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ENSO diversity

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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

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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.

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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

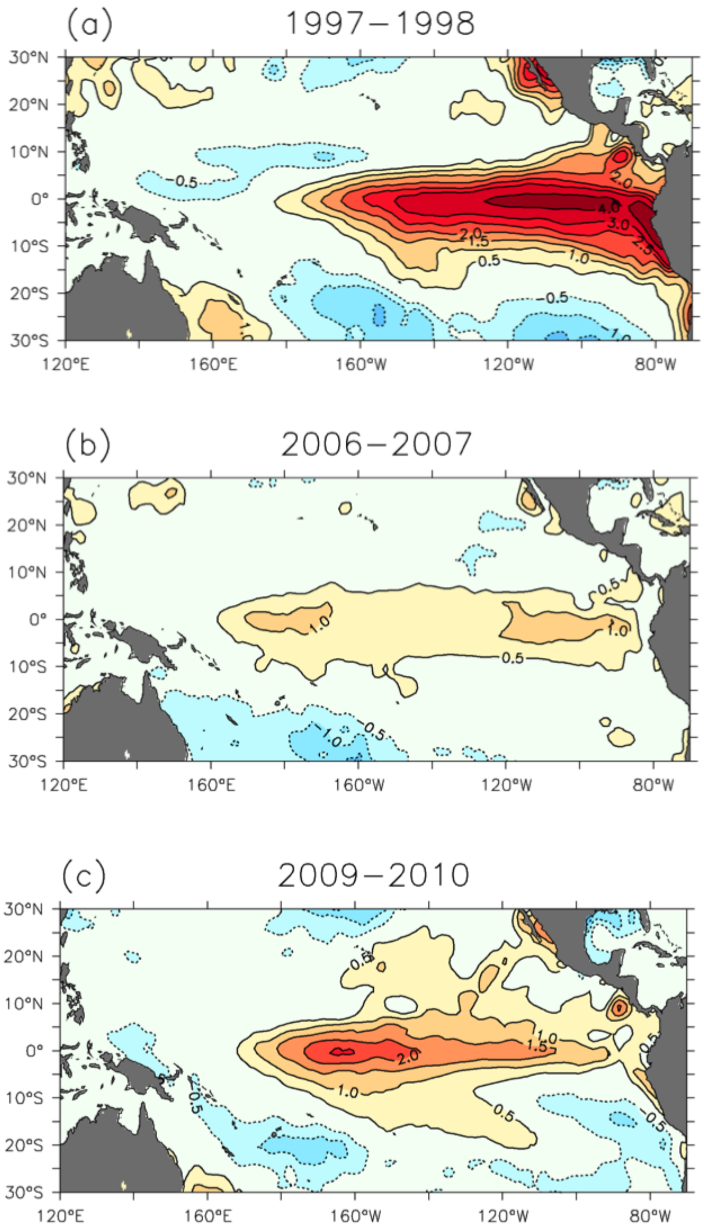

Figure 1. Sea surface temperature anomalies (°C) observed in December-January-February of the (a) 1997-98 El Niño event, (b) 2006-07 El Niño event, and (c) 2009-10 El Niño event.

"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 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).

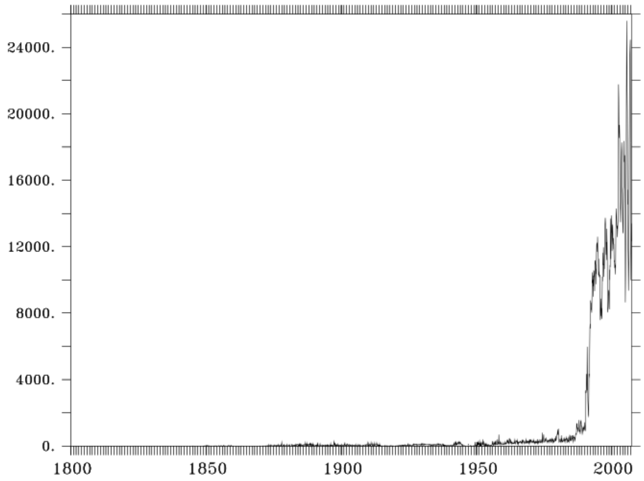

Figure 2. Number of SST observations per month in the Niño 3.4 region in the ICOADS 2.5 database.

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.

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.

Anderson, B. T., 2003: Tropical Pacific sea surface temperatures and preceding sea level pressure anomalies in the subtropical North Pacific. J. Geophys. Res., 108, doi:10.1029/2003JD003805.

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

Battisti, D. S., and A. C. Hirst, 1989: Interannual variability in the tropical atmosphere-ocean system: Influence of the basic state, ocean geometry, and nonlinearity. J. Atmos. Sci., 46, 1687-1712.

Capotondi, A., 2013: Dynamics of El Niño flavors in the NCAR-CCSM4 coupled GCM,J. Geophys. Res., in review.

Carton, J. A., and B. S. Giese, 2009: A reanalysis of ocean climate using Simple Ocean Data Assimilation (SODA). Mon. Wea. Rev., 136, 2999-3017.

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.

Giese, B. S., and S. Ray, 2011: El Niño variability in simple ocean data assimilation (SODA), 1871-2008. J. Geophys. Res, 116, C02024.

Guan, B., and S. Nigam, 2008: Pacific Sea Surface Temperatures in the Twentieth Century: An evolution-centric analysis of variability and trend. J. Climate, 21, 2790-2809.

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

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.

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.

Larkin, N. K., and D. E. Harrison, 2005: Global seasonal temperature and precipitation anomalies during El Niño autumn and winter. Geophys. Res. Lett., 32, L16705, doi:10.1029/2005GL022860.

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.

Lengaigne, M. and G.A. Vecchi, 2009: Contrasting the termination of moderate and extreme El Nino events in Coupled General Circulation Models. Climate Dynamics, DOI: 10.1007/s00382-009-0562-3

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.

Rasmusson, E. M. and T. H. Carpenter, 1982: Variations in tropical sea-surface temperature and surface wind fields associated with the Southern Oscillation El-Niño. Mon. Wea. Rev., 110, 354-384.

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.

Ren, H.-L., and F.-F. Jin, 2011: Niño indices for two types of ENSO. Geophys. Res. Lett., 38, L04704, doi:10.1029/2010GL046031.

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

Singh, A., T. Delcroix, and S. Cravatte, 2011: Contrasting the flavors of El Niño-Southern Oscillation using sea surface salinity observations. J. Geophys. Res., 116, C06016, doi:10.1029/2010JC006862.

Sun, F., and J.-Y. Yu, 2009: A 10-15year Modulation Cycle of ENSO Intensity. J. Climate, 22, 1718-1735.

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

Vimont, D., D. Battisti, and A. Hirst, 2001: Footprinting: A Seasonal Connection Between the Tropics and Mid-Latitudes. Geophys. Res. Lett., 28, 3923-3926.

Wang, C., and X. Wang, 2013: Classifying El Niño Modoki I and II by different impacts on rainfall in the southern China and typhoon tracks. J. Climate, 26, 1322-1338, doi:10.1175/JCLI-D-12-00107.1.

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.

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.

Yeh, S.-W., J.-S. Kug, B. Dewitte, B. Kirtman, and F.-F. Jin, 2009: Recent changes in El Niño and its projection under global warming. Nature, 461, 511-515.

Yu, J.-Y. and H.-Y. Kao, 2007: Decadal Changes of ENSO Persistence Barrier in SST and Ocean Heat Content Indices: 1958-2001. J. Geophys. Res., 112, D13106, doi:10.1029/2006JD007654.

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

Yu, J.-Y., H.-Y. Kao, T. Lee, and S. T. Kim, 2011: Subsurface Ocean Temperature Indices for Central-Pacific and Eastern-Pacific Types of El Niño and La Nina Events. Theor.App. Climatol., 103, 337-344.

Yu, J.-Y., and S. T. Kim, 2011: Relationships between Extratropical Sea Level Pressure Variations and Central-Pacific and Eastern-Pacific Types of ENSO. J. Climate, 24, 708-720.

Yu., J.-Y., Y. Zou, S. T. Kim, and T. Lee, 2012: The Changing Impact of El Niño on US Winter Temperatures. Geophys. Res. Lett., 39, L15702, doi:10.1029/2012GL052483.

Yu., J.-Y., and S. T. Kim, 2013: Identifying the Types of Major El Niño Events since 1870. Int. J. of Climatol., 33, 2105-2112, doi:10.1002/joc.3575.

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.