U.S. CLIVAR

SUMMER 2013, VOL. 11, NO. 2

VARIATIONS

ENSO diversity

Antonietta Capotondi
University of Colorado
Guest Editor

El Niño Southern Oscillation (ENSO) is a naturally occurring mode of tropical Pacific variability, which has global impacts of highly societal relevance. It has long been known that no two El Niño events are the same, as events differ in amplitude, location of maximum sea surface temperature anomalies, evolution, and triggering mechanisms. However, the recognition that differences in the longitudinal location of the anomalies lead to different atmospheric teleconnections and impacts has stimulated a renewed interest in the ENSO phenomenon and spurred animated debates on whether there are two distinct modes of variability, such as the "Eastern Pacific" and the "Central Pacific" types, as a large body of literature has emphasized, or whether ENSO diversity can be more properly described as a continuum with some interesting flavors.

A U.S. CLIVAR workshop on ENSO diversity was held in Boulder, CO, February 6-8 2013. The workshop brought together a broad scientific community actively involved in various aspects of ENSO diversity research. One important outcome of the workshop discussions is that a clear dichotomy between Eastern and Central Pacific events is not supported by observations and models. However, different dynamical modes of the tropical

ENSO diversity in observations

Jin-Yi Yu[1] and Benjamin S. Giese[2]
[1]Department of Earth System Science, University of California, Irvine
[2]Department of Oceanography, Texas A&M University

ENSO (El Niño-Southern Oscillation) is characterized by interannual sea surface temperature (SST) variations in the eastern-to-central equatorial Pacific. In the composite ENSO event portrayed by Rasmusson and Carpenter (1982) SST anomalies develop along the coast of South America before propagating westward along the equator. However, it has become clear that there are events in which anomalies develop and remain near the International Dateline in the central equatorial Pacific. In fact, most of the El Niño events in the 21st Century (the 2002/03, 2004/05, and 2009/10 events) have had their largest SST anomaly in the western Pacific (Yu and Kim 2013). An example of an ENSO event in the east (1997) and an ENSO event in the west (2009) are shown in Figure 1. The fact that warming is observed sometimes in the east Pacific (EP), sometimes in the central Pacific (CP), and sometime simultaneously in both eastern and central Pacific (e.g., the 2006-07 event; Figure 1) has led to the suggestion that there are two types of events that represent physically distinct phenomena (Larkin and Harrison 2005; Yu and Kao 2007; Ashok et al. 2007; Guan and Nigam 2008; Kao and Yu 2009; Kug et al. 2009). There are also studies that further separate the two types of ENSO into more sub-types (Wang and Wang 2013). An alternative interpretation is that ENSO normally occurs in the central Pacific, with events sometimes displaced to the east and sometimes displaced to the west.

One of the most pressing issues in understanding ENSO is resolving whether there really are distinctly different types of ENSO, or whether there is one type of ENSO with variability in its location. In addition, ENSO diversity in location is just one of several ways in which ENSO characteristics vary from event to event. Strong and moderate ENSO events appear to evolve differently and may belong to different dynamic regimes (Lengaigne and Vecchi 2009; Takahashi et al. 2011). ENSO diversity in longitudinal location and intensity are not uncorrelated. Weak events occur across the entire Pacific (Giese and Ray 2011; Wittenberg et al. 2006; Capotondi 2013) whereas strong El Niño events are largely confined to the eastern Pacific. It is less

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Pacific ocean-atmosphere system may exist, and each ENSO event can be viewed as the superposition of these modes, resulting in a "multiplicity" of flavors.

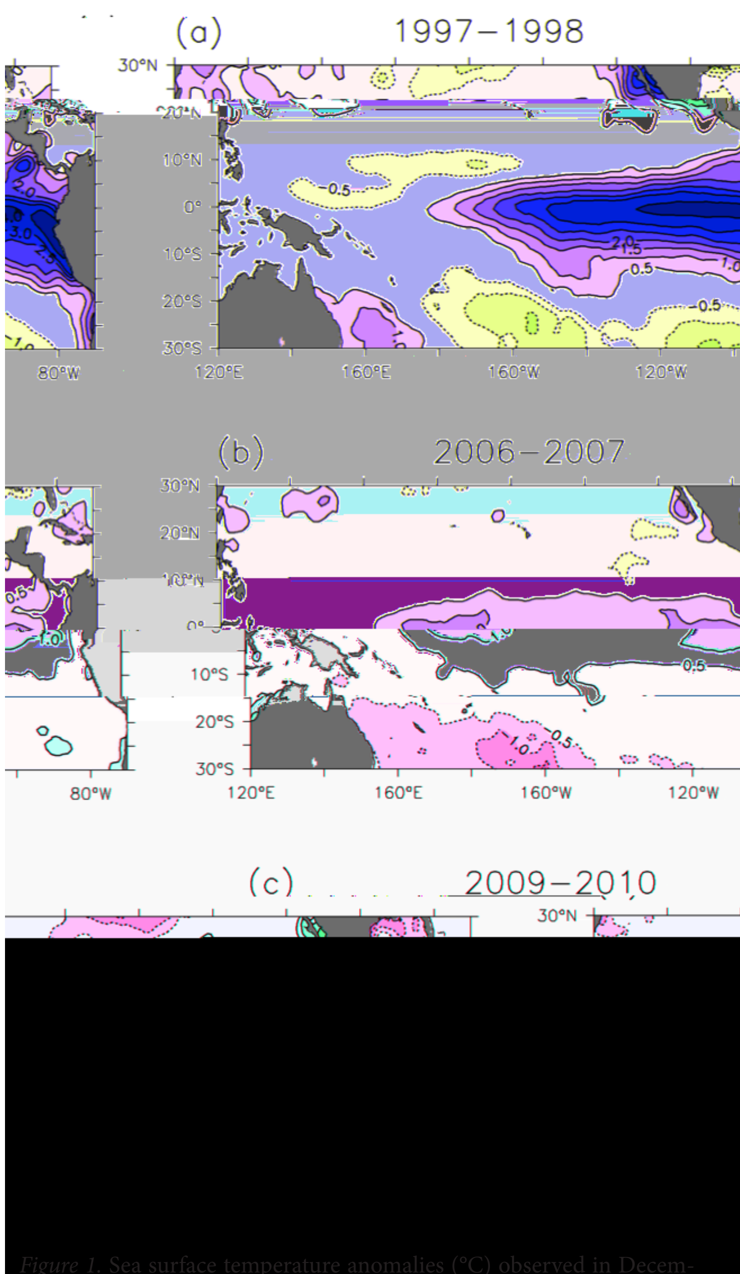
The workshop also addressed the issue of predictability of the different flavors, based on the existence of atmospheric forcing patterns and/or oceanic conditions that can be detected at some lead time, and favor the development of ENSO events. These "precursors" can be local (e.g., Westerly Wind Bursts in the western equatorial Pacific, or anomalous ocean heat content along the equator), originate from the extra-tropical Pacific (e.g., the Seasonal Footprinting mechanism in the northern tropical Pacific, and similar mechanisms from the Southern Hemisphere), or be associated with teleconnections from the Indian and tropical Atlantic Oceans. The ability of operational forecast models to predict the different ENSO flavors was also discussed at the workshop, as well as atmospheric teleconnections and impacts associated with the different flavors. Large uncertainties still remain on all of the above aspects of ENSO diversity. The articles in this issue of Variations provide a brief review of our present-state-of-knowledge on ENSO diversity, and highlight the remaining open questions.

U.S. CLIVAR VARIATIONS

Editors: Mike Patterson, Director
Jennifer Mays, Program Specialist
U.S. CLIVAR Project Office
1717 Pennsylvania Ave NW, Ste 850
Washington, DC 20006
202.419.1801 www.usclivar.org

clear what the relation between characteristics is for cold events (Newman et al. 2011; Ray and Giese 2012), but there is some evidence that strong cold events tend to occur in the central Pacific and weak cold events occur in the eastern Pacific (Sun and Yu 2009).

Ideally the issue of ENSO diversity would be resolved by the observational record. However, the observed record of SST is too short to be able to determine if there are uniquely different types of ENSO. The number of SST observations per month in the Niño 3.4 region in the COADS 2.5 database is shown in Figure 2. There are few observations for most of the 20th Century, with a dramatic increase in the last 30 years. Some ENSO diversity studies focus on this data-rich period. Lee and McPhaden (2010), for example, show an increase in intensity and occurrence of El Niño events in the central equatorial Pacific since the 1990s. However, with an average ENSO frequency of about 4 years, this means that there are only about 8 really well observed ENSO events. This may be too short of a record to definitively address the issue of ENSO diversity. To address the issue of limited ocean observations several attempts have been made to



[redacted]ber-January-February of the (a) 1997-98 El Niño event, (b) 2006-07 El Niño event, and (c) 2009-10 El Niño event.

"reconstruct" SST by using spatial patterns of variability calculated in times of dense observations (mostly the last 30 years) and using those patterns as basis functions to project SST anomalies into periods of sparse observations (e.g., HadISST, ERSST, Kaplan). There are several studies that use SST reconstructions to explore ENSO diversity (e.g., Yeh et al. 2009). But the reconstruction methodology carries a risk for identifying types of ENSO. Because the reconstructions rely on the structure of ENSO in the last 30 years (and are heavily weighted by the extreme events of 1982/83 and 1997/98), ENSO events in the reconstructions tend to look fairly similar. An alternative approach is to use an ocean reanalysis of SST. Far from being a perfect representation of the ocean state, an ocean reanalysis does not constrain SST anomalies to be like ENSO in recent years. In addition, the reanalysis uses information from the atmosphere (for example surface pressure records) via surface fluxes that complement the ocean observations. This is particularly important during times of sparse ocean observations. One such ocean reanalysis is SODA (Simple Ocean Data Assimilation; Carton and Giese 2009).

Those who emphasize the existence of two distinct types of ENSO generally suggest that these two ENSO types have different underlying dynamics. The CP ENSO has been found to be associated with subsurface ocean temperature anomalies that develop in-situ in the central Pacific (Kao and Yu 2009; Kug et al. 2009). The subsurface temperature anomalies show little of the

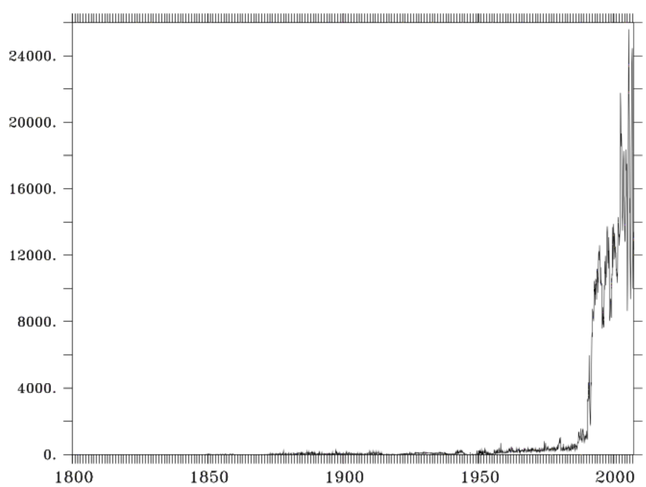


Figure 2. Number of SST observations per month in the Niño 3.4 region in the ICOADS 2.5 database.

propagation or basin-wide fluctuations characteristic of the delayed oscillator theory of the EP ENSO (Schopf and Suarez 1988; Battisti and Hirst 1989). The subsurface evolution of the CP ENSO implies that, in contrast to the EP ENSO, the underlying dynamics of the CP ENSO is not heavily dependent on thermocline variations. In the atmosphere, wind stress and precipitation anomaly patterns associated with the CP ENSO are also different from those associated with the EP ENSO. While the EP El Niño is associated with significant westerly wind stress anomalies covering a large part of the tropical Pacific, the westerly anomalies associated with the CP El Niño have a smaller spatial scale and are centered in the equatorial central-to-western Pacific (Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009). This more westward location is consistent with the location of the CP ENSO SST anomalies. Significant easterly anomalies also appear over the tropical eastern Pacific during the CP El Niño. Positive precipitation anomalies associated with the EP El Niño typically extend from the equatorial eastern to central Pacific, where the largest SST anomalies are located. For the CP El Niño, the precipitation anomalies are characterized by a dipole pattern within the tropical Pacific, with positive anomalies in the western Pacific and negative anomalies in the eastern Pacific (Kao and Yu 2009; Kug et al. 2009). Associated with wind and precipitation patterns, ocean surface current and salinity distribution have been shown to be different during these two types of El Niño (Singh et al. 2011). The different precipitation patterns imply that the associated anomalous convective heating locations and mid-latitude teleconnections are different as well (e.g., Larkin and Harrison 2005; Kim et al. 2009; Mo 2010; Yu et al. 2012; Yu and Zou 2013).

A near-surface ocean temperature budget analysis performed by Yu et al. (2010) shows that SST anomalies associated with CP ENSO undergo rapid intensification through ocean advection processes. However, they argue that the initial establishment of the SST anomalies in the central equatorial Pacific is related to forcing from the extratropical atmosphere and subsequent atmosphere-ocean coupling in the subtropics. They suggest that SST anomalies appear first in the northeastern subtropical Pacific and later spread toward the central equatorial Pacific. The specific coupling processes in the subtropics responsible for the equatorward spreading are similar to those described by the seasonal footprinting mechanism (Vimont et al. 2001). This mechanism explains how wintertime mid-latitude atmospheric variations can force subtropical SST anomalies, sustain them from winter into the next summer, and at the same time cause them to spread toward the central-to-western equatorial Pacific. The wind-evaporation-SST feedback (Xie and Philander 1994) is one of the primary coupling processes. Although it has been known for some time that extratropical sea level pressure (SLP) variations can be precursors to El Niño events (e.g., Anderson 2003; Chang et al. 2007; Alexander et al. 2010), these studies do not consider the existence of two types of El Niño. Recent studies argue that extratropical forcing is particularly important to the generation of the CP type of the ENSO (Yu et al. 2010; Yu and Kim 2011). However, further studies are still needed to more robustly demonstrate the association of the seasonal footprinting mechanism with the CP but not the EP type of ENSO.

An alternative view of ENSO diversity is that there may be a continuum, rather than two or a few distinct types of ENSO. By assigning names to ENSO events that have different characteristics (for example ENSO in the east Pacific versus ENSO in the central Pacific) suggests that we can uniquely identify how the events are different. There are many cases where a population can be categorized in this way. El Niño (warm) is distinct from La Niña (cold). But in some circumstances the characteristics do not obviously fall into well-defined categories. To address the question of different types of ENSO we need to first understand the distribution of ENSO characteristics. Giese and Ray (2011) attempt to address the question of whether there are different types of ENSO based on the location of the warm anomaly. To do that they use the first moment of the temperature anomaly, which they call the Center of Heat Index (CHI). Using an ocean reanalysis that spans the period from 1871-2008, Giese and Ray explore the distribution of the position of ENSO through the 20th Century. They find that the position of ENSO is normally distributed, so that most ENSOs are neither in the east or the west, but somewhere in the middle. They argue that EP and CP events are merely the end members of a normal distribution.

One possible way to study the ENSO diversity with the relatively short SST observation is to define ENSO indices that can separate or cluster ENSO events into different types or regimes. Several such efforts have been carried out in recent years (see Singh et al. 2011 for a summary of these indices). Several identification methods have been proposed to separate, for example, the EP and CP types of ENSO. Some of them determine the type based on the central location of surface or subsurface ocean temperature anomalies (e.g., Kug et al. 2009; Yeh et al. 2009; Yu et al. 2011). Kug et al. (2009) and Yeh et al. (2009) show that an El Niño event is classified as a CP type if SST anomalies averaged over the Niño 4 region are greater than those averaged over the Niño 3 region and vice versa for the EP type. To better separate these two types of the ENSO, Ren and Jin (2011) and Takahashi et al. (2011) propose modifications to these two Niño indices to increase the orthogonality between them. In contrast, Yu et al. (2011) use subsurface ocean temperature indices to identify the two types of ENSO. Other methods (e.g., Ashok et al. 2007; Kao and Yu 2009) have examined the spatial pattern of tropical Pacific SST anomalies to determine the type. Ashok et al. (2007), for example, argue that the CP type is characterized by an out-of-phase relation between the SST anomalies in the central Pacific and those in the eastern and western Pacific. Kao and Yu (2009) argue that the EP and CP types have different generation mechanisms and can coexist to contribute to the tropical Pacific SST anomalies, so that contrasting SST anomalies in specific regions of the Pacific cannot effectively separate the two types. Instead, they use a regression method to separate SST anomalies into components associated separately with the EP and CP types and then apply an Empirical Orthogonal Function (EOF) analysis to each of the components to obtain the leading spatial patterns of these two types. They then project tropical Pacific SST anomalies onto these two EOF patterns to determine the El Niño type.

Recent interest and efforts in the study of ENSO diversity is providing new ways to understand how El Niño may respond to and feedback to a changing climate. There is still much to learn about what causes variations of ENSO. Nevertheless, it is plausible that ENSO is changing and there is a need to re-visit the existing modeling and prediction strategies that were developed primarily for the conventional EP type of ENSO. It is unfortunate that there are only a few CP El Niño events available in the observations (less than 12 since the 1950s, depending on the way a CP event is defined). While much can still be learned from examining this limited number of events, we should look to long-term coupled climate model simulations for assistance, as well as paleoclimate records, to obtain a better understanding of ENSO diversity.

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ENSO diversity in the paleo record

Kim M. Cobb[1] and Julien Emile-Geay[2]
[1]Georgia Institute of Technology
[2]University of Southern California, Los Angeles

Reconstructions of pre-industrial El Niño-Southern Oscillation (ENSO) variability, while relatively rare, represent critical components of the observational record of ENSO, as they constrain the character and magnitude of ENSO variability for previous centuries to millennia. Such estimates serve two purposes: i) they provide important benchmarks for simulations of ENSO variability in coupled climate models, and ii) they quantify the relative importance of forced changes in ENSO (whether natural or anthropogenic) against a background of intrinsic variability in ENSO. The sensitivity of ENSO to past external radiative forcings, or lack thereof, bears on the question of ENSO's sensitivity to greenhouse gas forcing. Proxies for past ENSO variability can be divided into two categories: those that explicitly resolve ENSO over decades to centuries (corals and tree rings), along with those that more indirectly reflect ENSO's variability over many millennia (lake and marine sediments; Table 1). Multi-proxy reconstructions of ENSO employ networks of ENSO-sensitive proxy records, most commonly over the data-rich interval of the last millennium (Stahle et al. 1998; Mann et al. 2000; Wilson et al. 2010; McGregor et al. 2010; Li et al. 2011; Emile-Geay et al. 2013). Here, we highlight some of the recent advances in ENSO reconstruction, and provide examples of data-model intercomparison studies that such reconstructions enable. We close with a brief discussion of the current challenges and opportunities in paleo-ENSO research.

Proxy type	Climate sensitivity	Resolution	Length	Pros/Cons	Example references
Corals	SST, salinity	monthly	decades to centuries	Pros: explicity resolve ENSO Cons: pre-1800AD corals rare	Cole et al., 1993 Cobb et al., 2013
Tree rings	Precip	annual	centuries to millennia	Pros: networks of continuous, well-dated records Cons: teleconnected response	Stahle et al., 1998 Li et al., 2011
Lake sediments	Precip	event-based	millennia	Pros: long, continuous, in cold tongue Cons: skewness, conflates mean and variance	Moy et al., 2002 Conroy et al., 2008
Marine sediments	var(SST, salinity)	N/A	millennia	Pros: long, capture variance of cold tongue SST Cons: conflates seasonal and interannual variance	Koutavas et al., 2006 Koutavas & Joanides., 2012

Table 1. Overview of paleo-ENSO proxies with example references

Quantifying the range of intrinsic ENSO variability: Several recent studies suggest that the range of intrinsic ENSO variability is much greater than that observed in the instrumental record of ENSO. In a landmark study, Wittenberg (2009) documented a broad range of ENSO frequencies and amplitudes in a 2,000-yr-long control simulation of the GFDL CM2.1 coupled climate model. ENSO characteristics varied appreciably between multi-decadal to century-long epochs of the simulation. Qualitatively similar results come from analysis of the 1,300-yr-long control simulation from CCSM4 (Stevenson et al. 2012). These studies illustrate the limitations of the instrumental record in quantifying the long-term variability inherent in the ENSO system.

New paleoclimate reconstructions of ENSO constructed from central tropical Pacific corals provide empirical support for the model-derived estimates of ENSO variability. Monthly-resolved records from modern-day corals collected at such sites extend back in the 19th century, and are highly correlated to the NIÑO3.4 SST index on interannual timescales (R=0.8 to 0.9; Cobb et al. 2013). Fossil corals from these sites date back to 7,000 years ago, and cumulatively provide close to 1,000 year's worth of monthly-resolved ENSO timeseries (Cobb et al. 2013). The most striking aspect of the new reconstruction is the large spread of ENSO variance that they imply, with appreciable changes apparent within a single century of fossil coral data. The new paleo-ENSO variance estimates fall within the range of those calculated from previously published fossil coral records from the western and central equatorial Pacific (Tudhope et al. 2001; Cobb et al. 2003; Woodroffe et al. 2003; McGregor et al. 2004). Together, these data imply that changes in paleo-ENSO variance are roughly double those observed during the 20th century, in qualitative agreement with the ENSO variability exhibited in the control simulations of the CM2.1 and the CCSM4 climate model discussed above (Fig. 1c).

These findings carry important implications for ENSO researchers in both the climate modeling and paleoclimate domains. If these newly expanded estimates of ENSO variability are accurate, then the detection of forced changes in ENSO properties, whether natural or anthropogenic, will require time series of ENSO that span multiple centuries. For example, many of the CMIP5 projections are likely too short to fully characterize the response of a given coupled climate model to anthropogenic greenhouse forcing.

Paleo-ENSO constraints on future ENSO - near-term challenges and opportunities: The most pressing question to address with paleo-ENSO reconstructions is whether 20th century ENSO variability is statistically distinct from long-term estimates of pre-industrial ENSO variability. Several recent studies suggest that recent ENSO activity is significantly stronger than that of the recent geologic past. Based on a new reconstruction of fossil corals from the central tropical Pacific, Cobb et al. 2013 found that the corals' interannual variance was significantly higher during the 20th century than the average interannual variance for the entire reconstruction (Fig. 1a, b). In a contemporaneous study, McGregor et al. (2013) assessed the evolution of interannual variance in 14 different ENSO reconstructions over the last 600 years, compiling both single proxy records as well as multi-proxy reconstructions. They conclude that ENSO variance over the period 1979-2009 was significantly higher than ENSO variance for the last 400 years (Fig. 2). Taken at their face value, such studies suggest that ENSO may be strengthening in response to anthropogenic greenhouse forcing. However, both of these studies are associated with different types of uncertainties. In the case of Cobb et al. (2013), it is possible that the corals' original climate signals have been subtly altered by geochemical alteration over the last several millennia of exposure. In the case of McGregor et al. (2013), many of the multi-proxy reconstructions that they use to track ENSO variance may have accumulated dating errors in the older portions that average out interannual signals, leading to apparent reductions in ENSO variance.

The above discussion illustrates the profound uncertainties inherent in quantifying paleo-ENSO variance from the existing set of proxy data. First, as discussed in the previous section, multi-century records of ENSO are required to yield robust estimates of pre-industrial ENSO variance, given the high level of natural variability in ENSO. Second, proxy records often reflect

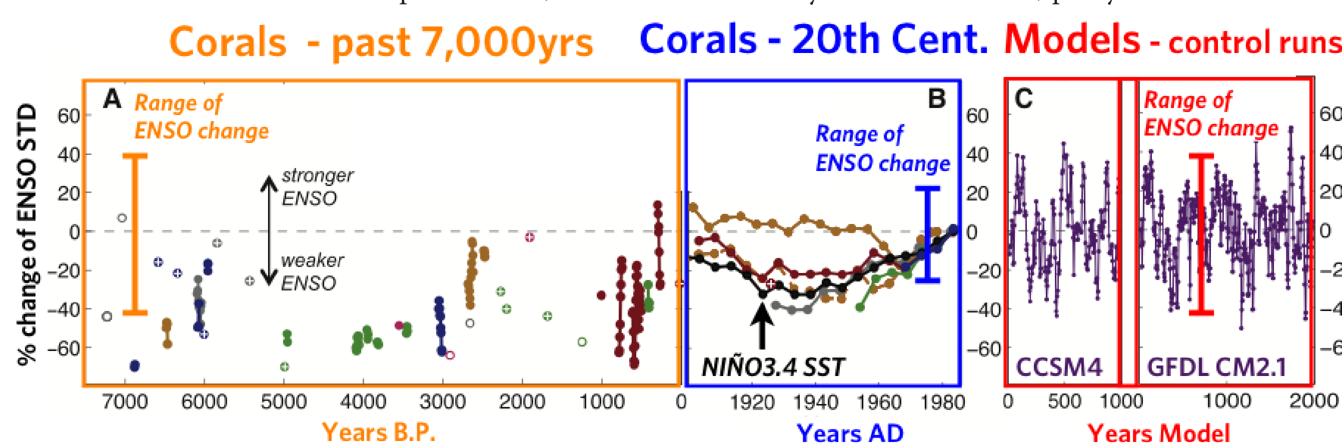

Figure. 1. Comparison of relative ENSO variance changes in fossil coral oxygen isotopic (δ18O) records (yellow box, left), 20th century coral δ18O records (blue box, middle; where colors represent coral records from different sites, and black represents the running variance of the NIÑO3.4 SST index), and the NIÑO3.4 indices of long control runs of the CCSM4 and GFDL CM2.1 coupled climate models (red box, right). Yellow, blue, and red brackets reflect the approximate range of ENSO variance across the paleo-data, instrumental era, and model control runs, respectively. Figure modified after Fig. 2 of Cobb et al. (2013).

a complex mixture of local environmental parameters that is often obscured by noise in the proxy recorder itself (see Cobb et al. 2008 and Jones et al. 2009 for reviews on high-resolution proxy uncertainties). Third, the spatial footprints of central Pacific vs. eastern Pacific ENSO extremes differ appreciably (e.g., Ashok et al. 2007), even in the core of the ENSO region. Therefore, ENSO reconstructions that rely on a single proxy record may under- or over-estimate ENSO variance during a given interval, depending on the frequency of central vs. eastern Pacific extremes. But the existing set of multi-proxy reconstructions of ENSO are not immune, given that they typically use some form of linear regression to an ENSO index such as NIÑO3 (e.g., Mann et al. 2000) or NIÑO3.4 (e.g., Emile-Geay et al. 2013). Such vagaries demand parallel multi-proxy reconstructions of central and eastern Pacific ENSO histories, which are underway for the last several centuries (Emile-Geay et al. 2012), when high-resolution proxy data are most plentiful. Coral oxygen isotopic ($\delta^{18}O$) records will play a key role in such reconstructions, as they record both sea-surface temperature and the $\delta^{18}O$ of the seawater (the latter linearly related to sea-surface salinity; Fairbanks et al. 1997; LeGrande and Schmidt 2006) at monthly resolution. While the spatial footprints of central vs. eastern Pacific ENSO-related SST anomalies are well-constrained by instrumental SST data, their corresponding salinity signals are poorly constrained by sparse datasets of sea-surface salinity (SSS).

Several recent studies have employed climate model output and reanalysis datasets to provide much-needed constraints on salinity anomalies across eastern vs. central Pacific ENSO extremes, but the accuracy of such datasets is difficult to assess. Singh et al. (2011) analyze a gridded SSS reconstruction available for the tropical Pacific (Delcroix et al. 2011) to isolate distinct salinity anomalies associated with the two ENSO “flavors”. Hasson et al. (2013) undertake a budget analysis of tropical Pacific mixed layer salinity, complementing the SSS data with salinity output from an ocean general circulation model. They find that mixed layer salinity is controlled by horizontal advection, vertical advection, and the balance of precipitation and evaporation, in roughly equal parts. Therefore, in order to take full advantage of the information contained in coral δ18O records, whether for assessment of past ENSO variability or 20th century trends in tropical Pacific climate, systematic investigations of salinity variability in both data and models will be required. As an added benefit of such an undertaking, the evolution of SSS over the 20th century can be used to probe trends in the tropical hydrological cycle (Nurhati et al. 2011; Pierce et al. 2012), given its role as “nature’s rain gauge” (Terray et al. 2012).

Ongoing efforts to model proxy records as a function of environmental and, when appropriate, biological influences, referred to as “forward-modeling”, provide a means of comparing model output with proxy records (Evans et al. submitted). Of specific relevance

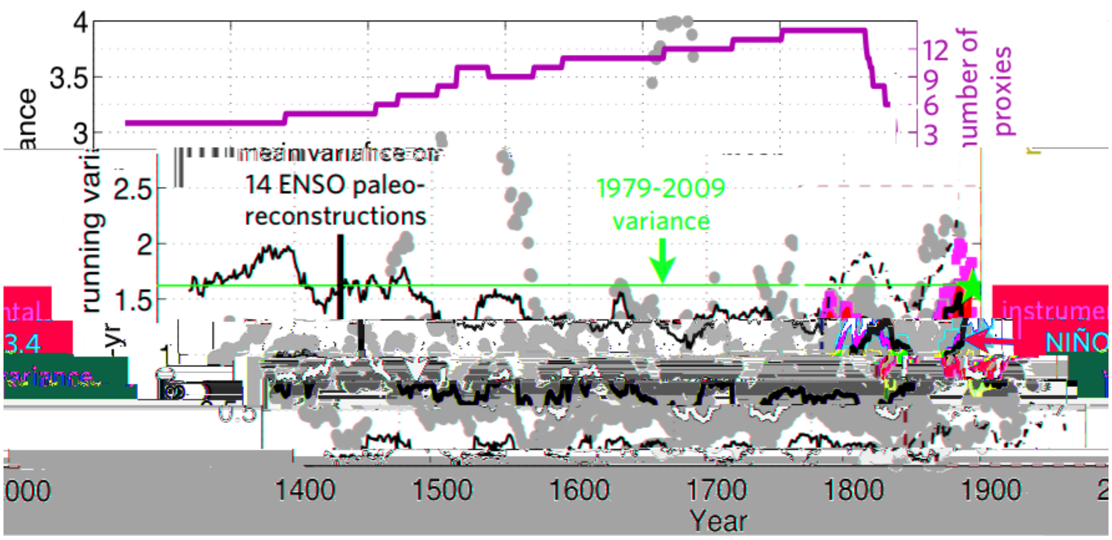

Figure. 2. Evolution of ENSO variance in 14 different proxy reconstructions of ENSO over the last 600 years, plotted as the running variance of 10-yr highpass filtered individual reconstructions (grey circles) and as their mean running variance (black line with error envelope). The number of proxy ENSO reconstructions available through time is show in pink. Also plotted is the evolution of the 10-yr highpass filtered NIÑO3.4 SST variance derived from four different instrumental products (cyan circles), with their mean running variance (blue line). The red star indicates the variance of the 1979-2009 NIÑO3.4 index. Modified after Fig. 7 of McGregor et al. (2013).

to ENSO reconstruction, forward models now exist for coral $\delta^{18}O$ (Thompson et al. 2011) and tree ring width (Tolwinski-Ward et al. 2011). As such models are further refined, they promise to unlock the full potential of paleoclimate datasets to constrain the impacts of future climate change through a mechanistic understanding of past climate variability. Such an approach is particularly well-suited to ENSO, whose response to anthropogenic forcing, if any, lies well-hidden in the relatively short instrumental record of climate.

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ENSO diversity in climate models

Antonietta Capotondi[1] *and Andrew Wittenberg*[2]
[1]*NOAA/Earth System Research Laboratory*
[2]*NOAA/Geophysical Fluid Dynamics Laboratory*

Understanding the nature of El Niño – Southern Oscillation (ENSO) diversity in observations is challenging. Due to the relatively short duration of the observational record and the sparsity of subsurface data, it is difficult to characterize different ENSO flavors, and understand their underlying dynamics, triggers, and impacts, with high statistical confidence (Vecchi and Wittenberg 2010).

Climate models can help overcome these limitations by providing long global time series of relevant physical quantities, with detailed and self-consistent surface and subsurface information. Climate model simulations exist for pre-industrial and historical periods, as well as for different climate change scenarios -- thus allowing characterization of ENSO diversity both in the context of natural variability and in the presence of anthropogenic forcing. However, climate models have biases in their ENSO simulation (as well as mean state), including amplitude, spatial pattern, spectral characteristics, and leading dynamical processes – as documented in studies that have examined the World Climate Research Program Climate Model Intercomparison Project (CMIP) phases 3 and 5 archives (Capotondi et al. 2006; Guilyardi et al. 2009; Delworth et al. 2012; Watanabe and Wittenberg 2012; Watanabe et al. 2012).

How well do climate models simulate ENSO diversity? One important aspect is the ability to represent events that differ in the amplitude and longitude of peak tropical Pacific sea surface temperature anomalies (SSTAs). Various diagnostic approaches have been proposed to characterize the longitudinal diversity. Following Kug et al. (2009), we focus on the warm ENSO phase and use SSTA averages over the Niño3 (eastern equatorial Pacific, 150˚W-90˚W, 5˚S-5˚N) and Niño4 (western/central equatorial Pacific, 160˚E-150˚W, 5˚S-5˚N) regions to stratify events by longitude. We refer to events with peak SSTAs in Niño3 as "Cold Tongue" (CT) events, and those with peak SSTAs in Niño4 as "Warm Pool" (WP) events.

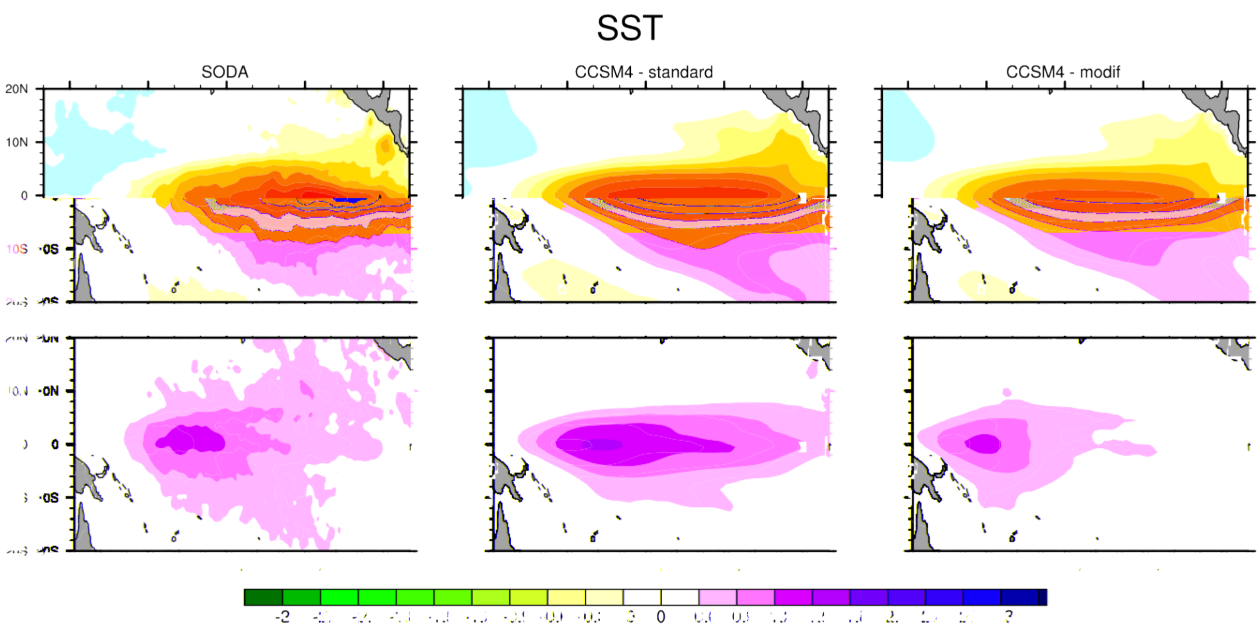

Figure 1. Composite SSTA patterns for SODA (left panels), CCSM4 (middle panels), and CCSM4 with modified indices (right panels). CT events are shown on the top row, and WP events in the bottom row. Units are °C. CT events are identified by requiring that the winter (JFM) Niño3 index is larger than 0.5°C and larger than the Niño4 index, and vice versa for WP events.

Climate models are characterized by SSTAs extending farther west than observed (Capotondi et al. 2006), and this bias may limit the models' ability to simulate events that peak at diverse longitudes. As a result, only a relatively small subset of the CMIP3 archive exhibits clearly distinguishable CT and WP extremes (Kug et al. 2010; Ham and Kug 2012), and several models show a large overlap between patterns of warming associated with the CT and WP events. Similarly, only a few models in the CMIP3 ensemble produce a realistic intensity ratio for the two El Niño types (Yu and Kim 2010).

Some models, however, do produce a rich spectrum of ENSO diversity, with characteristics similar to those observed. In this article, we show results from two climate models participating in the CMIP5: the National Center for Atmospheric Research Community Climate System Model version 4 (NCAR-CCSM4), and the Geophysical Fluid Dynamics Laboratory Climate Model version 2.1 (GFDL-CM2.1). Fig. 1 shows the spatial patterns of SSTAs, in a composite sense, for CT (top panels) and WP (lower panels) events in the Simple Ocean Data Assimilation (SODA) version 2.0.2/3 (left panels), and in the NCAR-CCSM4 (middle and right panels). This version of SODA covers the period 1958-2007, while the model results are based upon a 500-year pre-industrial control simulation. Modified indices – displaced 20° to the west of the standard Niño3 and Niño4, and defined here as Niño3-m and Niño4-m – are also examined to account for the model's tendency to displace its SSTAs west of the observed patterns. While this model bias is not very pronounced in the NCAR-CCSM4, the use of both standard and modified indices allows the identification of events whose anomalies peak at different longitudes. The relatively good agreement between SODA and the NCAR-CCSM4 is an indication of the model's ability to simulate different ENSO flavors.

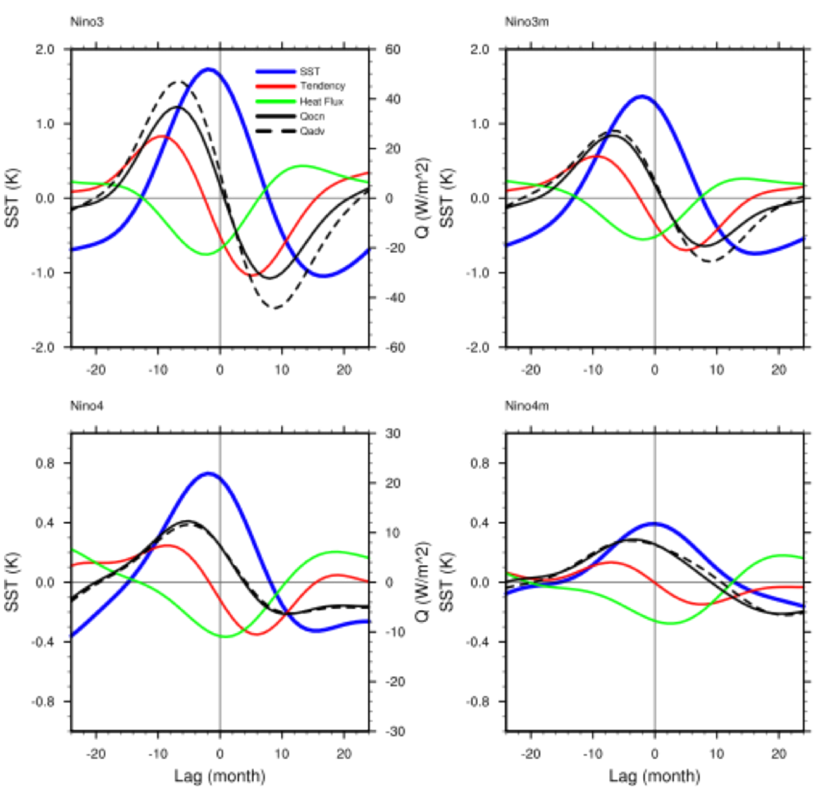

Figure 2. Composite evolution of the different heat budget terms (right y-axis) averaged over the Niño3 (top-left), Niño3-m (top-right), Niño4 (bottom-left), and Niño4-m (bottom-right) regions, and to 65m depth. For this analysis the regions extend meridionally from 2.5°S to 2.5°N, to better characterize processes that are confined near the equator, like upwelling. In each region, the composite is computed over the events peaking in that region. The SSTA evolution (thick blue curve, left y-axis) in each region is also shown for comparison. Lag 0 corresponds to the January of the event peak (events are identified by the DJF SSTA), and the evolution of each quantity is shown over a 48-month period. The black solid line shows the oceanic heat flux convergence (Q_{ocn}), computed as a residual between the tendency term (red line) and the surface heat flux (green line), while the black dashed line shows the oceanic advection term (Q_{adv}), diagnosed directly from the ocean model fields.

The dynamical processes associated with El Niño diversity in the NCAR-CCSM4 and GFDL-CM2.1 are also consistent with those found in observational studies (Kug et al. 2009). A heat budget analysis performed over the Niño3, Niño3-m, Niño4 and Niño4-m regions in NCAR-CCSM4 (Fig. 2) shows that ocean dynamical processes, in particular vertical and horizontal advection, play a key role in both the development and decay of warm events in the eastern Pacific, while in the central/western Pacific the decay of warm events is primarily due to the damping effect of the surface heat flux. Because the thermocline is shallower in the eastern than in the western Pacific, vertical advection processes are relatively more important in the evolution of eastern Pacific events, while zonal advection plays a key role in the growth of central/western Pacific events (not shown). The results for the NCAR-CCSM4 model are qualitatively similar to those obtained from the GFDL-CM2.1 model (Kug et al. 2010). Differences are found between the two models in the relative frequency of CT vs. WP cases, as well as in the exact role of different advection processes. A broader community effort toward model intercomparisons is needed to distinguish aspects of ENSO diversity that are robust from those that are model-dependent.

A key question regarding ENSO diversity is whether there is a clear bimodality with distinct ENSO types, or rather a broad continuum with interesting extremes. The short duration of the instrumental record is problematic for answering this question. Multi-proxy paleoreconstructions (e.g. Li et al. 2011; Emile-Geay et al. 2013a,b; McGregor et al. 2013) may eventually provide reliable longer records of ENSO, though these efforts are still in their infancy. Meanwhile, long model simulations can provide valuable insights. For example, a 4000-year pre-industrial control simulation from GFDL CM2.1 captures much of the observed diversity of ENSO, and permits a detailed look at the distribution of the model's ENSO events (Delworth et al. 2006; Wittenberg et al. 2006; Wittenberg 2009). Because this simulation uses unchanging external forcings, its ENSO diversity is entirely intrinsically generated. The CM2.1 simulation exhibits decadal-to-centennial modulation of its ENSO amplitude, period, skewness, spatial pattern, and predictability (Wittenberg 2009; Kug et al. 2010; Karamperidou et al. 2013), which in turn rectify into longer-term changes in the tropical Pacific mean state (Ogata et al. 2013).

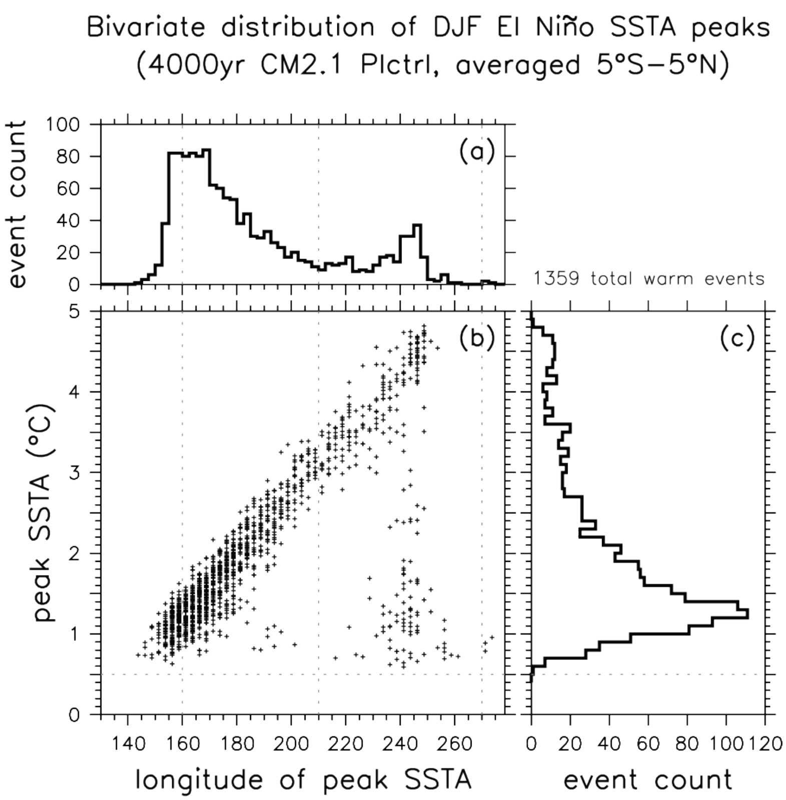

Figure 3: Distribution of equatorial Pacific SSTA maxima, for El Niños occurring in a 4000-year pre industrial control simulation from the GFDL CM2.1 coupled GCM. To qualify as an El Niño, the simulated DJF-mean SSTA averaged over either the Niño3 region (150°W-90°W, 5°-5N) or the Niño4 region (160°E 150°W, 5°S-5°N) must exceed 0.5°C. For each of the 1359 such events, the DJF-mean SSTA is averaged over the equatorial zone (5°S-5°N), and then the Pacific zonal maximum is located. (a) Distribution of peak SSTA longitudes (°E). (b) Scatterplot of the peak SSTA value (°C) versus the longitude (°E) at which it occurs. (c) Distribution of peak SSTA values (°C).

The scatterplot in Fig. 3 shows the peak DJF SSTA along the equator -- and the corresponding longitude where that peak occurs -- for every warm event in the 4000 year CM2.1 control simulation. The events with west Pacific SSTA peaks are always weak, and those with central Pacific peaks are always intermediate in strength. The strongest events always peak in the east Pacific, although east Pacific events can exhibit a wide range of amplitudes. While the marginal distribution of peak amplitudes offers no evidence of bimodality, the marginal distribution of peak longitudes does have a weakly bimodal character – with a tendency for SSTAs to peak most frequently near either 160˚E or 115˚W. However, a naive characterization of the simulated warm events as consisting of distinct "western" and "eastern" types is at odds with the bivariate distribution, which instead shows a continuum of events whose peaks shift eastward as they strengthen, plus a small group of weak cold tongue events.

One explanation for the triangular-shaped outline of the amplitude vs. longitude scatterplot in Fig. 3 may be that warming during El Niño is effectively capped at the radiative-convective equilibrium sea surface temperatures (SSTs) of the Indo-Pacific warm pool. The western equatorial Pacific, which is already near these values, has little room for additional warming. East Pacific events, however, can exhibit a wider range of strengths due to the much larger climatological difference between the local SST and the warm pool SST. Strong El Niños may produce more flattening of the equatorial thermocline, boosting vertical advective warming in the east at the expense of the west, and causing the peak warming for such events to appear in the east. Weak El Niños, in contrast, may fail to ignite such basin-wide coupled feedbacks.

One mysterious feature of Fig. 3 is the "hole" in the scatterplot triangle, indicating that moderate, central Pacific events never occur in the model. Perhaps the central Pacific is too far from the strong zonal SST gradients of the west, or the strong vertical temperature gradients of the east, to compete with the SSTAs generated at those locations. Or perhaps nascent central Pacific SSTAs are pulled westward by zonal advective feedbacks or eastward by thermocline feedbacks, causing such events to ultimately present their peak SSTAs in a different location. Further analyses are needed to understand the distributions and life cycles of these diverse events.

By providing long time series as well as platforms for perturbation experiments, CGCMs are helping to illuminate ENSO's teleconnections and impacts (Lee, this volume). As the models become more sophisticated, their simulations of ENSO's teleconnections are improving (e.g., Delworth et al. 2012). Besides being important for assessing societal and ecosystem impacts, teleconnections are also crucial for reconstructing pre-instrumental ENSO variability – since proxy recorders of ENSO (such as corals, tree rings, and lake sediments) are often remote from ENSO's centers of action in the tropical Pacific. Recent studies have used models to investigate the influence of ENSO diversity on proxy reconstructions, using simulated "pseudo-proxies" as a baseline against which to evaluate possible impacts of climatic forcings on ENSO (e.g. Emile-Geay et al. 2013a,b; Cobb et al. 2013; McGregor et al. 2013). By providing a global perspective, paleoclimate simulations can also reconcile seemingly conflicting local views seen by individual proxies (Karamperidou et al., in prep). Together, observations, models, and theory are helping to paint a more complete picture of ENSO's role in the global climate system.

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Extra-tropical precursors of ENSO flavors

Emanuele Di Lorenzo[1], Honghai Zhang[2], Amy Clement[2], Bruce Anderson[3], and Alexey Fedorov[4]
[1]School of Earth and Atmospheric Sciences, Georgia Institute of Technology
[2]Rosenstiel School of Marine and Atmospheric Science, University of Miami
[3]Department of Earth & Environment, Boston University
[4]Department of Geology and Geophysics, Yale University

Stochastic atmospheric forcing and ENSO flavors: When it comes to ENSO predictability many studies have exploited precursor dynamics in the ocean and atmosphere that lead to mature expressions of El Niño. These include dynamics associated with westerly wind bursts (WWB) with El Niño lead times on the order of half-a-year or longer (McPhaden 1999; McPhaden and Yu 1999; Fedorov 2002), and with extra-tropical wind forcing (ETWF) via the "seasonal foot-printing mechanism" (SFM; Vimont et al. 2001; Vimont et al. 2003) and the "trade wind charging" (TWC) mechanism (Anderson 2003; Anderson et al. 2013a), with lead times of ~12 months. The WWB, SFM, and TWC precursor dynamics have their origin in stochastic atmospheric variability and have been linked to stochastic excitations of ENSO (Moore and Kleeman 1999; Penland and Sardeshmukh 1995). While previous studies have explored these precursor dynamics in the context of the "canonical" or eastern Pacific El Niño, the recognition that El Niño events have different flavors like the central Pacific El Niño (Ashok et al. 2007), has opened a new discussion within the U.S. CLIVAR ENSO Diversity Working Group on the role of these precursor dynamics in energizing the different flavors of El Niño or more generally the ENSO continuum.

The WWB precursor dynamics occur in the equatorial Pacific near the Dateline where intraseasonal atmospheric variability can generate zonal wind anomalies that excite eastward propagating equatorial Kelvin waves, which in turn favor the development of El Niño by deepening the thermocline, reducing upwelling and initiating the Bjerknes feedback. Although this mechanistic link between WWB and ENSO is sometimes difficult to establish in observations, numerical simulations show that a WWB can lead to an Eastern Pacific El Niño (Lengaigne et al. 2004) if the ocean state is recharged (heat content is higher than normal). However, a more recent numerical study shows that if the ocean state is in neutral conditions the WWB lead to a central Pacific El Niño (Fedorov et al. 2013). This latter study was conducted using two sets of ensemble experiments. In the first set, the initial ocean heat content of the system is higher than the model climatology (or recharged), while in the second set it is nearly normal (neutral). For the recharged state, in the absence of WWBs, a moderate central Pacific El Niño (CP) develops in about a year. In contrast, for the neutral state, there develops a weak La Niña. However, when the WWB is imposed, the situation dramatically changes: the recharged state slides into an eastern Pacific El Niño (EP), possibly of an extreme amplitude, while the neutral set shifts into a weak CP El Niño instead of previous La Niña conditions. The different response of the system to the exact same perturbations is controlled by the initial state of the ocean and the subsequent ocean-atmosphere interactions involving the interplay between the warming of the eastern equatorial Pacific and the eastward shift of the warm pool. In this modeling framework the central Pacific El Niño can be considered as a failed excitation of the eastern Pacific El Niño in which the development of the Bjerknes feedback is arrested. Consequently, the occurrence of different types of El Niño, including extreme events, may depend on stochastic atmospheric processes.

Similar to the WWB, ENSO variability in the tropics has also been linked to stochastic variability of ETWF generated by the 2nd mode of sea level pressure variability in the atmosphere, also referred to as the North Pacific Oscillation (Fig. 1a). The NPO-generated ETWF can initiate a precursor sea-surface temperature anomaly (SSTa) pattern in the extra-tropical North Pacific (Fig. 1b), the optimal growth of which results in an eastern Pacific El Niño about 9-12 months later (Fig. 1c; Penland and Sardeshmukh 1995). The growth of this pattern is associated with the persistence of the NPO "seasonal footprint" onto SSTa into spring and summer when it subsequently influences the ocean-atmosphere coupling over the tropical Pacific (Vimont et al. 2001; Alexander et al. 2010). At the same time, observational and numerical results suggest that the NPO-generated ETWF also influences subsurface temperature anomalies across the equatorial and off-equatorial Pacific (Anderson 2004; Anderson and Maloney 2006). The NPO surface wind anomalies lead to a trade wind-induced charging of the heat content of the tropical Pacific and a subsequent initiation of El Niño onset (Anderson et al. 2013a). This NPO forcing not only initiates the onset of ENSO events, it can also modify the longitudinal positioning of the subsequent events (Anderson et al. 2013b). Indeed studies on the central Pacific ENSO now argue that the NPO is particularly important in the excitation of the central Pacific El Niño events (Yu and Kim 2011; Kim et al. 2012). A simple statistical analysis of the precursor patterns for the central Pacific El Niño shows the same NPO structures in the SLPa and SSTa (Fig. 1d, e, f) that are found for the eastern Pacific El Niño. This implies that NPO wind forcing can energize both flavors of ENSO. The selection of the type of ENSO response likely depends on the state of the tropical ocean (charged vs. discharged; Anderson 2007; Alexander et al. 2010), as in the case of the WWB.

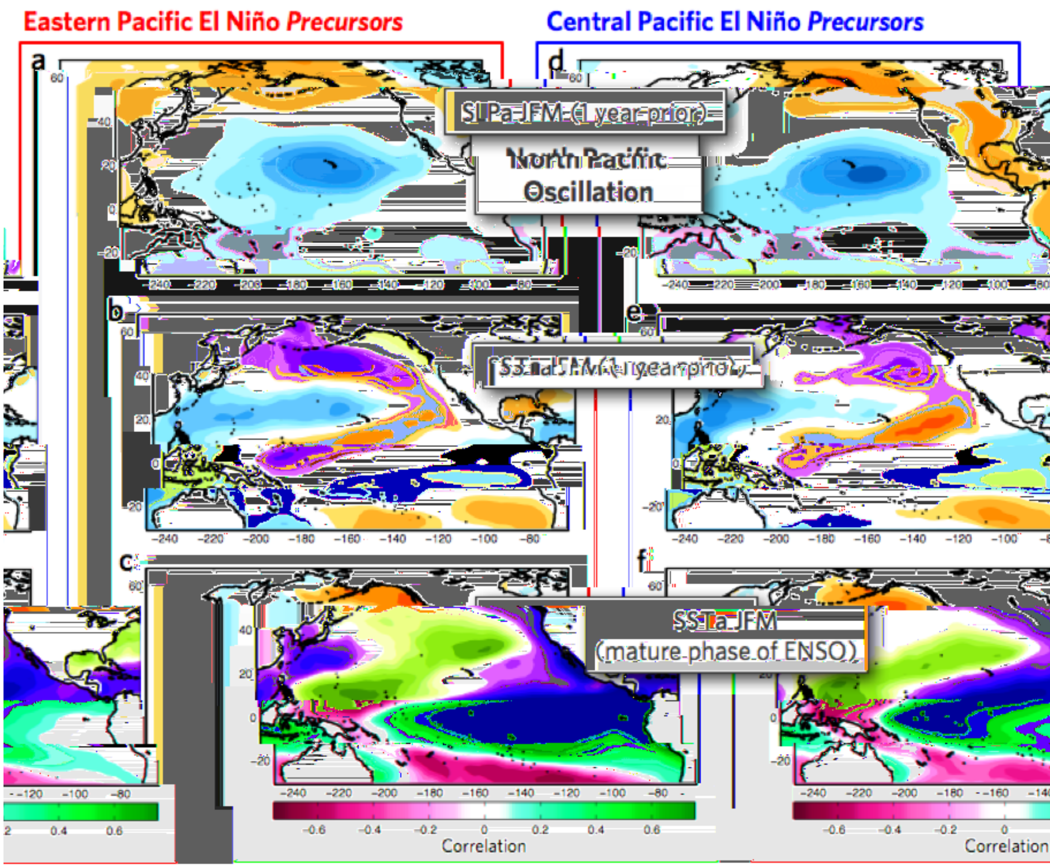

Figure 1. Extra-tropical El Niño precursors in North Pacific SLPa and SSTa. Correlation maps of Niño34 index with SLPa (a) and SSTa (b) in the January/February/March (JFM) one year prior to the mature phase of the eastern Pacific El Niño (c). The same analysis is performed using the central Pacific El Niño index (d,e,f). The maps use the NOAA SSTa and NCEP SLPa. Figure courtesy of Di Lorenzo et al. (2013).

Meridional Mode and Extra-Tropical Precursors of ENSO: While the WWB forcing mechanism occurs along the equatorial zonal plane, the ETWF mechanisms take place along the meridional plane. The coupled air-sea interactions along this plane are connected to the so-called North Pacific Meridional Mode (NPMM;

Chiang and Vimont 2004; Chang et al. 2007). In the NPMM dynamics, the extratropical meridional gradient in SSTa (Fig. 2a, b, c) forced initially by a reduction of trade winds associated with NPO-type atmospheric variability exerts a positive feedback that further weakens the winds and strengthens the existing SSTa gradient. The feedback is through the wind speed impact on anomalous evaporation and is also referred to as the wind–evaporation–SST (WES) feedback (Xie 1999). This positive thermodynamic feedback supports a southwestward co-evolution of the oceanic SSTa and winds that ultimately make it into the tropics where they have the ability to favor ENSO condition through a weakening of the Walker cell associated with the positive SSTa.

The NPMM dynamics are well reproduced in atmospheric general circulation models coupled to a simple slab ocean (AGCM-SLAB, Fig. 2a). The absence of active ocean dynamics in the AGCM-SLAB allows for the meridional modes, which rely only on thermodynamic coupling, to become the dominant modes of variability in a tropical basin (Vimont 2010). In fact in the tropical Atlantic, where the ocean dynamic coupling and ENSO feedbacks are weak, the meridional mode is the dominant mode of ocean and atmosphere variability (Chang et al. 1997). In the Pacific, meridional mode dynamics can generate ENSO-type variability also in the absence of ocean dynamic coupling by exploiting the positive cloud feedback (Clement et al. 2011). In the AGCM-SLAB the signature of the NPMM is clearly isolated by regressing an index of SSTa in the center of action of the mode (21°N–25°N, 138°W–142°W) with SSTa and SLPa (Fig. 2a). A similar analysis performed on fully coupled models and observations (Fig. 2c, e) reveals the

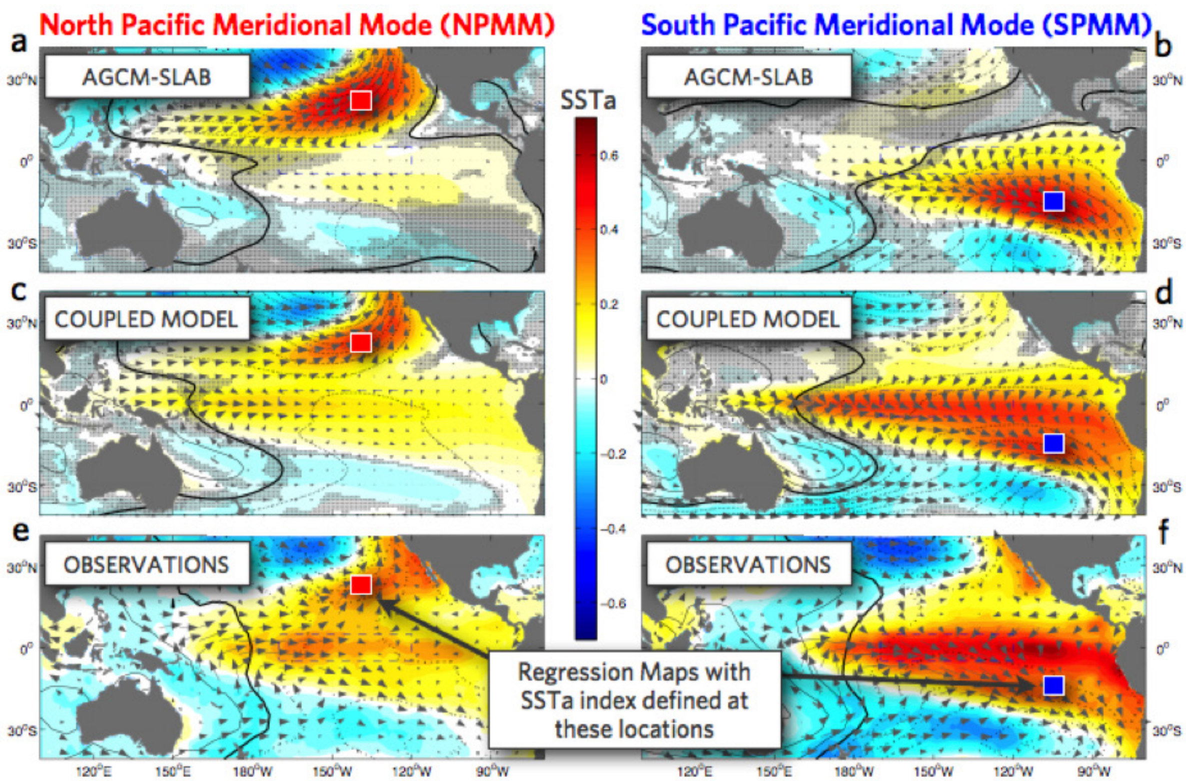

Figure 2. North and South Pacific meridional modes in observations and models. Regression of SSTa (shading), SLPa (contours) and surface winds (arrows) onto normalized SSTa time series averaged in Northeast (21°N–25°N, 138°W–142°W) (left column, red box) and Southeast (19°S–15°S, 103°W–107°W) (right column, blue box) Pacific, respectively. Top panels (a, b) are a multi-model mean of 11 AGCM-slab models, middle ones (c, d) show the same but for fully coupled version (preindustrial scenario) and bottom ones (e, f) indicate observation. All panels share the same color scale and all arrows are plotted relative to the same scale vector (0.5m/s). Negative SLP contours are dashed and positive contours solid with zero SLPa contours in heavy solid lines. Contour interval is 10Pa. Observations include the Met Office SST and SLP data and NCEP reanalysis surface winds. Figure courtesy of Zhang et al. (2013).

same NPMM pattern as in the AGCM-SLAB with the addition of a stronger SSTa signature in the equatorial Pacific associated the interactions with the ENSO zonal dynamics, which are now present.

In the South Pacific, a similar mode of thermodynamical variability, defined as the South Pacific Meridional Mode (SPMM), has recently been proposed by Zhang et al. (2013) on the basis of climate models with different degrees of coupling as well as observations. The signature of the SPMM is isolated in models and observations by regressing an index of SSTa in the center of action of the SPMM (19°S–15°S, 103°W–107°W) with SSTa and SLPa (Fig. 2b, d, e). Similar to the NPMM, AGCM-SLAB experiments show that the SPMM gives rise to the ENSO-like variability even in the absence of ocean-atmosphere dynamical coupling (Fig. 2b). When interactive ocean dynamics are included the SPMM signature shows also a clear ENSO signature in coupled climate models (Fig. 2d) that resembles the observed (Fig. 2f). Further, for one standard deviation of the SST indices used in the regression, the ENSO signal associated with the SPMM is larger than that for the NPMM (Fig. 2c versus Fig. 2d, Fig. 2e versus Fig. 2f), suggesting that the South Pacific has a stronger coupling to the tropical Pacific than the North Pacific. In fact, Zhang et al. (2013) argue that the SPMM acts as a potential precursor of the eastern Pacific ENSO. Because of the geographical location of the meridional modes center of actions, the NPMM exhibits an equatorial signature that is more reminiscent of the central Pacific El Niño while the SPMM has a more direct link to the eastern Pacific El Nino (Fig. 2). This result suggests that the two ENSO flavors may have different extra-tropical origins.

ENSO Precursor and Climate Change: As we try to resolve the uncertainties of how ENSO may be altered by climate change, one potentially important approach is to understand how the dynamics of the extra-tropical precursor patterns may change under greenhouse gas forcing. Given the important role that North and South Pacific meridional modes play in energizing different flavors of ENSO, it becomes critical to clearly identify the atmospheric stochastic forcing patterns that energize the meridional modes (e.g., NPO) in climate models and explore how the statistics of these patterns are influenced by natural and anthropogenic changes in the mean state. This approach may also prove useful to explore how Pacific decadal variability may be altered by climate change forcing. The interaction between meridional modes (e.g., thermodynamic coupling) and zonal dynamics along the equator (e.g., dynamic ocean coupling) not only have a strong control on the interannual ENSO timescale but also play a dominant role in energizing Pacific decadal variability (Di Lorenzo et al. 2013).

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The diversity of El Niño in the North American Multi-Model Prediction System

Ben P. Kirtman, Johnna M. Infanti, and Sarah M. Larson
Rosenstiel School of Marine and Atmospheric Science,
Department of Meteorology and Physical Oceanography,
University of Miami

Introduction: The longitudinal position of the center of maximum sea surface temperature anomaly (SSTA) associated with El Niño has become the subject of considerable scientific interest and debate. Much of the debate centers on whether there are two kinds of El Niño – the canonical El Niño that has its maximum close to the coast of South America and the second kind that has its maximum in the central Pacific – or whether there is simply a continuum of events (see the **ENSO Diversity Workshop report** and references therein for a full discussion of the key issues; Takahashi et al. 2011; Giese and Ray 2011; Newman et al. 2011; Kao and Yu 2009; Yeh et al. 2009; Kug et al. 2009; Larkin and Harrison 2005).

In this work, we are agnostic with respect to whether there are two kinds of El Niño or a continuum. We simply acknowledge that there is considerable variability in the central longitude of the maximum SSTA, and we ask whether the current generation of climate prediction systems can capture this variability. We do, however, need language to distinguish between warming that tends to maximize in the east and warming that tends to maximize further to the west. For simplicity, we will refer to this as central Pacific (CP) warm events and east Pacific (EP) warm events.

Our approach is to assess whether current models capture the variability in the location of maximum warming within the context of the North American Multi-Model Ensemble (NMME) prediction experiment. The NMME experiment includes nine state-of-the-art coupled ocean-land-atmosphere models in which retrospective forecast have been initialized each month of 1982-2009, and six of the nine models quality in terms of SSTA and rainfall anomalies. We include rainfall anomalies in the assessment given their potential importance for remote teleconnections. The forecast assessment summarized here is described in more detail in Kirtman et al. (2013b) along with an estimate of the limit of predictability give by the same set of model forecasts.

Overall Forecast Quality: The overall forecast quality of the NMME retrospective forecasts using deterministic and probabilistic metrics is provided in Kirtman et al.

(2013a). The analysis presented here focuses on the January-February-March (JFM) seasonal mean and we consider short lead times (i.e., forecasts initialized near January 1 of the same year as the JFM season) and long leader lead times (i.e., forecasts initialized near September 1 of the year before the JFM season). As an overall measure of the forecast quality we show in Fig. 1 the short lead and long lead correlation between the grand ensemble mean[1] predicted SSTA and precipitation anomaly with the observational estimates. The correlations are calculated based on forecasts initialized each January and each September from 1982-2009, and the confidence interval is noted on the figure. Conventional wisdom also suggests that correlations greater then 0.6 are indicative of skillful forecast.

Not surprisingly, for both lead times the SSTA correlation is larger than the rainfall anomaly correlation. At short leads the SSTA correlation (top left) is relatively large throughout most of the region shown, but particularly large and statistically significant (at the 99% confidence interval) in the central Pacific. The SSTA correlation falls off slightly in the far eastern Pacific at short leads. There are also notable relatively large correlations at short leads in the northern sub-tropics in the far west and central Pacific and in the eastern southern sub-tropics. The short lead relatively large rainfall correlations (bottom left) are more tropically confined compared

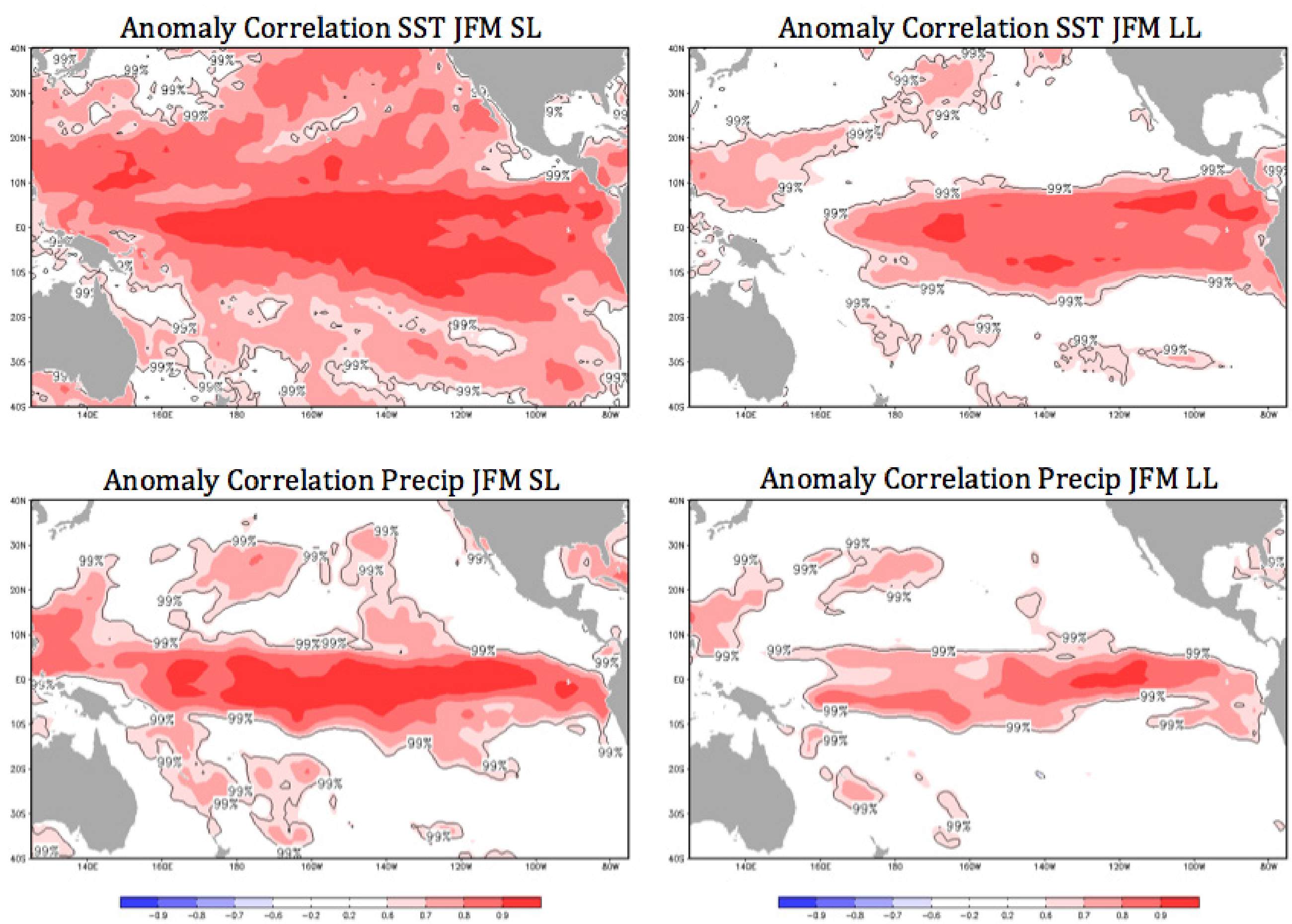

Figure 1. SSTA and precipitation anomaly correlation between the NMME grand ensemble mean and observational estimates for JFM 1982-2009. Left column shows the correlation for short lead (0.5 months) and the right column shows the correlation for long lead (3.5 months) retrospective forecasts. The SSTA correlation is given in the top row and the bottom row give the precipitation anomaly correlation. The contours indicate the 99% confidence interval that the correlation is different from zero.

[1] The grand ensemble mean is the average of all ensemble members where each ensemble member has equal weight. It should be noted that some models provide more ensemble members than others. This means that models that provide more ensemble members have greater influence over the grand ensemble mean.

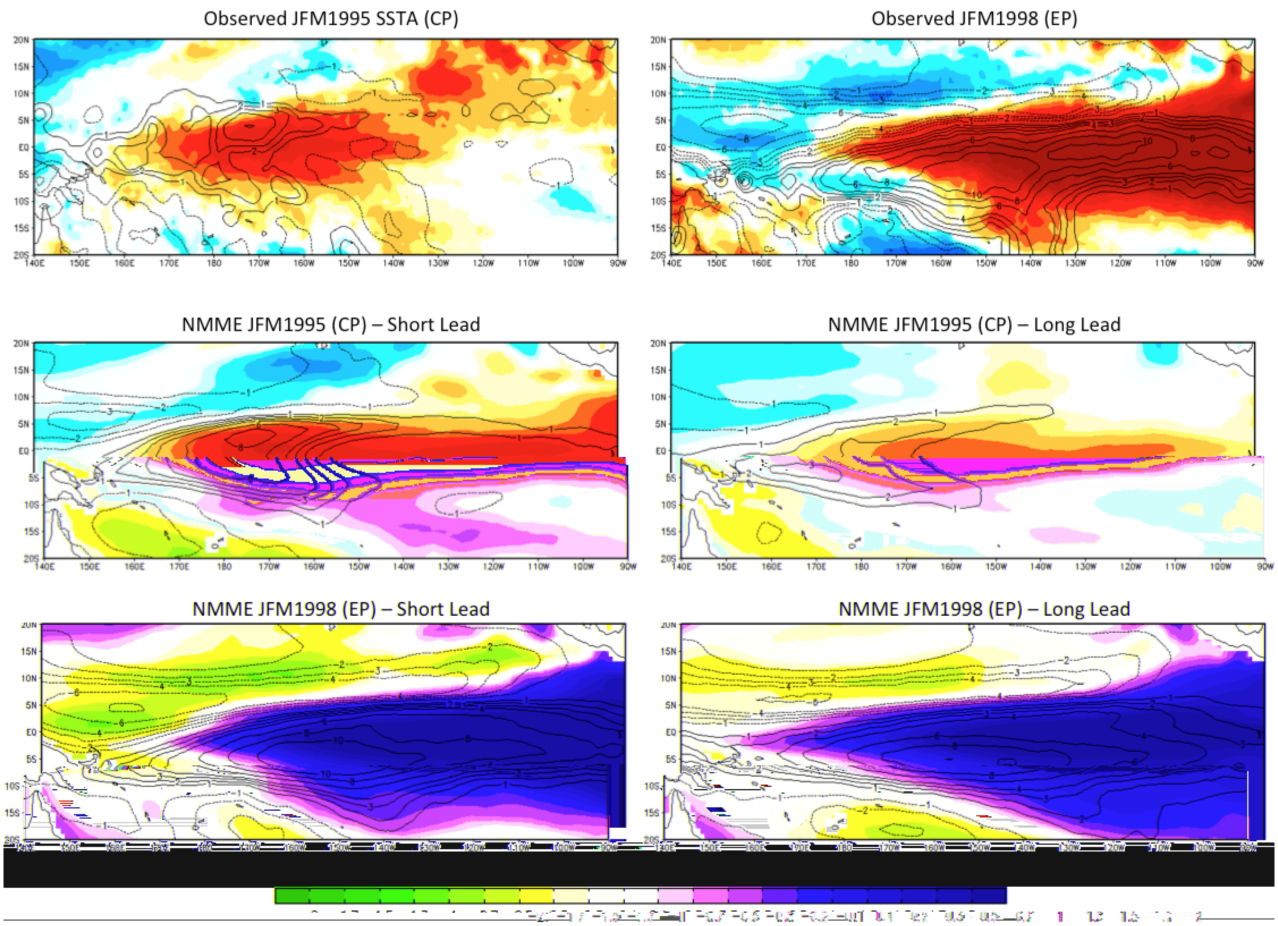

Figure 2. The top row shows SSTA (shaded) and rainfall anomaly (contours) for observational estimates for JFM1995 and JFM1998. Middle row shows the NMME grand ensemble mean JFM1995 SSTA and rainfall anomaly retrospective forecast for short leads (left panel) and long leads (right panel). The bottom row is the same as the middle row except for JFM1998. The rainfall anomaly contour interval is 1 mm day-1 and the SSTA is in °C.

to the SSTA, but there is also a suggestion of larger and more significant correlations narrowly confined to the equator in the eastern Pacific. At longer leads the above comments generally hold with a ubiquitous reduction in the correlation and the area of large confidence interval.

NMME Retrospective Forecast of CP and EP Events: In terms of the diversity of El Niño, Kug et al. (2009) provide a detailed classification of the events from 1970-2005. We have examined all of these events (that our record contains), but for the sake of brevity we focus on two cases that exemplify maximum warming in the west (JFM1995) and in the east (JFM1998), however we also briefly consider the composites of all east Pacific events versus west Pacific events as defined by Kug et al. (2009)[2] . For example, Figure 2 shows SSTA (shaded) and precipitation anomaly (contours) for the observational estimates, and the grand ensemble mean for the short lead (SL) and long lead (LL) NMME retrospective forecast for both JFM1995 and JFM1998. The observational estimates (top row) show a marked contrast between the warming of JFM1995 and JFM1998 – the maximum warm anomaly in JFM1995 is centered around 170°W, whereas in 1998 the maximum warming is shifted considerably further east, and 170°W is near the transition between warm and cold. Consistent with the differences in the SSTA, the rainfall anomaly is considerably larger and extends much further east in JFM1998.

[2] As defined in Kug et al. (2009) the west Pacific events in this record are JFM1991, JFM1995, JFM2003, JFM2005 and the east Pacific events are JFM1983 and JFM1998.

Overall, the NMME grand ensemble mean retrospective forecasts capture the contrast in terms of amplitude and more relative warming in the west vs. the east with respect to the two events, and the associated differences in the rainfall. However, it is also apparent that the forecast for JFM1995 has too much warming in the east even though this warming weakens considerably in the longer lead forecast (Fig. 2 middle right). The short lead rainfall anomaly for JFM1995 is considerably larger than the observational estimate, whereas the amplitudes for the JFM1998 hindcasts are quite comparable to the observational estimates. In some sense, it is also arguable that the rainfall anomaly contrasts between JFM1995 and JFM1998 may be better captured then the SSTA contrasts, i.e., there is clear indication at both short and long lead that the rainfall anomaly is pegged to the western Pacific.

In the same general format as Fig. 2, Fig. 3 shows the SSTA composite for central Pacific warm events (JFM1991, 1995, 2003 and 2005) and for east Pacific warm events (JFM1983 and 1998). The observed estimates of the SSTA composites are shown in the top row, the short lead retrospective predictions are shown in the middle row and the bottom row shows the long lead retrospective predictions for the NMME grand ensemble mean. The root mean squared error for the respective forecast is shown in contours. As with the individual event shown in Fig. 2, the distinction between EP and CP warm

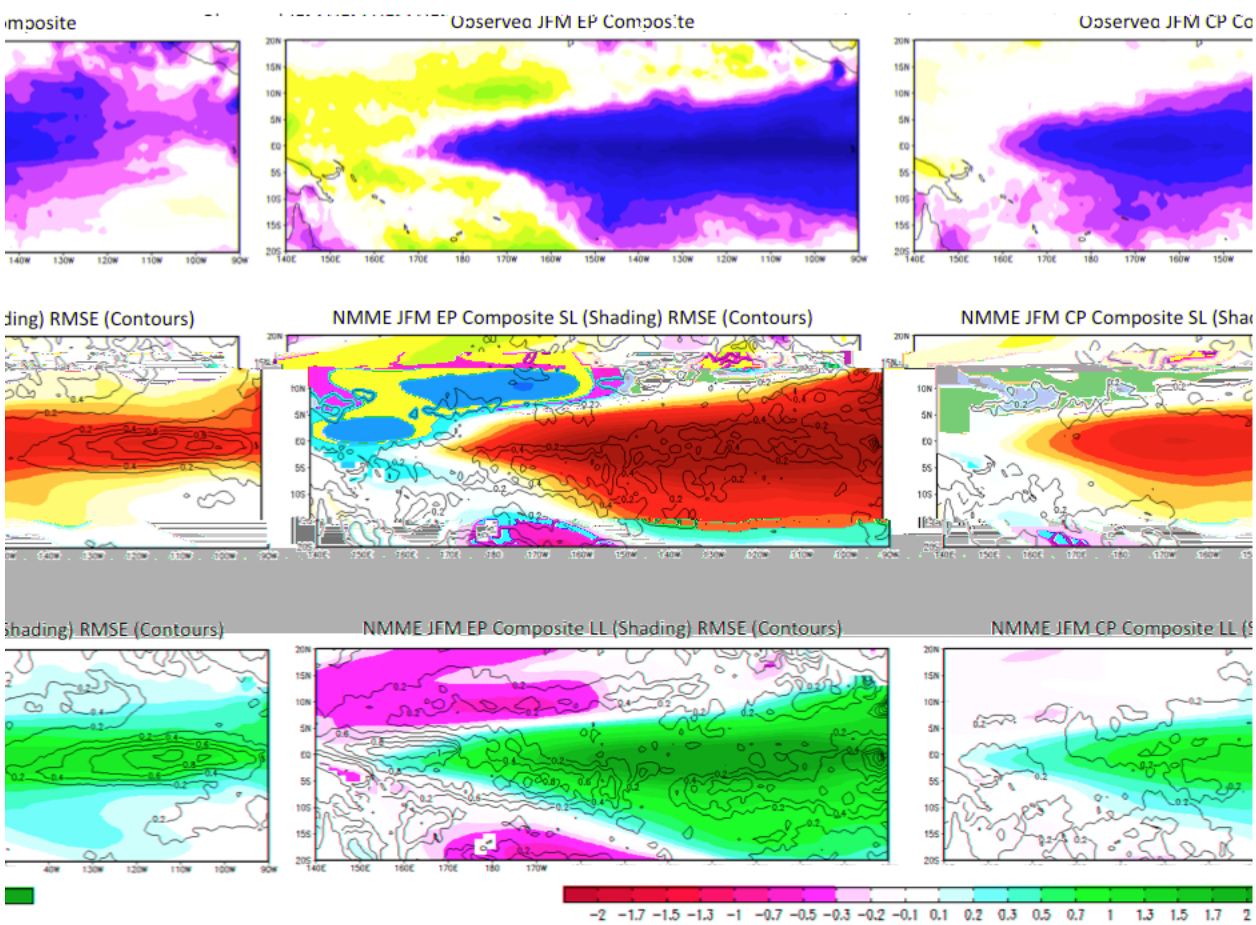

Figure 3. Top row shows the observed estimate for the SSTA composite (JFM1983 and JFM1998) for eastern Pacific events (left panel) and the SSTA composite (JFM1991, JFM1995, JFM2003 and JFM2005) for central Pacific events. The middle row shows the SSTA composite from the NMME grand ensemble mean at short lead for eastern Pacific events (left panel) and central Pacific events (right panel). The bottom row is the same as the middle row except for long lead retrospective forecasts. The bottom two rows also include the root mean squared error (RMSE) of the retrospective forecast composites. The SSTA is show in °C and the contour interval for the RMSE is 0.2 °C.

events is detected in composites and to a lesser degree the retrospective forecasts. In particular, very little of the observed east-west contrast in the warming can be detected in the long lead CP composite retrospective forecasts (bottom left panel). Most striking is the fact that the short lead RMSE is considerably larger for the CP events, especially in the east, even though they are typically weaker then EP warm events. At long lead, the eastern Pacific errors in the CP warm events are comparable to the western Pacific errors in the EP events.

Figures 2 and 3 raise the question as to whether the NMME models can predict the variability in the position of maximum warming. In order to address this issue further we consider each member of the ensemble. For example, Fig. 4 shows the JFM1995 (top row) and JFM1998 (bottom row) short and long lead SSTA along the equator in the Pacific for all 108-ensemble members (grey curves). The grand ensemble mean is in blue and the observational estimate is in red. At short lead, most, but not all of the individual ensemble members in the JFM1995 case have maximum warming to the west of 140°W, whereas in the short lead JFM1998 case all ensemble members have maximum warm anomalies

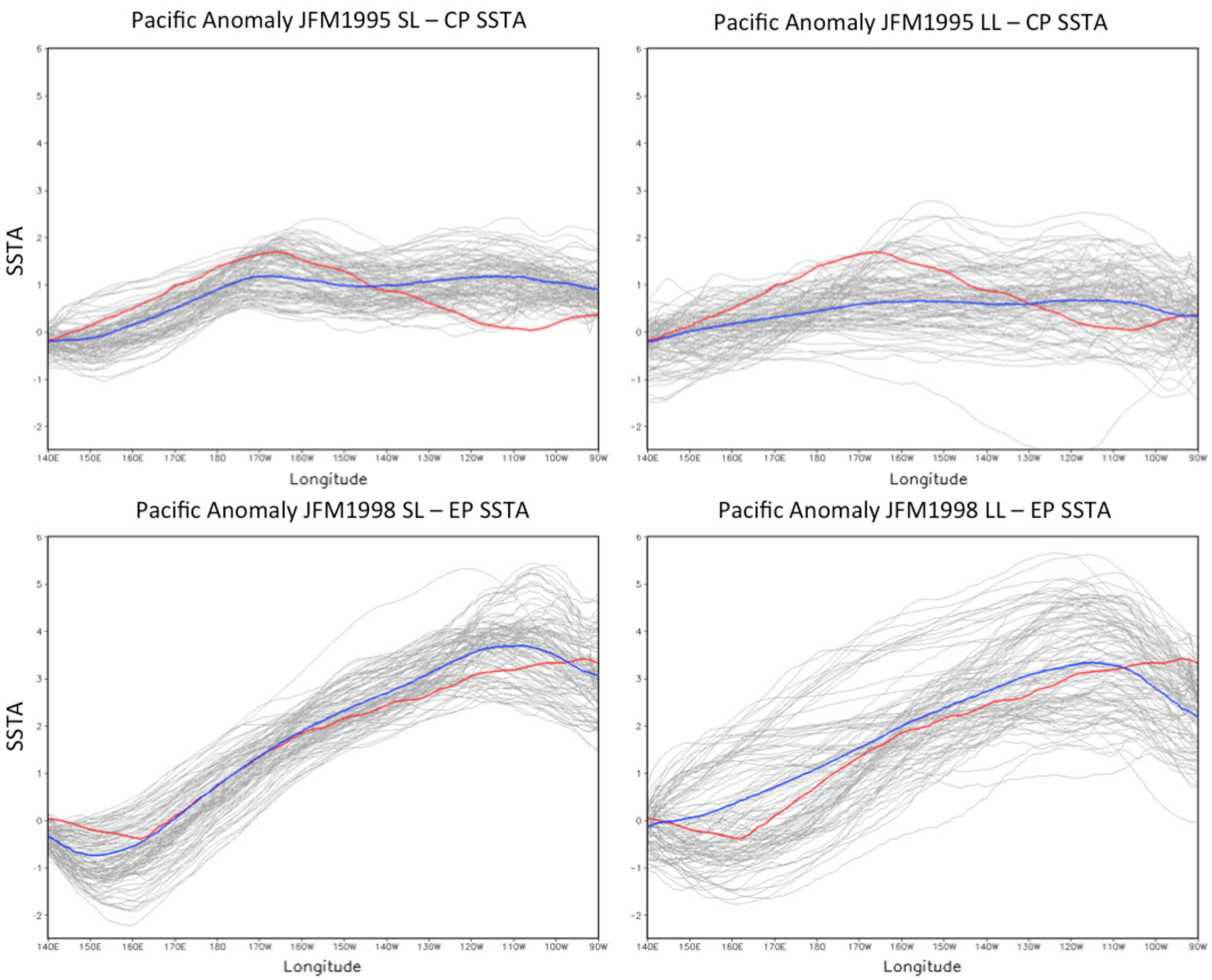

Figure 4. The curves show SSTA (°C) along the equator (2°S-2°N) in the Pacific for the individual ensemble members (grey), the grand ensemble mean (blue) and observational estimates (red). The left column corresponds to short leads and the right column corresponds to long leads. The top row is forecasts for JFM1995 and the middle row is for forecast for JFM1998.

to the east of 140°W. We also note that at short lead the observational estimate for eastern Pacific SSTA lies outside the plume of the NMME forecasts. At long lead, the JFM1995 ensemble members are nearly evenly split between maximum warming in the east vs. the west. In contrast, 90% of the long lead JFM1998 ensemble members produce more warming in the west compared to the east. It is also worth noting that a significant number of the JFM1998 long lead forecasts have warm anomalies that extend too far into the far western Pacific.

Summary: Here we showed a brief assessment of the NMME prediction quality ENSO events. Our emphasis was to focus on contrasting events that have their maximum warming in the east versus the central or western Pacific. Overall, the NMME experimental system captures the east-west contrast in the SSTA; however, it is also clear that the models systematically produce too much warming in the east compared to the observational estimates for events that have more localized warming in the west. This is particularly notable at relative short lead-times. Events that have maximum SSTA in the east appear to be better predicted at both short and long leads.

We also examined how well the NMME models predict the east-west contrast in the tropical rainfall anomalies. As with the SSTA, much of the east-west contrast is captured, but there is a suggestion that the models over-predicted the positive rainfall anomalies when the maximum warming is shifted further west.

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Teleconnection and impacts of ENSO diversity

Tong Lee
Jet Propulsion Laboratory, California Institute of Technology

ENSO is known to have far-reaching atmospheric teleconnection and widespread impacts around the world. The global response to ENSO is determined by the spatiotemporal structure of SSTA in the tropical Pacific. While there are diverse patterns of tropical SST variability, the diversity of their global impacts may be limited by their projections onto a far smaller number of "optimal SST forcing patterns" to which the global climate is most sensitive (e.g., Barsugli and Sardeshmukh 2002). Remote climates are affected by atmospheric teleconnection, which are most sensitive to SSTs over the Indo-Pacific warm pool region where atmospheric deep convection is most active. While the atmospheric sensitivity to SSTAs is lower over the eastern equatorial Pacific cold tongue, the ENSO SSTAs also tend to be stronger there. The remote impacts, which are a product of both the sensitivity and the SSTA forcing amplitude, tend to be controlled mostly by SSTAs in the central equatorial Pacific, where both the SSTAs and the atmospheric sensitivity are strong. Thus to the extent that different ENSO "flavors" produce the same SSTA projection on the patterns of atmospheric response, they can produce similar remote teleconnection. However, even then there can be spatial shifts that are subtle in a global sense but nevertheless critical for regional stakeholders. In addition, many stakeholders (e.g., those along the west coast of South America) are directly affected by ENSO's impacts on local upwelling and SST, regardless of the global atmospheric response.

A suite of studies in the past few years have discussed the different teleconnection and impacts associated with ENSO diversity, on a wide range of subjects such as rainfall pattern, land temperature, tropical cyclones, ocean biology, and stratospheric temperature. Many dynamical processes associated with the teleconnection and different regional responses have been discussed (e.g., atmospheric Rossby wave trains, the North and South Pacific Meridional Modes, the Walker Circulation and Hadley cell, tropical coupled ocean-atmosphere processes associated with the zonal advective and thermocline feedbacks, oceanic processes associated with horizontal advection and vertical advection/mixing, etc.). Examples of some of these studies are highlighted below to illustrate the scope of the research on ENSO diversity teleconnection and impacts. Note that the names El Niño Modoki, CP-El Niño, and warm-pool El Niño are used interchangeably below (respecting the way it was called in various papers discussed).

Based on analysis of observational data mainly from 1979-2005, Ashok et al. (2007) found that, like the classical El Niño, El Niño Modoki also significantly influence the temperature and precipitation patterns over many parts of the globe. Depending on the season, the impacts over regions such as the Far East (including Japan), New Zealand, western coast of the United States, are opposite to those of the conventional El Niño. Weng et al. (2007) found that the three relatively strong El Niño Modoki events during the 1979-2005 period have very different atmospheric teleconnection patterns from those associated with the three conventional El Niño events during the same period, resulting in different impacts on dry/wet conditions in the Pacific Rim during boreal summer.

Yu and Kim (2011) examined the teleconnection between leading patterns of extratropical (20°N-60°N) Pacific sea level pressure (SLP) with CP- and EP-El Niño. They found that the first mode of extratropical Pacific SLP (Aleutian Low) could be excited by both CP- and EP-ENSO, with the latter having a stronger and more immediate impact than the former. They also found that CP-ENSO is an extratropically excited mode of tropical Pacific variability, and that the decay of an EP-ENSO could lead to the onset of a CP- ENSO with the aid of the second mode extratropical Pacific SLP, the North Pacific Oscillation (NPO). CP-El Niño and NPO have also been linked on decadal time scales (e.g., Di Lorenzo et al. 2010; Furtado et al. 2011). In particular, Di Lorenzo et al. (2010) suggested that, on decadal time scales, CP-El Niño force changes in the extratropical atmosphere that in turn drive decadal fluctuations of the North Pacific Gyre Oscillation (an oceanic response to NPO).

El Niño's effect on the wintertime temperature over the continental U.S. had been traditionally described as a dipole pattern with warmer (colder)-than-normal temperatures over the northern (southern) states. Yu et al. (2012) found that this is because of a mixture of effects from EP- and CP-El Niño, with EP-El Niño generally causing a warmer northeast and colder southwest, and CP-El Niño generally causing a warmer northwest and colder southeast (Figure 1). The two flavors of El Niño also caused different regional patterns of wintertime precipitation over the U.S. because of different perturbations of the jet streams (Yu and Zou 2013). Ashok et al. (2009) found that El Niño Modoki events have a larger impact on Southern Hemisphere wintertime storm track activities than conventional ENSO and

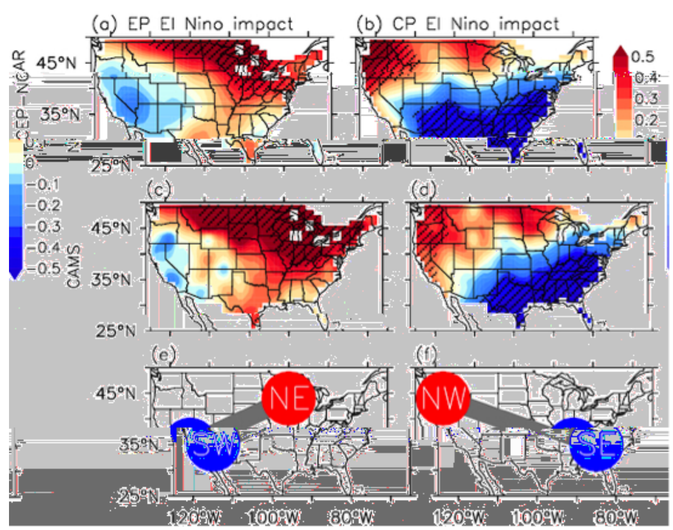

Figure 1. Observed U.S. winter (January–February–March) surface air temperature anomalies regressed onto the (left) EP and (right) CP El Niño indices. Observations correspond to (a, b) the NCEP-NCAR reanalysis and (c, d) the CAMS air temperature data set. Regression coefficients significant at the 90% confidence level based on the student-t test are shaded. (e, f) Schematic diagrams of the EP and CP El Niño impacts on U.S. winter surface air temperatures are also shown. After Yu et al. (2012).

Indian Ocean Dipole (IOD) events. In particular, El Niño Modoki events introduced an anomalous blocking over central eastern Australia, which suppressed the storm track activity reducing the storm-associated rainfall. On the other side the basin, the storm track activity in central Argentina was enhanced owing to the strengthened upper air westerlies. Lee et al. (2010) found that the strongest CP-El Niño observed in the past three decades, the 2009-10 event, caused a different impact on the South Pacific and western Antarctica than the strongest EP-El Niño, the 1997-98 event. In particular, the 2009-10 CP-El Niño event was linked to the 30-year record warming in the south-central Pacific and Wet Antarctica.

Kim et al. (2009) reported that the two flavors of El Niño have substantially different impacts on the frequency and tracks of North Atlantic tropical cyclones (Figure 2). Different from the classical EP-El Nino, CP-El Nino was generally associated with a greater-than-average frequency and increasing landfall potential along the Gulf of Mexico and Central America. These differences were associated with the modulation of vertical wind shear in the main development region forced by different teleconnection patterns associated with the two flavors of El Niño. They also argued that CP-El Niño is more predictable than EP-El Niño and therefore has a corresponding potential to increase the predictability of cyclones on seasonal time scales. Chen and Tam (2010) found that the frequency of tropical cycles (TC) in the western North Pacific is significantly positive correlated with the ENSO Modoki Index and negatively correlated with the Nino3 index, suggesting the different impacts of the two flavors of El Niño on TC in the northwest Pacific. They also discussed the associated difference in atmospheric teleconnection patterns. Wang and Wang (2013) noted that El Niño Modoki events that have SST anomaly structure being symmetric and asymmetric about the equator are associated with different rainfall patterns in Southern China and Typhoon tracks. Lee et al. (2013) discussed the optimal ENSO SSTA structure that can enhance large-scale atmospheric processes (advection of different air masses from different latitudes, changes in vertical wind shear, etc.) that are conducive to tornado outbreaks in the U.S.

The changes in the ocean circulation associated with ENSO diversity also affect ocean biology. Classical EP-El Niño is known to cause a substantial reduction in chlorophyll-a (chl-a) concentration in the eastern equatorial Pacific. Analysis of satellite-based ocean color data (Radenac et al. 2012) indicate that CP-El Niño events tend to cause a significant reduction of chl-a concentration in the central-equatorial Pacific rather than the eastern-equatorial Pacific. Gierach et al. (2012) contrast the differences in the physical state and chl-a concentration between the 1997-98 event, the strongest EP-EL Niño observed by satellites, and the 2009-10 event, the largest CP-El Niño event observed by satellites. They find that the large reduction of chl-a concentration in the eastern equatorial Pacific during 1997-98 is primarily due to the decrease of subsurface nutrient supply as a result of the reduced upwelling and vertical mixing associated with the weakened trade wind; the reduction of chl-a in the central-equatorial Pacific during 2009-10 was primarily a result of the westward advection of nutrient-depleted waters from the warm pool region associated with the anomalous westward surface current.

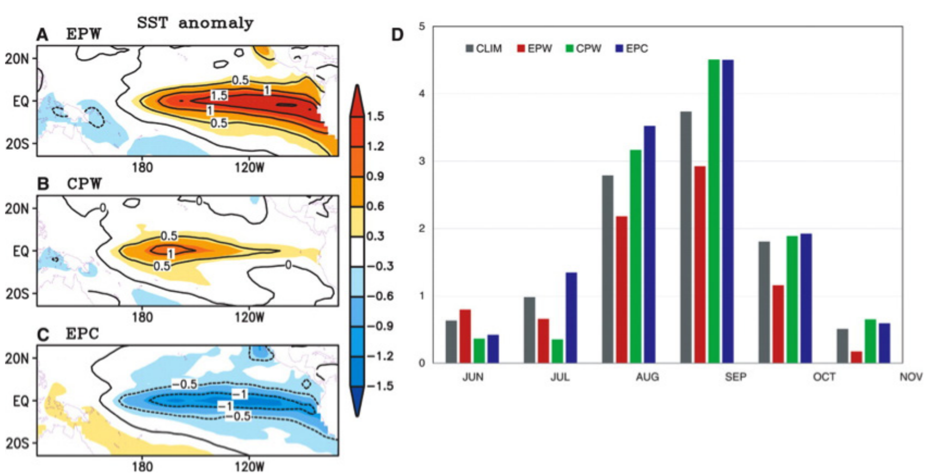

Figure 2. Composites of SST anomalies (contours interval is 0.5°C) during the August to October period for (A) EPW, (B) CPW, and (C) EPC. (D) The average number of North Atlantic tropical cyclones per month from June to November for climatology (gray bar), EPW (red), CPW (green), and EPC (blue). The time series has been detrended to eliminate the effects of decadal variability or climate trends. After Kim et al. (2009).

Studies of the teleconnection and impacts of ENSO diversity are not limited to the ocean and the troposphere, there have also been related studies for the tropopause and stratosphere as well (e.g., Hurwitz et al. 2011a,b; Xie et al. 2012; Zubiaurre and Calio 2012). For example, Hurwitz et al. (2011a) found that the Southern Hemisphere stratosphere responds differently to the two flavors of El Niño: EP-El Niño events have little impact on Antarctic stratosphere temperature. During CP-El Niño events, the poleward extension and increased strength of the South Pacific convergence zone favor an enhancement of planetary wave activity (during September-November) and leading to higher polar stratospheric temperatures and a weakening of the Antarctic polar jet in November and December.

Challenges and opportunities: The research on the teleconnection and impacts of ENSO diversity are often limited by the duration of the observational record or reanalysis products, especially in the presence of effects due to other climate modes such as the Arctic Oscillation, Southern Annual Mode, Indian Ocean Dipole, the Quasi-biennial Oscillation. This affects the statistical significance of the estimated differences between different flavors of El Niño. Therefore, sustaining various observing systems, especially the TOGA-TAO array or a system that evolves from it, is indispensible for ENSO diversity research. Paleo proxy data are becoming more useful in studying the history of ENSO before the instrumentation period. However, the interpretation of mechanisms of teleconnection and impacts from the proxy data are challenging. CMIP models provide an important tool for studying ENSO and the related teleconnection and impacts, in particular, in hypothesis testing. These perspectives are described in the article by Capotondi and Wittenberg in this volume. Moreover, it is imperative to enhance the effort to evaluate the ability of CMIP5 models to reproduce the structure of ENSO during the modern instrumentation period (including the diversity and mechanisms) and to provide recommendation to CMIP6 for the necessary improvement. Many areas of the teleconnection and impacts of ENSO diversity remain to be opportunities for further research. Among these are better understanding of the teleconnection mechanisms, the interaction of ENSO diversity with other climate modes and decadal variability, how the teleconnection and impacts might be different under a changing climate, and ENSO diversity effects on ecosystem structure and the carbon cycle.

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The NOAA MAPP Climate Prediction Task Force

Vasu Misra
Florida State University

The Climate Prediction Task Force is an initiative of NOAA's Modeling Analysis, Predictions, and Projections (MAPP) Program to achieve significant new advances in current capabilities to understand and predict intra-seasonal to inter-annual (ISI) climate variability. The Task Force primarily brings together MAPP-funded scientists from universities, research laboratories, and NOAA operational centers and research laboratories, hence leveraging expertise and investments across multiple institutions. It is envisioned that MAPP Climate Prediction Task Force research objectives, which build on the activities and objectives of individual MAPP research projects, will contribute to efforts to advance NOAA's ISI climate prediction capability and further quantify the limits of predictability. The Task Force includes investigators from the National Multi-Model Ensemble (NMME) Experiment, a NOAA-led interagency/multi-institution research project in the framework of MAPP-NCEP Climate Test Bed activities, as well as other MAPP investigators including research projects to advance ISI predictions based on dynamical/statistical methodologies and develop improved "best practices" for climate prediction. The Task Force plans to work in coordination with other relevant national and international research efforts working on ISI climate prediction (e.g. WCRP/WGSIP activities).

The Climate Prediction Task Force was formed to target most challenging research objectives within the broad realm of ISI climate prediction, those that can best be tackled by a community approach where comparison of methodologies, practices and views, and coordination among efforts are key to making progress. The Task Force research objectives are expected to be beyond the scope of any individual project while building on research from individual funded projects. The Task Force is intended to provide a forum for scientists engaged in climate prediction research to discuss their research and help identify synergies and opportunities for collaborations with other investigators. In this regard, the Task Force represents a working group where research activities and advances are discussed and confronted with operational needs and practices, hence allowing scientists to better refine their research goals and activities, and operational centers to optimally leverage from latest research advances.

The Task Force, with a 3 year lifetime, started its work officially on September 1, 2012 with several teleconferences amongst the leadership team and the members of the task force having already taken place. The leadership team of this Task Force comprises of Ben Kirtman (U. Miami), Scott Weaver (NOAA/CPC), Matt Newman (NOAA/ESRL), and Vasu Misra (FSU). Task Force research projects broadly fall in the following categories:

a. Evaluating/comparing different prediction methodologies
b. Evaluating the role of initial conditions on prediction skill at various timescales
c. Developing/assessing best prediction and post- processing practices
d. Testing and optimizing multi-model ensemble prediction systems for intraseasonal and seasonal predictions
e. Exploring the potential to develop outlooks for extremes (e.g. hurricanes, tornados)

Speaker	Topic
Jon Gottschalck	CPC Forecast Process
Kathy Pegion	A conditional skill mask for improved seasonal predictions
Paco Doblas-Reyes	SPECS: Seasonal-to-decadal climate prediction for the improvement of European climate services
Vasu Misra	The efficacy of two tiered and bias corrected SST forced seasonal hindcasts (with no cheating!)
Matt Newmann	Diagnosing predictability with a linear empirical dynamical model

Table 1. Past Webinars of the Climate Prediction Task Force

Initial discussions regarding Task Force research objectives have highlighted a general interest of the Task Force to initially focus on identifying sources and mechanism of forecast skill, conditional skill and complementary skill among the forecast tools. Towards this end the Task Force calls have featured 5 webinars (Table 1) on this topical interest, so as to help gather information regarding the state-of-the science on this topic, relevant Task Force and external research projects. Among other research objectives that have been discussed as of interest to the group and may be further pursued in some form, are the following:

a. Develop best practices for forecast bias corrections, calibration and skill assessments in the presence of a non-stationary climate.
b. Coordinate the development of "multi-tool" and/or multi-model methodologies for combining empirical and numerical predictions – essentially methodologies for how to make a forecast with multiple imperfect tools and to quantitatively determine the "orthogonal skill" that various prediction systems provide.
c. Develop best practices for quantifying uncertainty in the forecast, including uncertainty due to both initialization and model error. How do we forecast the forecast skill?

During the current preparatory phase, the Task Force plans to continue to gather relevant information and to enable for discussions to further refine and expand its research objectives while work progresses in the context of each individual project. Ultimately, Task Force research objectives and advances are expected to build upon individual MAPP research projects and their progress, while leveraging on the breadth, expertise and interests of the full group. Task Force research activities are expected to help achieve significant new advances in current capabilities to understand and predict intra-seasonal to inter-annual (ISI) climate variability in support of NOAA's prediction capabilities.

For more information regarding the Climate Prediction Task Force please visit:
http://www.cpo.noaa.gov/ClimatePrograms/ModelingAnalysisPredictionsandProjections/MAPPTaskForces/ClimatePredictionTaskForce.aspx.

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U.S. Climate Variability and Predictability Research Program (CLIVAR)
1717 Pennsylvania Ave NW, Suite 850
Washington, DC 20006
202.419.1801
www.usclivar.org
uscpo@usclivar.org
twitter.com/usclivar

U.S. CLIVAR acknowledges support from these U.S. agencies:

This material was developed with federal support of NASA (AGS-093735), NOAA (NA06OAR4310119), NSF (AGS-0926904), and DOE (DE-SCOOO8494). Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsoring agencies.