Report on the ENSO Diversity Workshop

1. Introduction

The El Niño–Southern Oscillation (ENSO) is a naturally occurring fluctuation of the coupled ocean-atmosphere system, which originates in the tropical Pacific region. ENSO affects ecosystems, agriculture, freshwater supplies, hurricanes and other severe weather events worldwide. Over the last thirty years significant progress has been made in understanding and predicting ENSO, including the dynamical processes and ocean-atmosphere feedbacks that are essential to this coupled phenomenon. The alternation between El Niño and La Niña events results from a basin-scale multi-year coupling among sea surface temperature (SST), equatorial wind stress, thermocline depth, and currents, and can be described in terms of the evolution of a "recharge oscillator" (Jin 1997) or "delay oscillator" (e.g. Suarez and Schopf 1988) involving the tropical thermocline, ocean heat content, or warm water volume (WWV). In their simplest form, these paradigms of ENSO capture the basic dynamical processes but fail to fully explain differences among events, asymmetries between warm and cold episodes, and the role of "atmospheric noise" (e.g. westerly wind bursts) and other non-linear effects. Understanding the full diversity of El Niño and La Niña is a key scientific challenge, given that their global impacts can depend sensitively on the spatial patterns of SST anomalies (SSTAs).

An aspect of ENSO diversity that has received increasing attention over the last decade is the longitude of maximum SSTA, as many warm events after 1990 have been characterized by peak SSTAs located in the central equatorial Pacific, rather than the eastern Pacific, as in so-called "canonical" or "east Pacific" (EP) El Niños. Such central-Pacific (CP) events, which have been variously termed "dateline El Niño" (Larkin and Harrison 2005), "El Niño Modoki" (Ashok et al. 2007), "Central Pacific El Niño" (Kao and Yu 2009), or "Warm Pool El Niño" (Kug et al. 2009), has been considered by some to be a phenomenon distinct from the "canonical" type, due to the different centers of action (Ashok et al. 2007). Some literature has described the existence of "two types" of El Niño, while other work has emphasized a continuum of events. Although CP El Niños have been somewhat more frequent than EP events in recent decades, it remains unclear whether this reflects a secular change due to anthropogenic influence (Yeh et al. 2009) or simply intrinsic random modulation (Wittenberg 2009; Newman et al. 2011).

Different centers of equatorial warming are associated with different teleconnection patterns and impacts. Surface temperature and precipitation anomalies over North America appear to differ in both pattern and sign, depending upon the longitudinal position of the equatorial SST anomalies (Larkin and Harrison 2005, Mo et al. 2010, Yu et al. 2012, Yu and Zou 2013). Central Pacific warming has also been related to North Atlantic tropical cyclones (Kim et al. 2009), precipitation variability over Australia (Hendon et al. 2009), Eurasia (Graf and Zanchettin 2012), and India (Kumar et al. 2006), as well as warming in Antarctica (Lee et al. 2010; Ding et al. 2011). Thus, it is important not only to predict that an El Niño will occur, but also which "flavor" it is likely to be.

Yet our understanding of ENSO diversity is still limited, and the existence of specific "precursors" to the different flavors is unclear.

Under the mandate of U.S. CLIVAR, a Working Group on ENSO Diversity was created in February 2012 to: 1) assess the ability of the existing observational data sets to characterize ENSO diversity in a statistically significant manner, 2) examine the ability of the state-of-the-art climate models to realistically reproduce that diversity, and 3) promote further research to elucidate the driving mechanisms, dynamical processes, teleconnections and impacts, as well as predictability and predictions of the ENSO flavors. An ENSO diversity workshop was held in Boulder, CO, 6-8 February 2013. A broad representation of the scientific community attended the workshop, and provided input on several aspects of ENSO diversity. This report presents a synthesis of the results, along with major outstanding issues highlighted at the meeting.

2. Synthesis of our present state of knowledge

2.1 What is ENSO diversity?

The concept of ENSO diversity has been primarily associated with differences in the longitude of the largest SSTAs during the warm ENSO phase. The emphasis on the location of the center of warming has been motivated by differences in the associated teleconnections. For example, Larking and Harrison (2005) first noticed the dramatic difference in the spatial pattern and even the sign of surface air temperature and precipitation anomalies over the U.S. associated with the canonical vs. the "dateline" El Niño. One year later, Kumar et al. (2006) related the failure of the summer Indian monsoon to Pacific warm events centered in the western Pacific, whose pattern was very similar to what was later termed the "El Niño Modoki" (Ashok et al. 2007). Apart from the longitude of the warming, the details of the spatial pattern may also be important. Wang and Wang (2012) further distinguished an El Niño Modoki I (characterized by an equatorially symmetric pattern) and II (characterized by an asymmetric pattern extending northeastward from the central Pacific), with apparently different influences upon the rainfall in Southern China during boreal Fall. The northeastward extension of the SST anomalies was also emphasized in Kao and Yu (2009) as the main feature to contrast the Central and Eastern Pacific El Niños.

Another approach has been to distinguish ENSO events by intensity, as strong and moderate events evolve differently, and may belong to different dynamical regimes (Lengaigne & Vecchi 2009, Takahashi et al. 2011). Longitude and intensity of warm events are not independent, however; CP warm events are generally weak, while EP events can be weak or very strong, as shown in a century-long ocean reanalysis (20th century reanalysis, covering the period 1870-2008, Giese and Ray 2010) as well as in the Geophysical Fluid Dynamics Laboratory Coupled Model 2.1 (GFDL-CM2.1, Wittenberg et al. 2006; Wittenberg, workshop presentation) and in the National Center for Atmospheric Research Community Climate System Model version 4 (NCAR-CCSM4, Capotondi 2013). Strong events always peak in the eastern Pacific.

One of the central questions the workshop addressed is: Is ENSO diversity best described as two distinct El Niño types, as presented in a large body of literature, or rather as a continuum with some interesting extremes? The 20th century reanalysis examined by Giese and Ray (2010) shows that the distribution of longitudes of the "Center of Heat" (CHI) index (the SST-weighted longitude of the anomaly) for historical events is indistinguishable from a Gaussian, providing no evidence for bimodality in the preferred El Niño longitude. Similarly, the analysis of 4000 years of a pre-industrial control integration of the Geophysical Fluid Dynamics Laboratory Climate Model 2.1 (GFDL-CM2.1) shows only a weak bimodality in the longitude of maximum warming; however, when stratified by amplitude, strong and moderate El Niños in this simulation of the GFDL-CM2.1 model appear to correspond to distinct dynamical regimes (Wittenberg and Takahashi, workshop presentations).

Modes of variability similar to the Eastern and Central Pacific El Niño emerge as the mature phases of the two leading optimal structures obtained from a Linear Inverse Model (LIM) of ENSO (Newman et al. 2011). Within some parameter values, a modified Cane-Zebiak model can also develop unstable modes characterized by dominant timescales that are consistent with those of the two El Niño types (Jin, workshop presentation), although the original version of the model does not simulate central Pacific El Niño. The two modes can coexist to give rise to a rich ENSO diversity, with a multiplicity of flavours. This view is supported by the observational studies of Kug et al. (2009) and Kim et al. (2012), as well as the analyses of the GFDL-CM2.1 (Kug et al. 2010) and NCAR-CCSM4 (Capotondi 2013) coupled models, where the dynamical balances associated with the various El Niño flavours vary as the centre of warming moves westward: events peaking in the eastern Pacific are driven more by thermocline processes, while for events centered further west show a greater role for zonal advection at onset and surface heat fluxes at decay. Although zonal advection is the largest process during central Pacific events, thermocline feedback may be also important for setting the characteristics of the air-sea instability associated to this type of event (Dewitte, workshop presentation). The use of weekly SST data and pentad zonal wind stress over the period 1982-2011 also supports the idea that events centered in the eastern and central Pacific are distinguishable and somewhat independent, and exhibit a wide spectrum of flavors in SSTA pattern and propagation characteristics (Karnauskas et al. 2013).

In summary, the view emerged from the workshop supports the existence of discrete El Niño "modes". However, their superposition and interplay leads to a multiplicity, and perhaps continuum, of flavors.

2.2 How well can instrumental data characterize ENSO diversity?

Observations in the tropical Pacific are generally sparse, especially before 1970 (Ray and Giese 2012). Various interpolation techniques have been used to fill in the gaps in the spatial and temporal coverage. The problem with interpolated data sets for ENSO studies is that the spatial patterns used in the reconstruction schemes are determined from recent periods of denser observations, which may not be representative of the spatial structure of ENSO events during prior periods of sparse observations. For example, the strong El Niño events of 1877 and 1997 have very similar spatial patterns in the HadISST data set, with anomalies that peak along the South American coast and decrease away from the coast. However, the 20th century SODA reanalysis shows different spatial patterns for the two events: the 1997 El Niño has a "canonical" pattern, typical of Eastern Pacific events, while the 1877 event has maximum anomalies around 140°-120°W, and weaker anomalies close to the coast of South America. Although ocean reanalyses also have uncertainties associated with forcing data sets, ocean model biases, and assimilation techniques, the differences between the two El Niño events raise concerns about the reliability of statistically-interpolated data sets for studies of ENSO diversity.

The short duration of the densely-observed epoch limits the statistical significance of the characterization of longer-term changes in El Niño characteristics. Only 11 El Niños occurred after 1970, while it takes a minimum of 30 events to detect a 6-month change in the El Niño frequency if a normal distribution with unchanging variance is assumed. The time between warm events shows a negative trend after the 1990s, but no appreciable trend can be detected when the total duration of the 20th century SODA reanalysis is considered (Ray and Giese 2012). Whether historical observations are adequate to detect secular trends in ENSO characteristics before the satellite era, especially before WWII, needs further investigation. Although different SST reconstructions exhibit a reasonable level of consistency in characterizing past ENSO diversity, a similar set of historical observations enters in all the reconstructions. The uncertainties in reconstructed SST products arising from the limited spatial and temporal sampling of the historical observing network are not well documented.

Weekly temporal resolution is also helpful for capturing the evolution of events, and for understanding the connection between events peaking at different longitudes, as exemplified by the study of Karnauskas et al. (2013). The availability of consistent data sets of surface and subsurface quantities at high temporal resolution would help to clarify the existence of precursors (as described in section 2.5), forcings (e.g. westerly wind bursts), dynamical processes (e.g. Kelvin and Rossby waves) and the details of the growing and decaying phases of different ENSO flavors.

2.3 How well can paleo proxy data characterize ENSO diversity?

Proxies for the tropical Pacific climate, including corals, tree rings, and ice cores, provide a longer-term view of ENSO variability beyond the historical epoch. A 7,000-year record from central Pacific corals (Cobb et al. 2013) suggests a strong decadal-to-centennial modulation of ENSO, in qualitative agreement with the amplitude modulation seen in unforced CGCM control runs (Wittenberg 2009; Stevenson et al. 2012). In these central Pacific coral records the inferred interannual variance over the instrumental epoch approaches the 95th percentile of the pre-instrumental variance, suggesting a possible strengthening of ENSO. However, the variance over the last 1,000 years is statistically indistinguishable from that during the mid-Holocene (6,000 years ago, or 6ka), in contrast to proxy records from the east Pacific, which suggest reduced interannual variability at 6ka.

One interpretation of these proxy results is that ENSO SSTA variability was displaced westward at 6ka. This is supported by CCSM4 control runs, which show fewer EP events (but a similar number of CP events) with 6ka forcings than with modern pre-industrial (1860) forcings (Karamperidou, workshop presentation). Compared to the 1860 case, the CCSM4 6ka case shows weaker growth and earlier termination of EP events, due to (1) changes in boreal summer thermal stratification in the eastern equatorial Pacific, and (2) an earlier and stronger southward shift of central equatorial Pacific zonal wind stress anomalies, which helps to re-establish the equatorial thermocline zonal slope and terminate the EP warm event. Just how these changes in feedbacks may be related to changes in mean climate or seasonality (associated with the seasonal timing of perihelion) is the subject of active investigation.

A tree-ring-based reconstruction over the past 700yr suggests that volcanoes may induce an ENSO-like response of the tropical Pacific (Li, workshop presntation). Tropical volcanoes tend to be associated with a cold event the year of the eruption, and a warm event the following year; extratropical volcanoes are associated with a cold event the year after the eruption.

Attempts to reconstruct pre-instrumental equatorial Pacific climate and ENSO variability, from the full network of available paleo proxy data, have met with some success. Emile-Geay et al. (2013a) found that while their multiproxy reconstruction was able to capture the timing of large events, it was less reliable at capturing the event amplitude, based on a series of cross-validation tests. They also found that the largest uncertainty in their NINO3.4 SST reconstructions, ironically, stemmed from the still-substantial uncertainties in the pre-satellite instrumental records used to calibrate the various proxies to represent SST; thus ongoing data archaeology efforts, like **oldweather.org**, can help to improve not only instrumental ENSO records but paleo-ENSO records as well.

Correlating their last-millennium reconstruction with estimated past variations in solar irradiance, Emile-Geay et al. (2013b) found that on multi-century scales, the east Pacific appears to cool when solar irradiance is high. This is reminiscent of the so-called "ocean-dynamical thermostat" response (Clement et al. 1996) -- in which the west Pacific warms, but the east Pacific, with continued upwelling of cold subsurface water, stays relatively cold; this enhancement of the zonal SST contrast and trade winds induces further upwelling, accentuating the east Pacific cold tongue. This inferred response is in contrast to CGCM simulations, which tend to show the opposite ("weaker Walker Cell") response to increased solar irradiance – in which warmer SSTs pump more moisture into the atmosphere, releasing more latent heat aloft, increasing atmospheric static stability, slowing the tropical convective mass flux, and weakening the equatorial Walker Cell, trade winds, upwelling, thermocline slope, and cold tongue (Held and Soden 2006; Vecchi et al. 2006b). This apparent discrepancy between proxy-inferred and GCM-simulated solar responses has yet to be resolved.

2.4 How well do climate models simulate ENSO diversity?

The spatial patterns of interannual SST anomalies in most climate models have the largest anomalies separated from the eastern ocean boundary, and extending further west than observations. This bias, found in both the CMIP3 (Capotondi et al. 2006) and the CMIP5 (Yang and Giese 2013) archives, is extreme in some models and generally limits their ability to reproduce the observed range of ENSO flavors (Ham and Kug 2012). Unlike observations and reanalysis products, many models have relatively symmetric El Niño and La Niña patterns (Yang and Giese 2013), indicating that the models fail to capture nonlinear processes in ENSO dynamics. However, some models can reproduce ENSO diversity with some realism (Yu and Kim 2010, Kim and Yu, 2012).

In-depth examination of ENSO diversity, however, has only been performed in few climate models. Workshop presentations have focused on analyses of the GFDL-CM2.1 and NCAR-CCSM4 models, which simulate different ENSO flavors as well as asymmetries in the pattern of the warm and cold ENSO phases. Different flavors of ENSO have been identified in these two models using different ENSO indices, with an approach similar to that used in observational studies (Kug et al. 2010, Choi et al. 2011, Capotondi 2013). As in observations (Kao and Yu 2009, Kug et al. 2009), both models indicate that warming in the central Pacific is associated with wind and precipitation anomalies that are limited to the western side of the basin, thermocline anomalies that are very weak, and recharge/discharge of warm water to/from the equatorial thermocline that is very weak or absent – all in contrast to canonical ENSO events. Also, as in observations, zonal advection and air-sea heat fluxes are relatively more important in the heat budget of the central Pacific events.

Other aspects of ENSO diversity need to be more fully examined in climate models. They include the assessment of possible precursors to the different flavors, as well as teleconnections and impacts (described in sections 2.5 and 2.6). Models can be key in complementing the observational record to assess whether there are aspects of atmospheric forcing which can lead, in a predictable fashion, to specific ENSO flavors -- and if so, by what processes and on what timescales. Simulations with changing forcings, as well as long unforced control runs, are both helpful for clarifying what gives rise to different regimes of ENSO activity – e.g. random chaotic modulation, changing stochastic forcings, and/or changing background conditions. Fortunately, simulations with higher resolution and more comprehensive physical parameterizations are showing improved simulations of both ENSO and its teleconnections (e.g. Kim et al. 2008; Guilyardi et al. 2012a; Delworth et al. 2012).

2.5 Predictability of the different flavors

Predictability of ENSO events in general, and specific flavors in particular, relies on the existence of precursors or “triggers” (atmospheric and/or oceanic) responsible for the excitation of events at some lead time. Recent studies have linked the onset of ENSO to extra-tropical atmospheric variability (Pierce et al. 2001, Vimont et al. 2001, 2003).

Vimont et al. (2001, 2003) proposed an extratropical-to-tropical connection termed the "seasonal footprinting mechanism" (SFM), where fluctuations in the intensity of the subtropical lobe of North Pacific Oscillation (NPO), an intrinsic mode of North Pacific variability, modulates the strength of the northeasterly tropical trade winds during winter imparting a "footprint" on the ocean through changes in surface heat fluxes. The SST footprint, termed the North Pacific Meridional Mode (NPMM) because of its association with a north-south SST gradient, which peaks in spring and persists through summer in the subtropical Pacific (Chiang and Vimont 1997, Chang et al. 2007), impacts the atmospheric circulation including zonal wind stress and surface energy fluxes that extend deep into the tropics and may lead to ENSO events the following winter. The wind-evaporation-SST feedback (WES, Xie and Philander 1994) is one of the primary coupling processes. High heat content anomalies in the western equatorial Pacific may be an important oceanic preconditioning for the SFM mechanism to excite an ENSO event (Anderson 2007). Indian summer monsoon variability has also been suggested as a possible ENSO trigger (Kirtman and Shukla 2000).

Recent studies argue that the SFM is particularly important to the generation of the Central Pacific type of events (Yu et al. 2010; Yu and Kim 2011; Kim et al. 2012). In this view, the CP ENSO can be considered as an extratropically-excited mode of the tropical Pacific variability (Yu and Kim 2011). While the lag-regression analysis performed in previous studies shows that the NPO precedes central Pacific events, sensitivity experiments where a NPO-type surface heat flux forcing is prescribed in an atmospheric GCM coupled to a reduced-gravity ocean model in the tropics and to a slab ocean model in the extra-tropics does not show a clear indication for a preferred ENSO type (Alexander et al. 2010). In the experiments described by Alexander et al. (2010) warming does occur in the central Pacific, but anomalies propagate eastward leading to a canonical El Niño. In contrast, another study argued that the NPO is forced by central Pacific warming (i.e. CP ENSO) at low frequencies (Di Lorenzo et al. 2010). Thus, it is not clear whether the NPO is a specific precursor for central Pacific events or is forced by them.

An SST anomaly pattern similar to the NPMM exists also in the Southern Hemisphere, and has been termed the South Pacific Meridional Mode (SPMM) by Zhang et al. (2013). Although similar in nature to the NPMM, the SPMM extends all the way to the eastern and central equatorial Pacific, while the NPMM is limited to the Northern Hemisphere subtropics. It is possible that the SPMM is more effective in exciting eastern Pacific events, while the NPMM may be more effective in triggering central Pacific events (Zhang et al. 2013). The relative role of the Northern and Southern Hemisphere modes needs to be further investigated.

Westerly Wind Bursts (WWBs) are often associated with the onset of El Niño events. Sensitivity experiments performed with a climate model in which a WWB perturbation was imposed, show that the ocean state can affect the resulting El Niño flavor. When the ocean is in a recharge state (larger Warm Water Volume) a timely occurrence of a WWB can turn a moderate CP El Niño into a strong EP El Niño (Vecchi et al. 2006a), whereas for a neutral oceanic state a WWB can turn a weak La Niña into a weak CP El Niño. The wind conditions over the eastern equatorial Pacific during WWB episodes can also influence the resulting El Niño type. For example, easterly wind anomalies east of the WWB region appear to be responsible for the comparatively weak WWB-related cold tongue warming after 1998 (Harrison and Chiodi 2009).

EP and CP ENSO have different spectral characteristics, as shown by spectral analysis of the corresponding indices. While the spectrum of the EP ENSO is characterized by a dominant peak at 2-5 years, spectral analysis of the CP ENSO shows a significant peak at two years and a broader peak at lower frequencies (Yu and Kim 2010, Furtado et al. 2011). In particular, the analysis of Furtado et al. (2011) indicates that the CP ENSO has large power in the decadal range, and these low-frequency variations in the central equatorial Pacific SSTs are highly correlated with Sea Level Pressure (SLP) low-frequency variations in the southern pole of the NPO as well as SLP variations in a region near Hawaii. Sensitivity experiments with an atmospheric GCM forced by observed SSTs in the 12°S-12°N latitude band and coupled to a mixed layer model elsewhere suggest that the low-frequency content of the southern pole of the NPO may be driven by tropical SSTs.

A synthetic view of tropical-extratropical interactions at decadal timescales involves a two-way coupling between equatorial ocean dynamics (the “Zonal Mode”), and extratropical atmospheric forcing (the “Meridional Mode”, Di Lorenzo, workshop presentation). The Meridional Mode provides stochastic forcing that ignites the equatorial oceanic processes, the Zonal Mode. The latter, in turn, amplifies the forcing, particularly at lower frequencies, and feeds back to the extratropics. In this view, ENSO diversity originates from the modulation of the coupling efficiency between Zonal and Meridional Modes. This is an intriguing hypothesis that should be further investigated in future work.

2.6 Teleconnections and impacts

The spatiotemporal structure of the tropical SSTA affects the global response to ENSO. 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. Remote climates are affected by atmospheric teleconnections, which are most sensitive to SSTs over the IndoPacific 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 teleconnections. 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.

Many aspects of the teleconnections and impacts of ENSO diversity (e.g., CP- and EP-El Nino or moderate and strong El Nino) can induce different regional responses. How significant the differences are, especially given the limited length of the observational data, need to be ascertained further. The studies of the remote response to ENSO diversity is also complicated by other modes of variability (e.g., the Southern Annular Mode). Nevertheless, even if the different teleconnections and impacts may not be statistically significant, there are important implications and societal relevance. Examples of different regional responses to ENSO diversity include tropical and North Pacific teleconnections (e.g., associated with the PNA-like pattern), tropical and Southern Ocean/Antarctica teleconnections (e.g., associated with the PSA patterns), impacts on Atlantic hurricanes, Pacific tropical cyclones, patterns of wintertime temperature, precipitation, and tornados over the North America continent, and biology in the Pacific Ocean.

Many dynamical processes responsible for the different regional responses to ENSO diversity have been discussed. These include atmospheric Rossby wave trains (e.g., associated with the PNA and PSA patterns), the North and South Pacific Meridional Modes, the Walker Circulation and Hadley cell, coupled ocean-atmosphere processes associated with the equatorial zonal advective and thermocline feedbacks, oceanic processes associated with horizontal advection and vertical advection/mixing, and coastal upwelling induced by alongshore wind and wind stress curl. The workshop presentations, discussion, and the research cited highlighted many fronts of new investigation related to ENSO diversity. Continuing efforts are imperative to improve the understanding of teleconnections and impacts.

2.7 Prediction of ENSO flavors

One of the goals of the workshop and the working group was to begin to assess how well state-of-the-art prediction systems capture the diversity of ENSO. In this regard there was a presentation that examined the retrospective forecast skill of tropical Pacific SSTA and tropical Pacific rainfall anomalies in the North American Multi-Model Ensemble (NMME) prediction system (Kirtman et al. 2013; see also http://www.cpc.ncep.noaa.gov/products/NMME/). The NMME system includes ensemble retrospective forecasts (1982-present) from nine different models. For each start month there are 109 ensemble members, which allows for detailed statistical analysis. For lead-times up to six months and from a qualitative basin scale perspective, the models are able to capture some of the observed contrasts between the warming in the east vs. west Pacific and the associated differences in the rainfall anomalies. More quantitatively, based on pattern correlation, the strong eastern Pacific events are demonstrably better predicted, and this distinction becomes even more dramatic as lead time increases. While the retrospective predictions capture some of the contrasts between east and west, they systematically warm too much and too rapidly in the far east compared to observational estimates.

Much of the workshop discussion on prediction quality emphasized the issue of initialization. For instance, the NMME systems typically rely on ocean data assimilation systems to provide the initial condition for the ocean. These data assimilation efforts emphasize the importance of the thermal structure of the upper ocean – little attention is paid to currents. Indeed, most ocean data assimilation systems do not even assimilate current information. Given the importance of the zonal advective feedback in capturing SSTA in the central and western Pacific, it was hypothesized that the lower skill for SSTA maximum in the western or central Pacific requires a more careful consideration of the ocean currents initial state.

2.8 On the recent prevalence of CP-type events

Similar to the lack of full agreement concerning CP ENSO dynamics, the cause of the increased occurrence of the CP ENSO in the past few decades is still a matter of debate. Future anthropogenic warming is expected to alter ENSO and the background climate of the tropical Pacific (Xie et al. 2010; Vecchi and Wittenberg 2010; Collins et al. 2010; DiNezio et al. 2012; Stevenson 2012; Stevenson et al. 2012; Watanabe and Wittenberg 2012; Watanabe et al. 2012). Yeh et al. (2009) compared the ratio of the CP to EP type of El Niño events in the CMIP3 model simulations and noticed that the ratio is projected to increase under global warming scenarios, a result that was further verified in the CMIP5 archive (Kim and Yu, 2012). Yeh et al. (2009) argued that the recent increase in the occurrence of the CP El Niño is related to a weakening of the mean Walker circulation and a flattening of the mean thermocline in the equatorial Pacific, which might be a result of global warming (Vecchi et al. 2006b). While the weakened trade winds and upwelling reduce SST variability in the eastern Pacific, the shallower thermocline in the central Pacific enhances SST variations in that area due to stronger thermocline feedbacks (DiNezio et al. 2012). In this view, the increased frequency of CP events over the last few decades is associated with an anthropogenically-forced change in the background state of the tropical Pacific.

This view has been challenged on several fronts. Newman et al. (2011) used a Linear Inverse Modeling technique to suggest that natural random variations in the atmosphere can project to two particular initial SST anomaly patterns, each of which can eventually develop into either the EP or CP type of ENSO through thermocline and zonal advection feedbacks, respectively. Such natural random variations can produce shifts between periods dominated by either type of event, without the need for anthropogenically-forced changes in the background state. This behavior is also seen in coupled GCMs, where unforced control runs can spontaneously generate multi-decade epochs populated entirely by CP or EP events, due to intrinsic modulation (Wittenberg, workshop presentation). Lee and McPhaden (2010) noticed that not only has the occurrence of the CP El Niño increased since the 1980s but its intensity has also doubled in the past three decades. However, the intensity of CP La Niña events has not changed during the same period. As a result, they argued that the warming trend observed in the central Pacific is a result of the increasing frequency and intensity of the CP El Niño, rather than a result of global warming. McPhaden et al. (2011) further showed that the background state change in the tropical Pacific between 2000-2010 and 1980-1999 is characterized by a steeper east-west thermocline slope, which is the opposite of that hypothesized by Yeh et al. (2009). Yu et al. (2012) argued that the selection of the EP or CP type of ENSO depends on the relative strengths of the Walker and Hadley circulation. They suggested that the increasing strength of the Hadley circulation has enhanced the influences of the extra tropical atmosphere to the tropical Pacific, which results in the increasing occurrence of the CP type of the ENSO in the past two decades. On the other hand, other studies relate the increased frequency of CP-type El Niños to a shift to a La Niña-like interdecadal mean state with a negative phase of PDO (Xiang et al. 2012, Chung and Li, 2013). However, it is not clear why a La Niña-like mean state would produce a predominance of CP El Niño events relative to the previous period.

3. Outstanding issues and research priorities

a. ***Causes of ENSO diversity regime changes***. To understand the impacts of global climate change and multi-decadal/centennial variability upon tropical Pacific interannual variability we need to elucidate what determines the transition between periods dominated by different ENSO flavors. Long control model simulations show the existence of different ENSO "regimes". Paleoclimate simulations of epochs that are considered to have ENSO characteristics different from the present (e.g. Holocene) also exist. In-depth diagnostics of those simulations in conjunction with statistical approaches (e.g. Linear Inverse Modeling), and experiments with intermediate complexity anomaly coupled models tuned to the CGCMs could be used to assess whether these transitions are random, or driven by low-frequency modulations of background conditions or by changes in the statistics of the atmospheric "noise". Model results should be compared with the "regime shifts" that have occurred in nature, as represented in observational data sets and reanalysis products, to both assess model realism, and improve our understanding of those regime transitions.

b. **Precursors and Triggers**. We have clear indications that regions outside the tropical Pacific, as well as local atmospheric noise (e.g. westerly wind bursts, WWBs) can excite ENSO events. However, the relative influence of the various regions (North Pacific, South Pacific, Indian and Atlantic Oceans) in exciting specific types of events is not fully understood. The "efficiency" of the extra-tropical forcing in producing an event is also unclear. For example, the study of Alexander et al. (2010) showed that an El Niño was produced in 70% of the cases after an NPO-type heat flux anomaly was applied to their coupled model. On the other hand, the observational study of Park et al. (2013) showed that only 45% of NPO events lead to El Niño events. The role played by the ocean state and phase of the annual cycle, in conjunction with extra-tropical forcing, in the development of a ENSO event, and in the selection of the event type is also not understood. The possible influence of forcing from regions outside the tropical Pacific upon WWBs needs to be examined, as well as the feedbacks from the tropical Pacific to other regions.

c. **Sustained and enhanced ocean observations for ENSO**. The TAO/TRITON array is the cornerstone of the ENSO observing system because it systematically measures co-located upper ocean temperature, salinity, velocity, winds, and air-sea fluxes that contribute to understanding of the dynamics of ENSO, and are essential for ENSO monitoring and prediction (Ji et al. 1998; Alves et al. 2003; Sun et al. 2007; Balmaseda and Anderson 2009; Stockdale et al. 2011). However, the data return rate from TAO/TRITON has declined significantly in the past year, and the data void could not be compensated by other ocean observing systems, such as Argo. The important role of oceanic advective processes for ENSO diversity, as stressed in the workshop, also indicates the need for more extensive current observations. Thus, sustaining and enhancing the ocean observing systems for ENSO is an urgent priority.

d. **Teleconnections and impacts**. Improved understanding of how ENSO diversity affects local (e.g., the tropical Pacific) and remote regions (e.g., weather and climate over the Continental US, Indian Ocean, Antarctica), in both their physical and biogeochemical aspects, is a key priority. Also important is enhancing understanding of the statistical significance, physical mechanisms, and societal relevance of the various teleconnections and impacts.

e. Assessment of climate model performance in simulating ENSO diversity. Climate models are an essential tool for improving our understanding of ENSO, and for providing ENSO predictions and projections. In-depth analyses similar to those performed on the GFDL-CM2.1 and NCAR-CCSM4 need to be extended to a larger set of models. Specific aspects of the models that need to be extensively diagnosed include dynamical processes, precursors, teleconnections and impacts. While the current model diagnostics are generally in agreement about the relative influence of vertical and zonal advection on the different El Niño flavors, there are discrepancies regarding the exact role of each term, and the importance of linear vs. nonlinear terms in the heat budget. Also, most heat budget analyses have been performed over a broad layer of the upper ocean, and may have glossed over the influence of mixing and entrainment processes very near the surface. Differences in the heat budget across models are likely related to model biases in their mean climate and/or variability, which are important to identify and improve. Models can be extremely valuable for assessing the existence, nature, and role of precursors to the different ENSO flavors, as described in section 2.5, due to the availability of different types of simulations (pre-industrial, historical, scenario simulations, and simulations where the atmospheric model is coupled to a slab ocean model), their ability to test ENSO sensitivities to external forcings and physical parameters, the long duration of the simulations, and the completeness and consistency of their atmospheric and oceanic variables. Similarly, it is very important to examine teleconnections and impacts of the different ENSO flavors across climate models, and understand the associated mechanisms. Consistency among models can be a measure of the robustness of both specific precursors as well as regional impacts of ENSO diversity. Metrics should be developed to assess model performance in simulating the various aspects of ENSO diversity (Guilyardi et al. 2009b, 2012b). For example, the Bjerknes stability index (Jin et al. 2006) has been very useful to detect model errors (Guilyardi et al. 2009a), and to assess changes in the leading ENSO feedbacks in epochs dominated by different El Niño types (McPhaden and Luebbecke, workshop presentation). Its formalism should be further adjusted/developed to account for model biases, since the region where the Bjerknes Index is computed in observations may not be appropriate for models depending upon the their biases. In addition, metrics that reflect the evolving nature of ENSO events, and the non-locality of the associated feedbacks, should be devised.

f. **Prediction**. Associated with the decadal shift from dominant EP to more frequent CP El Ninos after 2000, the real-time predictions of ENSO during the 2002-2011 period have been less skillful than during the 1980s and 1990s (Wang et al. 2010; Barnston et al. 2012). The lower skill can be partially attributed to the changes in ENSO predictability and partially to model errors that limit the model ability to distinguish between CP and EP events (Hendon et al. 2009; Xue et al. 2013). In addition, the impacts of ocean initial condition errors and initialization shocks on ENSO forecast skill are still not fully understood (Kirtman et al. 2003; Jin et al. 2008; Zhu et al. 2012; Xue et al. 2013). More studies are needed in the area of ocean initializations and their impacts on ENSO forecast skill.

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.

Alves, O., M. Balmaseda, D. Anderson, and T. Stockdale, 2003: Sensitivity of dynamical seasonal forecasts to ocean initial conditions. *Q.J.R. Meteorol. Soc*., **130**, 647– 668.

Anderson, B.T., 2007: Intra-seasonal atmospheric variability in the extra-tropics and Its relation to the onset of tropical Pacific sea-surface temperature anomalies, *J.Climate*, **20**, 1593-1599.

Ashok, K., et al. 2007: El Niño Modoki and its possible teleconnection. *J. Geophy. Res*., **112**, C11007, doi:10.1029/2006JC003798.

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

Barnston, A. G., M. K. Tippett, M. L. L'Heureux, S. Li, D. G. DeWitt, 2012: Skill of Real-Time Seasonal ENSO Model Predictions During 2002–11: Is Our Capability Increasing?. Bull. Amer. Meteor. Soc., 93 (5), 631-651.

Behringer, D. W., Ji, M., and A. Leetmaa, 1998: An improved coupled model for ENSO prediction and implications for ocean initialization. Part I: The ocean data assimilation system. *Mon. Wea. Rev*, **126**, 1013-1021.

Capotondi, A., A. Wittenberg, and S. Masina, 2006: Spatial and temporal structure of Tropical Pacific interannual variability in 20th century climate simulations. *Ocean Modeling*, **15**, 274, 298.

Capotondi, A., 2013: Dynamics of El Niño flavors in the NCAR-CCSM4 coupled GCM, in preparation.

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.

Choi, J., S.-I. An, J.-S. Kug, and S.-W. Yeh, 2011: The role of mean state on changes in El Nino flavor. *Clim. Dyn*., **37**, 1205-1215. DOI:10.1007/s00382-010-0912-1.

Clement, A.C., R. Seager, M.A. Cane, and S.E. Zebiak, 1996: An ocean dynamical thermostat. *J. Climate*, **9**, 2190-2196.

Cobb, K.M., N. Westphal, H. Sayani, E. Di Lorenzo, H. Cheng, R.L. Edwards, and C.D. Charles, 2013: Highly variable El Niño-Southern Oscillation throughout the Holocene. *Science*, 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 Geoscience*, **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. Zeng, 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.

Di Lorenzo, K. M. Cobb, J. C. Furtado, N. Schneider, B. T. Anderson, A. Bracco, M. A. Alexander, and D. J. Vimont, 2010: Central Pacific El Nino and decadal climate change in the North Pacific Ocean. *Nature-Geoscience*, **17**, DOI:10.1038/NGEO0984.

DiNezio, P. N., B. P. Kirtman, A. C. Clement, S.-K. Lee, G. A. 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.

Ding, Q., E. Steig, D. Battisti, and M. Küttel (2011), Winter warming in West Antarctica caused by central tropical Pacific warming. *Nature Geoscience*, **4**, 398 403, doi:10.1038/ngeo1129.

Emile-Geay, J., K. Cobb, M. Mann, and A. T. Wittenberg, 2013a: Estimating central equatorial Pacific SST variability over the past millennium. Part 1: Methodology and validation. *J. Climate*, in press. doi: 10.1175/JCLI-D-11-00510.1.

Emile-Geay, J., K. Cobb, M. Mann, and A. T. Wittenberg, 2013b: Estimating central equatorial Pacific SST variability over the past millennium. Part 2: Reconstructions and uncertainties. *J. Climate*, in press. doi: 10.1175/JCLI-D-11-00511.1.

Furtado, J. C., E. Di Lorenzo, B.T. Anderson, and N. Schneider, 2011: Linkages Between the North Pacific Oscillation and central tropical Pacific SSTs at low frequencies. *Climate Dynamics*, doi:10.1007/s00382-011-1245-4.

Giese, B. S., and S. Ray, 2011: El Niño variability in simple ocean data assimilation (SODA), 1871-2008. J. Geophys. Res., 116, doi: 10.1029/2010JC006695.

Graf, H. and D. Zanchettin, 2012: Central Pacific El Nino, the 'subtropical bridge', and Eurasian climate, *J. Geophys. Res*., doi:10.1029/2011JD016493.

Guilyardi, E., P. Braconnot, F.-F. Jin, S.T. Kim, M. Kolasinski, T. Li, and I. Musat, 2009a: Atmosphere feedbacks during ENSO in a coupled GCM with a modified atmospheric convection scheme. *J. Climate*, **22**, 5698-5718.

Guilyardi, E., A. Wittenberg, A. Fedorov, M. Collins, C. Wang, A. Capotondi, G. J. van Oldenborgh, and T. Stockdale, 2009b: 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*, **17**, 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. Met. Soc.*, **93**, 235-238. doi: 10.1175/BAM S-D-11-00106.1.

Ham, Y.-G, and J.-S. Kug, 2012: How well do current climate models simulate two-types of El Nino? *Clim. Dyn*., 39, 383-398. DOI:10.1007/s00382-011-1157-3

Harrison, D.E., and A. Chiodi, 2009: Pre- and Post-1997/98 Westerly Wind Events and equatorial Pacific Cold Tongue Warming. *J. Climate*, **22**, 568-581.

Hendon, H. H., E. Lim, G. Wang, O. Alves, and D. Hudson, 2009: Prospects for predicting two flavors of El Niño. *Geophys. Res. Lett*., **36**, L19713, doi:10.1029/2009GL040100.

Ji, M., D.W. Behringer, and A. Leetmaa, 1998: An improved coupled model for ENSO prediction and implications for ocean initialization. Part II: The coupled model. *Mon. Wea. Rev.*, **126**, 1022–1034.

Jin, F.-F., 1997: An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. *J. Atmos. Sci.,* **54**, 811-829.

Jin, F.-F., S.T. Kim, and L. Bejarano, 2006: A coupled-stability index for ENSO. *Geophys. Res. Lett*., **33**, L23708, doi:10.1029/2006GL027221.

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. Scheme, J. Shukla, T. Yamagata, 2008: Current status of ENSO prediciton skill in coupled ocean-atmosphere models. Clim. Dyn., 31, 647-664.

Kao, H. Y., and J. Y. Yu, 2009: Contrasting Eastern-Pacific and Central-Pacific Types of ENSO. *J. Climate*, **22**, 615-632.

Karnauskas, K.B., 2013: Can we differentiate canonical El Niño from Modoki? *Geophys. Res. Lett*., in revision.

Kim, D., J.-S. Kug, I.-S. Kang, F.-F. Jin, and A. 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.

Kim, H.-M., P. J. Webster, and J. A. Curry, 2009: Impact of shifting patterns of Pacific Ocean warming on north Atlantic tropical cyclones. *Science*, **325**, 77-80.

Kim, S. T. and J.-Y. Yu, 2012: The Two Types of ENSO in CMIP5 Models*, Geophysical Research Letters*, **39**, L11704, doi:10.1029/2012GL052006.

Kim, J.-S., K.-Y. Kim and S.-W. Yeh, 2012: Statistical evidence for the natural variation of the central Pacific El Nino. *J. Geophy. Res*., **117**, C06014, doi:10.1029/2012JC008003.

Kirtman, B.P., and J. Shukla, 2000: Influence of the Indian summer monsoon on ENSO. *Quarterly Journal of the Royal Meteorological Society*, **126**, 213-239.

Kirtman, B. P., J. Shukla, M. Balmaseda, N. Graham, C. Penland, Y. Xue, and S. Zebiak, 2002: Current status of ENSO forecast skill: A report to the Climate Variability and Predictability (CLIVAR) Numerical Experimentation Group (NEG), CLIVARWorking Group on Seasonal to Interannual Prediction, Clim. Variability and Predictability, Southampton Oceanogr. Cent., Southampton, UK. (Available at http://www. clivar.org/publications/wg_reports/wgsip/nino3/report.htm.).

Kirtman, B.P, and co-authors, 2013: The North American Multi-Model Ensemble (NMME) for Intra-Seasonal to Interannual Prediction. *Bull. Amer. Met. Soc*., submitted.

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.

Kug, J.-S., J. Choi, S.-I. An, F.-F. Jin, and A. T. Wittenberg, 2010: Warm pool and cold tongue El Niño events as simulated by the GFDL CM2.1 coupled GCM. *J. Climate*, **23**, 1226-1239. doi: 10.1175/2009JCLI3293.1.

Kumar, K.K., B. Rajagopalan, M. Hoerling, G. Bates, and M. Cane, 2006: Unraveling the mystery of Indian Monsoon failure during El Niño. *Science*, **314**, 115-118.

Larkin, N. K., and D.E., Harrison ,2005: Global seasonal temperature and precipitation anomalies during El Niño autumn and winter. *Geophys. Res. Lett*. **32**, L13705, doi:10.1029/2005GL022738

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.

Lee, T., W. Hobbs, and J. Willis, et al. (2010), Record warming in the South Pacific and western Antarctica associated with the strong central-Pacific El Niño in 2009-10. *Geophys. Res. Lett.*, 37, L19704, doi:10.1029/2010GL044865.

Lengaigne, M., and G. Vecchi, 2009: Contrasting the termination of moderate an extreme El Niño events in coupled general circulation models. *Climate Dynamics*, doi:10.1007/s00382-009-0562-3.

McPhaden, M. J., T. Lee, and D. McClurg, 2011: El Niño and its relationship to changing background conditions in the tropical Pacific. *Geophys. Res. Lett. 38,* L15709, doi:10.1029/2011GL048275.

Mo, K. C., 2010: Interdecadal Modulation of the Impact of ENSO on Precipitation and Temperature over the United States. *J. Climate*, **23**, 3639–3656.

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

Park, J.-Y., S.-W. Yeh, J.-S. Kug, and J. Yoon, 2013: Favorable connections between seasonal footprinting mechanism and El Nino. Clim. Dyn. 40, 1169-1181.

Pierce, D.W., T.P. Barnett, and M. Latif, 2000: Connections between the Pacific Ocean Tropics and midlatitudes on decadal timescales. *J. Climate*, **13**, 1173-1194.

Ray, S., and B.S. Giese, 2012: Changes in El Niño and La Niña characteristics in an ocean reanalysis and reconstructions from 1871-2008. *J. Geophys. Res*., **117**, C11007, doi:10.1029/2012JC008031.

Schopf, P.S., and M.J. Suarez, 1988: Vacillations in a coupled ocean-atmosphere model. *J. Atmos. Sci.*, **45**, 549-566.

Stevenson, S. L., 2012: Significant changes to ENSO strength and impacts in the twenty-first century: Results from CMIP5. *Geophys. Res. Lett.*, **39**, L17703, doi:10.1029/2012GL052759.

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

Stockdale, T.N., D. Anderson, M. A. Balmaseda, F. Doblas-Reyes, L. Ferranti, K. Mogensen, T. N. Palmer, F. Molteni, and F. Vitart, 2011: ECMWF seasonal forecast system 3 and its prediction of sea surface temperature. *Clim. Dyn*., doi:10.1007/s00382-010-0947-3.

Sun, C., M. M. Rienecker, A. Rosati, M. Harrison, A. Wittenberg, C. L. Keppenne, J. P. Jacob, and R. M. Kovach, 2007: Comparison and sensitivity of ODASI ocean analyses in the tropical Pacific. *Mon. Wea. Rev.*, **135**, 2242-2264. doi: 10.1175/MWR3405.1.

Takahashi, K., Montecinos, A., Goubanova, K., Dewitte, B., 2011: ENSO regimes: Reinterpreting the canonical and Modoki El Niño, Geophysical Research Letters, 38, L10704, doi:10.1029/2011GL047364

Tashetto, A.S., and M.H. England, 2009: El Niño Modoki impacts on Australian rainfall. *J. Climate*, **22**, 3167.

Vecchi, G. A., A. T. Wittenberg, and A. Rosati, 2006a: Reassessing the role of stochastic forcing in the 1997-8 El Niño. *Geophys. Res. Lett.*, **33**, L01706. doi: 10.1029/2005GL024738.

Vecchi, G. A., B. J. Soden, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison, 2006b: 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.

Vecchi, G.A., and B.J. Soden, 2007: Global Warming and the weakening of the tropical circulation. *J. Climate*, **20**, 3300-3319.

Vimont, D. J., D. S. Battisti, and A. C. Hirst, 2001: Footprinting: a seasonal link between the mid-latitudes and tropics. *Geophys. Res. Lett.,* **28**, 3923–3926.

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.

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

Wang, C., and X. Wang, 2013: El Niño Modoki I and II classifying by different impacts on rainfall in Southern China and typhoon tracks. *J. Climate*, in press.

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.

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

Xiang, B., B. Wang, and T. Li, 2012: A new paradigm for the predominance of standing Central Pacific Warming after the late 1990s. *Climate Dynamics*, doi:10.1007/s00382-012-1427-8.

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.

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.

Xue, Y., M. Chen, A. Kumar, Z.-Z. Hu, W. Wang, 2012: Prediction Skill and Bias of Tropical Pacific Sea Surface Temperatures in the NCEP Climate Forecast System Version 2. *Early Online J. Climate.*

Yang, C., and B.S. Giese, 2013: El Niño Southern Oscillation in an ensemble ocean reanalysis and coupled climate models. *J. Geophys. Res*., submitted.

Yeh, S.-W., J.-S. Kug, B. Dewitte, M.-H. Kwon, B. Kirtman, and F.-F. Jin, 2009: El Niño in a changing climate. *Nature*. **461**. doi: 10.1038/nature08316.

Yu., J.-Y., H.-Y. Kao and T. Lee, 2010: Subtropics-Related Interannual Sea Surface Temperature Variability in the Equatorial Central Pacific. *Journal of Climate*, 23, 2869-2884.

Yu., J.-Y. and S. T. Kim, 2010: Identification of Central-Pacific and Eastern-Pacific Types of ENSO in CMIP3 Models*, Geophysical Research Letters*, 37, L15705, doi:10.1029/2010GL044082.

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*, Journal of Climate*, 24, 708-720.

Yu., J.-Y., Y. Zou, S. T. Kim, and T. Lee, 2012: The Changing Impact of El Nino on US Winter Temperatures*, Geophysical Research Letters*, doi:10.1029/2012GL052483.

Yu, J.-Y. and Y. Zou, 2013: The enhanced drying effect of Central-Pacific El Nino on US winter*, Environmental Research Letters*, **8**, doi:10.1088/1748-9326/8/1/014019.

Zhang, H., A. Clement, and P. Di Nezio, 2013: The South Pacific Meridional Mode: A mechanism for ENSO-like variability. *J. Climate*, submitted.

Zhu, J., B. Huang, L. Marx, J.L. Kinter, M.A. Balmaseda, R.-H. Zhang, and Z.-Z. Hu, 2012: Ensemble ENSO hindcasts initialized from multiple ocean analyses. *Geophys. Res. Lett.*, **39**, 9, doi:10.1029/2012GL051503.