifying ENSO by strengthening the influence of zonal and vertical current fluctuations on SST. Given this competition, it is perhaps not surprising that models – which exhibit a wide range of strengths for these competing processes – also exhibit a wide range of ENSO responses to increasing CO_2.

Challenges and opportunities

The models used to project low-frequency variations in ENSO have known biases (see article by Capotondi et al., this issue). A model with the wrong level of intrinsic variability, incorrect forcings, or wrong sensitivity to forcings, might well produce a biased projection of ENSO. The projected eastward/equatorward shift of future ENSO rainfall variability (Figure 3d,e), for example, depends on SSTs in the equatorial/eastern Pacific warming faster than the off-equatorial/western Pacific (Grose et al. 2014). But a debate continues on whether that will be the case in the real world (Tokinaga et al. 2012; Newman 2013; DiNezio et al. 2013; Yang et al. 2014; Carilli et al. 2014; Sandeep et al. 2014; Bayr et al. 2014; Kociuba and Power 2015). Improved models, and better understanding of how to extrapolate from biased models to real-world sensitivities, are both greatly needed.

A major challenge for improving climate models is that the complex interplay of ENSO feedbacks – involving surface air-sea fluxes, atmospheric convective and cloud feedbacks, and three-dimensional oceanic advection and mixing - is not well constrained from the available instrumental record, in part because that record is short, and ENSO and its feedbacks are interdecadally modulated (Wittenberg 2009; Russell and Gnanadesikan 2014). Advances in data assimilation (Rosati et al., this issue) offer potential improvements in this regard. Going forward, there will be a continuing need for sustained tropical Pacific observing systems, as well as improved instrumental and paleo reconstructions of the past, to advance understanding, improve models, and enable clearer projections of ENSO's future.

References

Aceituno, P., M. del Rosario Prieto, M. E. Solari, A. Martinez, G. Poveda, M. Falvey, 2009: The 1877–1878 El Niño episode: Associated impacts in South America. *Clim. Change*, **92**, 389-416. doi:10.1007/s10584-008-9470-5.

An, S.-I., and J. Choi, 2014a: Mid-Holocene tropical Pacific climate state, annual cycle, and ENSO in PMIP2 and PMIP3. *Climate Dyn.*, **43**, 957-970, doi:10.1007/s00382-013-1880-z.

An, S.-I., and J. Choi, 2014b: Why the twenty-first century tropical Pacific trend pattern cannot significantly influence ENSO amplitude? *Climate Dyn.*, **44**, 133-146, doi:10.1007/s00382-014-2233-2.

An, S.-I., and B. Wang, 2000: Interdecadal change of the structure of ENSO mode and its impact on the ENSO frequency. *J. Climate*, 13, 2044-2055, doi:10.1175/1520-0442%282000%29013<2044%3AICOTSO>2.0.CO;2

Bayr, T., D. Dommenget, T. Martin, and S. B. Power, 2014: The eastward shift of the Walker Circulation in response to global warming and its relationship to ENSO variability. *Climate Dyn.*, **43**, 2747-2763. doi:10.1007/s00382-014-2091-y.

Borlace, S., W. Cai, and A. Santoso, 2013: Multidecadal ENSO amplitude variability in a 1000-yr simulation of a coupled global climate model: Implications for observed ENSO variability. *J. Climate*, **26**, 9399-9407. doi:10.1175/JCLI-D-13-00281.1.

Cai, W., S. Borlace, M. Lengaigne, P. van Rensch, M. Collins, G. Vecchi, A. Timmermann, A. Santoso, M. J. McPhaden, L. Wu, M. H. England, G. Wang, E. Guilyardi, and F.-F. Jin, 2014: Increasing frequency of extreme El Niño events due to greenhouse warming. *Nat. Climate Change*, **4**, 111-116, doi:10.1038/nclimate2100.

Cane, M. A., S. E. Zebiak, and Y. Xue, 1995: Model studies of the long-term behavior of ENSO. *Natural Climate Variability on Decade-to-Century Time Scales*, D. G. Martinson, K. Bryan, M. Ghil, M. M. Hall, T. R. Karl, E. S. Sarachick, S. Sorooshian, and L. D. Talley, Eds, Natl. Acad. Press, 442–457, http://www.nap.edu/openbook.php?record_id=5142.

Cane, M., 2005: The evolution of El Niño, past and future. *Earth Planet. Sci. Lett.*, **230**, 227-240, doi:10.1016/j.epsl.2004.12.003.

Capotondi, A., A. T. Wittenberg, M. Newman, E. Di Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B. Dewitte, B. Ciese, E. Guilyardi, F.F. Jim, K. Karnauskas, B. Kirtman, T. Lee, N. Schneider, Y. Xue, and S.-W. Yeh, 2015: Understanding ENSO diversity. *Bull. Amer. Meteor. Soc.*, in press. doi:10.1175/BAMS-D-13-00117.1.

Carilli, J. E., H. V. McGregor, J. J. Gaudry, S. D. Donner, M. K. Gagan, S. Stevenson, H. Wong, and D. Fink, 2014: Equatorial Pacific coral geochemical records show recent weakening of the Walker Circulation. *Paleoceanography*, **29**, 1031-1045, doi:10.1002/2014PA002683.

Carré, M., J. P. Sachs, S. Purca, A. J. Schauer, P. Braconnot, R. A. Falcon, M. Julien, and D. Lavallee, 2014: Holocene history of ENSO variance and asymmetry in the eastern tropical Pacific. *Science*, **345**, 1045-1048, doi:10.1126/science.1252220.

Choi, J., S.-I. An, and S.-W. Yeh, 2012: Decadal amplitude modulation of two types of ENSO and its relationship with the mean state. *Climate Dyn.*, **38**, 2631-2644, doi:10.1007/s00382-011-1186-y.

Choi, J., S.-I. An, S.-W. Yeh, and J.-Y. Yu, 2013a: ENSO-like and ENSO-induced tropical Pacific decadal variability in CGCMs. *J. Climate*, **26**, 1485-1501, doi:10.1175/JCLI-D-12-00118.1.

Choi, K.-Y., G. A. Vecchi, and A. T. Wittenberg, 2013b: ENSO transition, duration and amplitude asymmetries: Role of the nonlinear wind stress coupling in a conceptual model. *J. Climate*, **26**, 9462-9476, doi: 10.1175/JCLI-D-13-00045.1.

Christensen, J.,K. Krishna Kumar, E. Aldrian, S.-I. An, I. F. A. Cavalcanti, M. De Castro, W. Dong, P. Goswami, A. Hall, J. K. Kanyanga, A. Kitoh, J. Kossin, M.-C. Lau, J. Renwick, D. B. Stephenson, S.-P. Xie, And T. Zhou, 2013: Climate phenomena and their relevance for future regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, Eds., Cambridge University Press, 1217–1308, doi:10.1017/CBO9781107415324.028.

Coats, S., J. E. Smerdon, B. I. Cook, and R. Seager, 2013: Stationarity of the tropical Pacific teleconnection to North America in CMIP5/PMIP3 model simulations. *Geophys. Res. Lett.*, **40**, 4927-4932, doi:10.1002/grl.50938.

Cobb, K. M., N. Westphal, H. R. Sayani, J. T. Watson, E. Di Lorenzo, H. Cheng, R. L. Edwars, C. D. Charles, 2013: Highly variable El Niño-Southern Oscillation throughout the Holocene. *Science*, **339**, 67-70, doi:10.1126/science.1228246.

Collins, M.,S.-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F.-F. Jin, M. Jochum, M. Lengaigne, S. Power, A. Timmermann, G. Vecchi, and A. Wittenberg, 2010: The impact of global warming on the tropical Pacific and El Niño. *Nature Geosci.*, **3**, 391-397, doi:10.1038/ngeo868.

Davis, M., 2001: Late Victorian holocausts: El Niño famines and the making of the Third World. Verso Press, 465 pp. ISBN-10:1859843824.

Di Lorenzo, E., K. M. Cobb, J. C. Furtado, N. Schneider, B. T. Anderson, A. Bracco, M. A. Alexander, and D. J. Vimont, 2010: Central Pacific El Niño and decadal climate change in the North Pacific Ocean. *Nature Geosci.*, **3**, 762-765, doi:10.1038/ngeo984.

DiNezio, P. N.B. Kirtman, A. Clement, S.-K. Lee, G. Vecchi, and A. Wittenberg, 2012: Mean climate controls on the simulated response of ENSO to increasing greenhouse gases. *J. Climate*, **25**, 7399-7420, doi:10.1175/JCLI-D-11-00494.1.

DiNezio, P. N., G. A. Vecchi, and A. C. Clement, 2013: Detectability of changes in the Walker Circulation in response to global warming. *J. Climate*, **26**, 4038-4048, doi:10.1175/JCLI-D-12-00531.1.

Eade, R., D. Smith, A. Scaife, E. Wallace, N. Dunstone, L. Hermanson, and N. Robinson, 2014: Do seasonal-to-decadal climate predictions underestimate the predictability of the real world? *Geophys. Res. Lett.*, **41**, 5620-5628, doi:10.1002/2014GL061146.

Emile-Geay, J., K. Cobb, M. Mann, and A. T. Wittenberg, 2013: Estimating central equatorial Pacific SST variability over the past millennium. Part II: Reconstructions and implications. *J. Climate*, **26**, 2329-2352, doi:10.1175/JCLI-D-11-00511.1.

Grose, M. R., J. Bhend, S. Narsey, A. Sen Gupta, and J. R. Brown, 2014: Can we constrain CMIP5 rainfall projections in the tropical Pacific based on surface warming patterns? *J. Climate*, **27**, 9123-9138, doi:10.1175/JCLI-D-14-00190.1.

Guilyardi, E., W. Cai, M. Collins, A. Fedorov, F.-F. Jin, A. Kumar, D.-Z. Sun, and A. Wittenberg, 2012: New strategies for evaluating ENSO processes in climate models. *Bull. Amer. Meteor. Soc.,* **93,** 235-238, doi: 10.1175/BAMS-D-11-00106.1

Huang, B., V. F. Banzon, E. Freeman, J. Lawrimore, W. Liu, T. C. Peterson, T. M. Smith, P. W. Thorne, S. D. Woodruff, and H.-M. Zhang, 2015: Extended Reconstructed Sea Surface Temperature version 4 (ERSST. v4), Part I. Upgrades and intercomparisons. *J. Climate*, in press, doi:10.1175/JCLI-D-14-00006.1.

Kang, I.-S., H. No, and F. Kucharski, 2014: ENSO amplitude modulation associated with the mean SST changes in the tropical central Pacific induced by Atlantic Multidecadal Oscillation. *J. Climate*, **27**, 7911-7920, doi:10.1175/JCLI-D-14-00018.1.

Karamperidou, C., M. A. Cane, U. Lall, and A. T. Wittenberg, 2014: Intrinsic modulation of ENSO predictability viewed through a local Lyapunov lens. *Climate Dyn.*, **42**, 253-270, doi:10.1007/s00382-013-1759-z.

Kociuba, G., and S. B. Power, 2015: Inability of CMIP5 models to simulate recent strengthening of the Walker Circulation: Implications for projections. *J. Climate*, **28**, 20-35. ,doi:10.1175/JCLI-D-13-00752.1.

Kravtsov, S., 2012: An empirical model of decadal ENSO variability. *Climate Dyn.*, **39**, 2377-2391, doi:10.1007/s00382-012-1424-y.

Li, J., S.-P. Xie, E. R. Cook, M. S. Morales, D. A. Christie, N. C. Hohnson, F. Chen, R. D'Arrigo, A. M. Fowler, X. Gou, and K. Fang, 2013: El Niño modulations over the past seven centuries. *Nat. Climate Change*, **3**, 822-826, doi:10.1038/nclimate1936.

Liu, Z., S. Vavrus, F. He, N. Wen, and Y. Zhong, 2005: Rethinking tropical ocean response to global warming: The enhanced equatorial warming. *J. Climate*, **18**, 4684-4700, doi:10.1175/JCLI3579.1.

Liu, Z., Z. Lu, X. Wen, B. L. Otto-Bliesner, A. Timmermann, and K. M. Cobb, 2014: Evolution and forcing mechanisms of El Niño over the past 21,000 years. *Nature*, **515**, 550-553, doi:10.1038/nature13963.

Lübbecke, J. F., and M. J. McPhaden, 2014: Assessing the twenty-first-century shift in ENSO variability in terms of the Bjerknes Stability Index. *J. Climate*, **27**, 2577-2587, doi:10.1175/JCLI-D-13-00438.1.

McGregor, S., A. Timmermann, M. H. England, O. Elison Timm, and A. T. Wittenberg, 2013: Inferred changes in El Niño-Southern Oscillation variance over the past six centuries. *Climate Past*, **9**, 2269-2284, doi:10.5194/cp-9-2269-2013.

Newman, M., 2013: Atmospheric science: Winds of change. *Nat. Climate Change*, **3**, 538-539.,doi:10.1038/nclimate1915.

Newman, M., M. A. Alexander, and J. D. Scott, 2011a: An empirical model of tropical ocean dynamics. *Climate Dyn.*, **37**, 1823-1841, doi:10.1007/s00382-011-1034-0.

Newman, M., S.-I. Shin, and M. A. Alexander, 2011b: Natural variation in ENSO flavors. *Geophys. Res. Lett.*, **38**, L14705, doi:10.1029/2011GL047658.

Ogata, T., S.-P. Xie, A. Wittenberg, and D.-Z. Sun, 2013: Interdecadal amplitude modulation of El Niño/Southern Oscillation and its impacts on tropical Pacific decadal variability. *J. Climate*, **26**, 7280-7297, doi:10.1175/JCLI-D-12-00415.1.

Power, S., F. Delage, C. Chung, G. Kociuba, and K. Keay, 2013: Robust twenty-first-century projections of El Niño and related precipitation variability. *Nature*, **502**, 541-545, doi:10.1038/nature12580.

Russell, A. M., and A. Gnanadesikan, 2014: Understanding multidecadal variability in ENSO amplitude. *J. Climate*, **27**, 4037-4051, doi:10.1175/JCLI-D-13-00147.1.

Russon, T., A. W. Tudhope, M. Collins, and G. C. Hegerl, 2015: Inferring changes in ENSO amplitude from the variance of proxy records. Geophys. Res. Lett., in press. doi:10.1002/2014GL062331.

Sandeep, S., F. Stordal, P. D. Sardeshmukh, and G. P. Compo, 2014: Pacific Walker Circulation variability in coupled and uncoupled climate models. *Climate Dyn.*, **43**, 103-117, doi:10.1007/s00382-014-2135-3.

Stevenson, S., B. Fox-Kemper, M. Jochum, R. Neale, C. Deser, and G. Meehl, 2012: Will there be a significant change to El Niño in the twenty-first century? *J. Climate*, **25**, 2129–2145, doi:10.1175/JCLI-D-11-00252.1.

Stevenson, S., H. V. McGregor, S. J. Phipps, and B. Fox-Kemper, 2013: Quantifying errors in coral-based ENSO estimates: Toward improved forward modeling of $\delta^{18}O$. *Paleoceanography*, **28**, 633-649, doi:10.1002/palo20059.

Sun, D.-Z., T. Zhang, Y. Sun, and Y. Yu, 2014: Rectification of El Niño-Southern Oscillation into climate anomalies of decadal and longer time scales: Results from forced ocean GCM experiments. *J. Climate*, **27**, 2545-2561, doi:10.1175/JCLI-D-13-00390.1.

Taschetto, A. S., A. Sen Gupta, N. C. Jourdain, A. Santoso, G. Ummenhofer, and M. England, 2014: Cold tongue and warm pool ENSO events in CMIP5: Mean state and future projections. *J. Climate*, **27**, 2861-2885, doi:10.1175/JCLI-D-13-00437.1.

Timmermann, A., F.-F. Jin, and J. Abshagen, 2003: A nonlinear theory for El Niño bursting. *J. Atmos. Sci.*, **60**, 152-165, doi:10.1175/1520-0469%282003%29060<0152%3AANTFEN>2.0.CO%3B2.

Tokinaga, H.,S.-P. Xie, C. Deser Y. Kosaka, and Y. M. Okumura, 2012: Slowdown of the Walker circulation driven by tropical Indo-Pacific warming. *Nature*, **491**, 439-443, doi:10.1038/nature11576.

Tudhope, A. W., C. P. Chilcott, M. T. McCulloch, E. R. Cook, J. Chappeli, R. M. Ellam, D. W. Lea, J. M. Lough, and G. B. Shimmield, 2001: Variability in the El Niño-Southern Oscillation through a glacial-interglacial cycle. *Science*, **291**, 1511-1517, doi:10.1126/science.1057969.

Vecchi, G. A., B. J. Soden, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison, 2006: Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature*, **441**, 73-76, doi:10.1038/nature04744.

Vecchi, G. A., and A. T. Wittenberg, 2010: El Niño and our future climate: Where do we stand? *Wiley Interdisciplinary Reviews: Climate Change*, **1**, 260-270, doi:10.1002/wcc.33.

Vimont, D. J., 2005: The contribution of the interannual ENSO cycle to the spatial pattern of ENSO-like decadal variability. *J. Climate*, **18**, 2080-2092, doi:10.1175/JCLI3365.1.

Watanabe, M., and A. T. Wittenberg, 2012: A method for disentangling El Niño-mean state interaction. *Geophys. Res. Lett.*, **39**, L14702, doi:10.1029/2012GL052013.

Watanabe, M., J.-S. Kug, F.-F. Jin, M. Collins, M. Ohba, and A. T. Wittenberg, 2012: Uncertainty in the ENSO amplitude change from the past to the future. *Geophys. Res. Lett.*, **39**, L20703, doi:10.1029/2012GL053305.

Watanabe, M., Y. Kamae, and M. Kimoto, 2014: Robust increase of the equatorial Pacific rainfall and its variability in a warmed climate. *Geophys. Res. Lett.*, **41**, 3227-3232, doi:10.1002/2014GL059692.

Wittenberg, A. T., 2009: Are historical records sufficient to constrain ENSO simulations? *Geophys. Res. Lett.*, **36**, L12702, doi:10.1029/2009GL038710.

Wittenberg, A. T., A. Rosati, T. L. Delworth, G. A. Vecchi, and F. Zeng, 2014: ENSO modulation: Is it decadally predictable? *J. Climate*, **27**, 2667-2681, doi:10.1175/JCLI-D-13-00577.1.

Xie, R., F. Huang, F.-F. Jin, and J. Huang, 2014: The impact of basic state on quasi-biennial periodicity of central Pacific ENSO over the past decade. *Theor. Appl. Climatol.*, doi:10.1007/s00704-014-1150-y.

Xie, S.-P., C. Deser, G. A. Vecchi, J. Ma, H. Teng, and A. T. Wittenberg, 2010: Global warming pattern formation: Sea surface temperature and rainfall. *J. Climate*, **23**, 966-986, doi:10.1175/2009JCLI3329.1.

Yang, C., B. S. Giese, and L. Wu, 2014: Ocean dynamics and tropical Pacific climate change in ocean reanalyses and coupled climate models. *J. Geophys. Res. Oceans*, **119**, 7066-7077, doi:10.1002/2014JC009979.

ANNOUNCEMENTS

US CLIVAR Panel Nominations Due February 26

The US CLIVAR Scientific Steering Committee (SSC) seeks qualified individuals to serve on its three subsidiary Panels: Phenomena, Observations, and Synthesis (POS) Panel; Process Study and Model Improvement (PSMI) Panel; and Predictability, Prediction, and Applications Interface (PPAI) Panel.

These Panels formulate science goals and implementation strategies, catalyze and coordinate activities, and work with agencies and international partners to advance the progress of the climate research community. It is a particularly exciting time to join the US CLIVAR Panels, as they embark on planning activities to address the goals and research challenges articulated in the US CLIVAR Science Plan (released December 2013). During the next fifteen years, the program will foster understanding and prediction of climate variability and change on intraseasonal-to-centennial timescales through observations and modeling with emphasis on the role of the ocean and its interaction with other elements of the Earth system, and to serve the climate community and society through the coordination and facilitation of research on outstanding climate questions. Key research challenges include decadal variability and predictability, climate and extreme events, polar climate changes, and climate and marine carbon/biogeochemistry.

Each Panel is seeking members to enhance current strengths while adding expertise in new areas. Qualified nominees are expected to represent the broader interests of the research community, be willing and able to engage in scientific as well as programmatic discussions to advance Panel activities, and work with other members of the US and international CLIVAR communities.

- The **US CLIVAR POS Panel** seeks new panelists with expertise in one or more of the following areas: (a) observations and synthesis of ocean phenomena; (b) linkages of climate and extreme weather events; (c) ocean-sea ice and ocean-land ice interactions; (d) air-sea exchange and mixed layer dynamics; and (e) model diagnostics with focus on climate variability and predictability studies.
- The **US CLIVAR PSMI Panel** seeks new panelists with expertise in one or more of the following areas: (a) experience in a current or former Climate Process Team (CPT); (b) air-sea interaction process studies and collection of oceanographic or atmospheric observations; (c) Earth System modeling or parameterization development (potentially with connections to major climate modeling centers); (d) topical areas including large-scale ocean dynamics, Southern Ocean research, or tropical processes and sea surface temperature.
- The **US CLIVAR PPAI Panel** seeks new panelists with expertise in the following areas: (a) polar and/or Arctic climate; (b) low frequency and/or interannual-to-decadal climate dynamics and forecasts, and (c) regional climate and climate extremes—preferably with regional climate modeling experience.

New panelists will serve for a term of four years and must have an affiliation with a US institution. Self-nominations are encouraged and welcomed. To nominate yourself or a colleague, please visit the Panel Nominations Page and submit your nomination by **February 26**.

www.usclivar.org
uscpo@usclivar.org
twitter.com/usclivar

US Climate Variability and Predictability (CLIVAR) Program
1201 New York Ave. NW, Suite 400
Washington, DC 20005
(202) 787-1682

US CLIVAR acknowledges support from these US agencies:

This material was developed with federal support of NASA (AGS-0963735), NOAA (NA11OAR4310213), NSF (AGS-0961146), and DOE (AGS-1357212). Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect