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Can we distinguish canonical El Niño from Modoki?

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[1] Following the recent discovery of the “Modoki” El Niño, a proliferation of studies and debates has ensued concerning whether Modoki is dynamically distinct from “Canonical” El Niño, how Modoki impacts and teleconnections differ, and whether Modoki events have been increasing in frequency or amplitude. Three decades of reliable, high temporal-resolution observations of coupled ocean-atmosphere variability in the equatorial Pacific reveal a rich diversity of El Niños. Although central and eastern Pacific sea surface temperature (SST) anomalies appear mechanistically separable in terms of local and remote forcing, their frequent overlap precludes robust classifications. All observed El Niños appear to be a mixture of locally (central Pacific) and remotely forced (eastern Pacific) SST anomalies. Submonthly resolution appears essential for this insight and for the proper dynamical diagnosis of El Niño evolution; thus, the use of long-term monthly reconstructions for classification and trend analysis is strongly cautioned against.

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1. Introduction

[2] The El Niño-Southern Oscillation (ENSO) is among the most intensely studied natural climate phenomena by meteorologists and oceanographers. The interconnectedness of global weather patterns owing to ENSO was suspected as early as the 1830s [*Cerveny*, 2005] and pieced together with global weather observations in the 1920s and 1930s [*Walker*, 1925; *Walker and Bliss*, 1932]. The earliest theories invoking strong ocean-atmosphere coupling to explain ENSO [*Bjerknes*, 1969] remain generally accepted and have been refined throughout recent decades [*Jin*, 1997; *Picaut et al.*, 1997; *Suarez and Schopf*, 1988]. Despite decades of progress in observing, modeling, and understanding ENSO, surprises abound. A new type of El Niño, one in which the sea surface temperature (SST) warming occurs primarily in the central rather than eastern equatorial Pacific Ocean, was first reported in peer-reviewed literature in 2005 [*Larkin and Harrison*, 2005]. This phenomenon was coined “Dateline” El Niño; some discussion of semantics followed as the term “Modoki” (a Japanese word meaning “similar but different”) was used one year earlier in the Japanese Media [*Ashok et al.*, 2007]. (East Pacific (EP) and Central Pacific (CP) are used hereafter.) In the five years since these papers, over 50 studies have been published in the ocean/atmosphere/climate literature identifying [*Ren and Jin*, 2011; *Yu et al.*, 2011], contrasting [*Hu et al.*, 2012; *Kao and Yu*, 2009; *Kug et al.*, 2009; *Ramesh and Murtugudde*, 2013; *Shinoda et al.*, 2011; *Singh et al.*, 2011; *Trenberth and Smith*, 2009; *Yu and Kim*, 2011], diagnosing [*Kim et al.*, 2011; *Yu and Kim*, 2010], and predicting [*Hendon et al.*, 2009; *Jeong et al.*, 2012] CP El Niños and their impacts on monsoons [*Taschetto et al.*, 2009], Australian rainfall [*Cai and Cowan*, 2009], tropical cyclones [*Kim et al.*, 2009], ocean biology [*Gierach et al.*, 2012], Antarctic climate [*Ding et al.*, 2011], and stratospheric variability [*Zubiaurre and Calvo*, 2012]. Furthermore, several studies have investigated whether CP El Niños are becoming more frequent and/or stronger [*L'Heureux et al.*, 2012; *Lee and McPhaden*, 2010; *McPhaden et al.*, 2011; *Newman et al.*, 2011; *Nicholls*, 2008; *Yeh et al.*, 2009], while others have questioned whether EP and CP El Niños are in fact distinct phenomena [*Kug and Ham*, 2011; *Takahashi et al.*, 2011]. This paper is concerned primarily with the latter question.

[3] Patterns of SST during 1997–1998 and 2002–2003 illustrate key spatial similarities and differences between EP and CP El Niños, respectively (Figure 1). The commonly cited distinction is the location of maximum SST anomaly (Figures 1a and 1b). However, in terms of total SST, both events featured similar equatorward contractions and eastward expansions of the Indo-Pacific warm pool, while a suppression of the eastern Pacific cold tongue occurred only in the EP El Niño (Figures 1d and 1e). It may therefore be hypothesized that EP El Niños are fundamentally related to CP El Niños except that a Bjerknes-like thermocline feedback progresses and leads to a suppression of the cold tongue. It is also interesting to contrast either El Niño pattern with that of the linear trend over the period 1982–2011 (Figures 1c and 1f). The trend is characterized by a meridional expansion (but no zonal translation) of the warm pool edge and a small but significant westward extension of the cold tongue, therefore resembling neither the warm nor cold form of an EP or CP event. The response of the mean state of the tropical Pacific to the anthropogenic rise in atmospheric CO_2 concentration is a subject debated with equal vigor [*Collins et al.*, 2010]; note that the trend over the most recent 30 years—a period during which the mean annual growth rate of atmospheric CO_2 (1.73 ppm/year [*Tans*, 2012]) was greater than at any point in modern recorded history—offers no evidence of the strong warming in the central and eastern equatorial Pacific Ocean predicted by global models.

[4] Common diagnostic methods in climate research such as simple box averaging, threshold-based compositing, linear regression, and principal component analysis ask phenomena to fit a mold that is linear, stationary, and/or symmetric. ENSO is known to defy all of these assumptions [*An and Jin*, 2004; *Boucharel et al.*, 2009; *Okumura and Deser*, 2010].

Additional supporting information may be found in the online version of this article.

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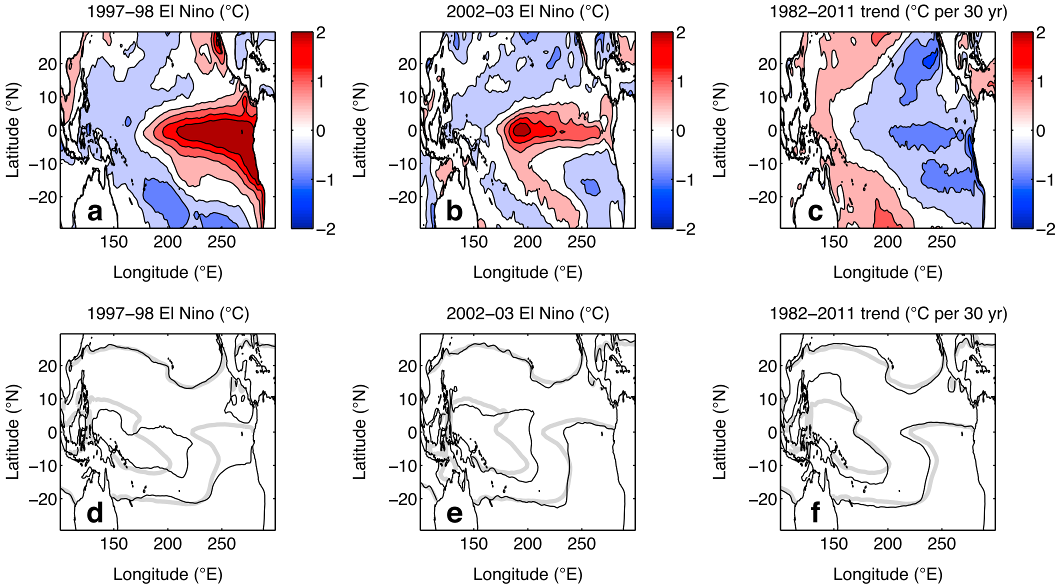

Figure 1. (a) SST anomalies (°C) averaged from 27 April 1997 through 7 June 1998, widely considered a "canonical" or East Pacific El Niño. (b) As in Figure 1a but for 8 September 2002 through 2 February 2003, widely considered a "Modoki" or Central Pacific El Niño. (c) Linear trend in SST (°C per 30 years) computed over the period January 1982 through December 2011. The El Niños shown in Figures 1a and 1b correspond to events #6 and #7, respectively, in Figure 2. (d–f) As in Figures 1a–1c but displaying the 26°C and 29°C isotherms averaged over the same periods (thin black lines) and the mean climatology for those periods (heavy gray lines).

Further, such methods are necessary for generalizing large numbers of realizations. Within the satellite era, the expected number of El Niños that have been adequately and consistently sampled (record length × frequency ~10) does not generally meet this criterion. The challenge of studying ENSO diversity should therefore begin with a minimum of assumptions. It follows that data sets relying heavily on such assumptions to reconstruct past spatiotemporal variability from ship measurements with uneven sampling in space and time, such as gridded SST reconstructions spanning the instrumental era (beginning ~1850), may require caution in this regard.

2. Data and Methods

[5] To identify El Niños (and La Niñas) of any origin, a simple index is defined that does not assume a priori the geographic region where SST anomalies are most important or distinguishing of different types of events (e.g., the Niño_3 index, which is a measure of the equatorial SST anomaly averaged between 150°W and 90°W). Indices for warm and cold events are calculated separately to allow the possibility of concurrent events of opposite sign in the equatorial Pacific:

$$\text{Niño}_\infty(t) = \overline{T'_{\varphi=0}(\lambda,t)} \text{ for } T' > 0$$

$$\text{Niña}_\infty(t) = \overline{T'_{\varphi=0}(\lambda,t)} \text{ for } T' < 0$$

where T' represents the SST anomaly with respect to the mean climatology (base period 1982–2011), overbars indicate the zonal mean $120°\text{E} \le \lambda \le 80°\text{W}$, and subscripts $\varphi = 0$ indicate meridional averaging $1°\text{S} \le \varphi \le 1°\text{N}$. The Niño_∞ index is thus simply the average of all positive SST anomalies along the Pacific equator at a given time t. A widely used and well validated gridded SST product with weekly temporal resolution (and 1° spatial resolution) that blends satellite and in situ observations is used [*Reynolds et al.*, 2002]. ENSO events are transient departures from a baseline climatology. Given the cooling trend observed across much of the equatorial Pacific Ocean over the analysis period (Figure 1c), the SST data were first detrended by removing the linear trend over 1982–2011. This step ensures meaningful comparison of anomalous events at opposing temporal ends of the record in the presence of a trending baseline and does not alter the results of this paper. The Niño_∞ and Niña_∞ indices, along with numeric identifiers for each of the 11 events in which the weekly Niño_∞ value exceeded 2 standard deviations, are shown in Figures 2a and S1a, respectively.

[6] Analysis of SST variability is complemented by pentad/0.25° wind stress measurements from the Cross-Calibrated Multi-Platform (CCMP) Ocean Surface Wind Components [*Atlas et al.*, 2011], daily/1° surface heat flux measurements from the Objectively Analyzed air-sea Fluxes (OAFlux) product [*Yu and Weller*, 2007], pentad/1° surface ocean currents estimated by the Ocean Surface Current Analyses Real-time (OSCAR) product [*Bonjean and Lagerloef*, 2002], weekly/0.33° sea surface height measurements from the Archiving, Validation, and Interpretation of Satellite define Oceanographic data (AVISO) product (see Acknowledgments), and pentad thermocline depth observations from the Tropical Atmosphere-Ocean (TAO) array of moorings [*McPhaden et al.*, 1998].

3. Results

[7] The evolution of warm equatorial SST anomalies through time-longitude space at weekly temporal resolution reveals a surprising diversity of anomaly patterns (Figure 2b). The prevalence of anomalies developing in different regions simultaneously and propagating zonally in different directions clearly renders objective classification schemes limited in

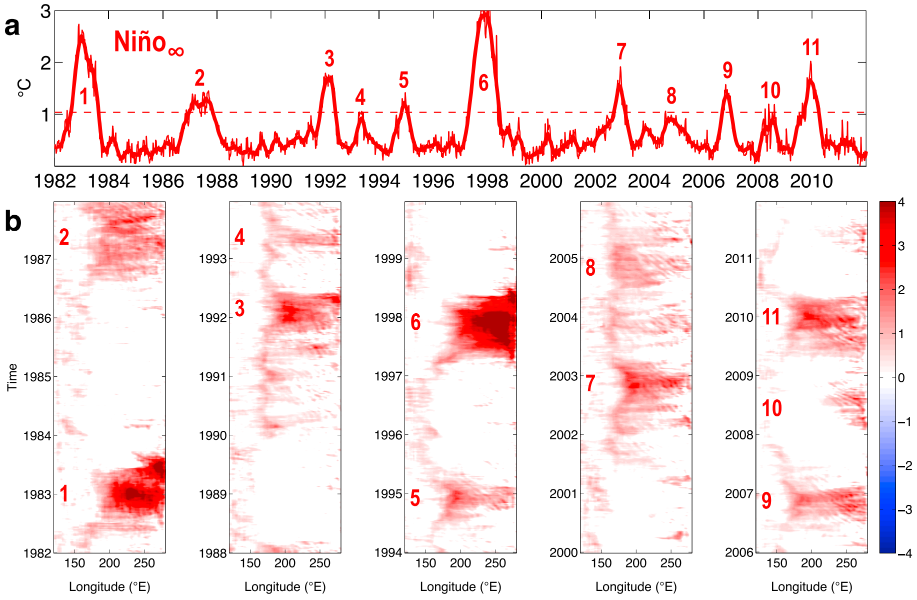

Figure 2. (a) The weekly Niño$_\infty$ index (°C) as described in the main text. Also shown is a 13 week (roughly 3 month) running mean (heavy line). Event numbers are assigned for each El Niño, where the weekly Niño$_\infty$ value exceeded 2 standard deviations of the Niño$_\infty$ index (dashed line). (b) Weekly SST anomalies along the equator as a function of longitude and time (°C; averaged 2°S–2°N; positive only for clarity and consistency with the Niño$_\infty$ index definition). Black numbers correspond to event numbers indicated in Figure 2a. The Niña$_\infty$ index and negative SST anomalies are provided in Figure S1.

universal applicability. Some El Niños are, however, observed to include warm anomalies west of the dateline (i.e., an eastward expanded warm pool), which propagate eastward several thousands of kilometers—but not to the eastern boundary—and then retreat westward (e.g., #5). Furthermore, all obvious instances of such evolution did so within a multiyear setting of an anomalously eastward position of the warm pool edge. In this view, it may be tempting to use such evolution as a characteristic fingerprint of CP El Niño. It will be shown in the following paragraphs that this is an oversimplification and

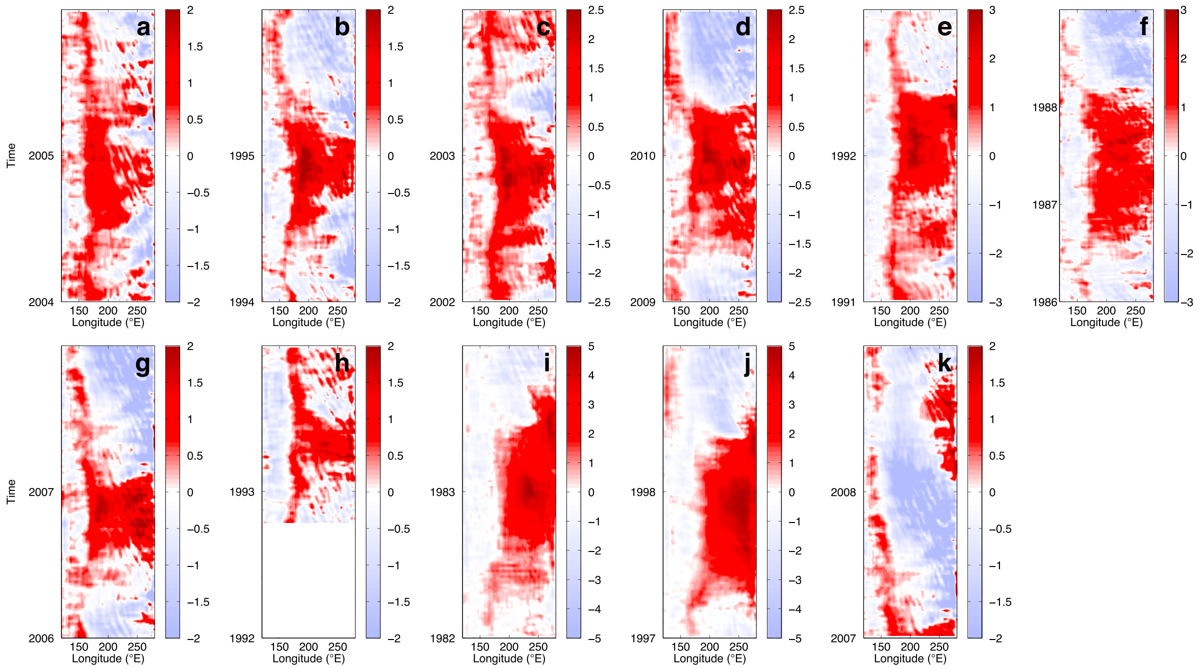

Figure 3. Weekly SST anomalies along the equator as a function of longitude and time for all 11 events indicated in Figure 2 (°C; averaged 2°S–2°N). Results computed from a coarser-resolution monthly SST product [*Smith et al.*, 2008] are provided in Figure S2. Note that the color scales are adjusted appropriately for each event. Also note that the events are not ordered chronologically (a–k) from left to right; they are ordered based on an initial, subjective judgment of the extent to which the event appears dominated by SST anomalies in the central (left) or eastern (right) Pacific. Three events from across this spectrum (Figures 3b, 3g, and 3j) are chosen for deeper analysis in Figure 4.

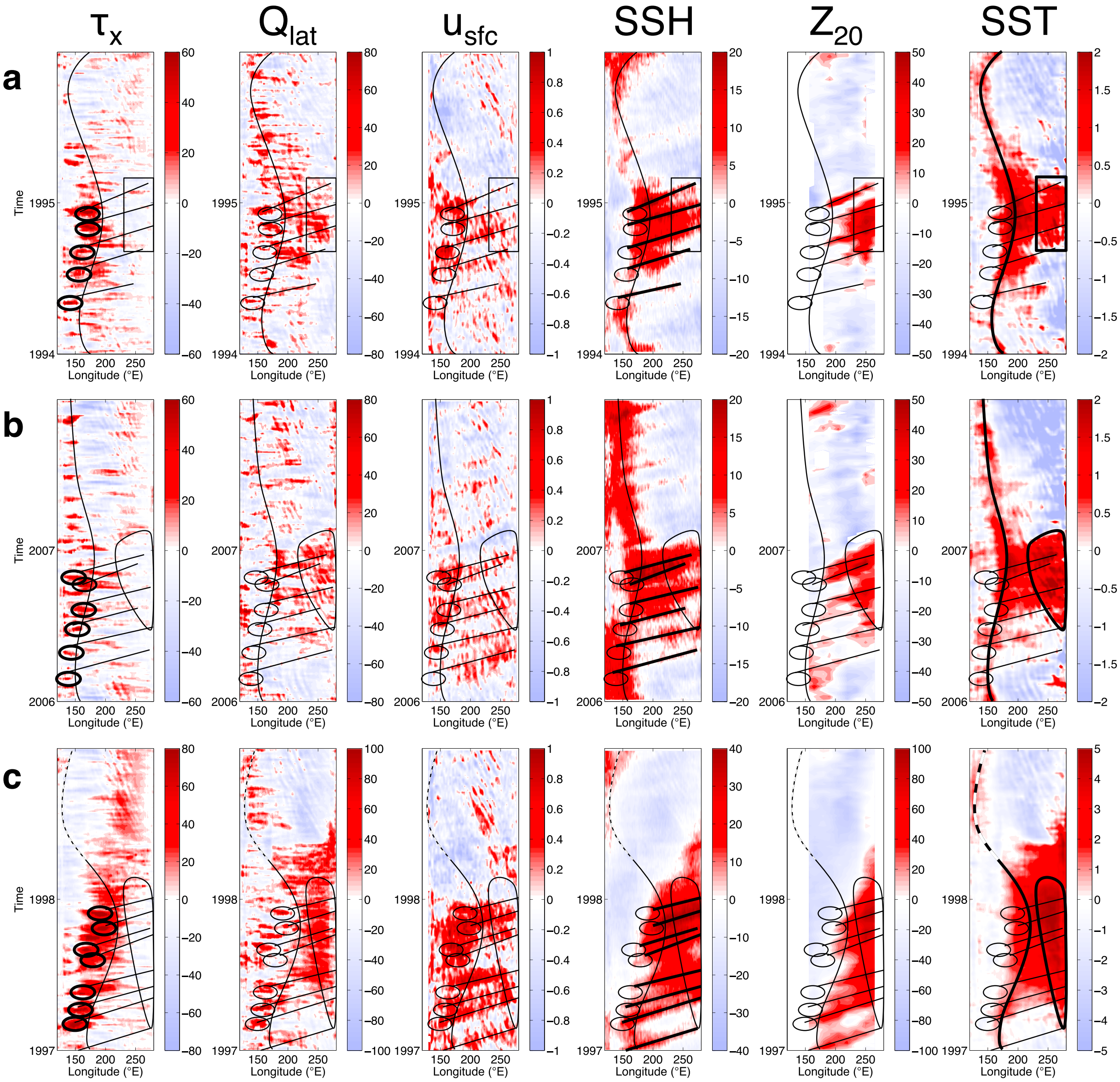

Figure 4. Time-longitude plots of weekly anomalies of surface zonal wind stress (τ_x; $\mathrm{m^2\,s^{-2}}$), surface latent heat flux (Q_{lat}; $\mathrm{W\,m^{-2}}$), surface ocean zonal velocity (u_{sfc}; $\mathrm{m\,s^{-1}}$), sea surface height (SSH; cm), thermocline depth (Z_{20}; m), and SST (°C) averaged 2°S–2°N for the (a) 1994–1995 El Niño (Figures 2 (event #5) and 3b), (b) 2006–2007 El Niño (Figures 2 (event #9) and 3g), and (c) 1997–1998 El Niño (Figures 2 (event #6) and Figure 3j). Heavy lines are based on inspection of the fields on which they are overlaid, while thin lines are transposed from a different field (e.g., ovals encircling westerly wind bursts are based on the τ_x field but are also transposed to each subsequent field across that event for convenience).

not a useful distinction. La Niñas, on the other hand, appear entirely dominated by westward propagating EP-type events (Figure S1b) consistent with *Kug and Ham* [2011].

[8] A closer examination of the spatiotemporal evolution of SST anomalies during the 11 warm events noted in Figure 2 is provided in Figure 3. Rather than ordering chronologically and using a consistent color scale for each event, the events are displayed from left to right based on an initial, subjective judgment of the extent to which each El Niño appears dominated by SST anomalies in the central or eastern Pacific. What is immediately clear that was less obvious in Figure 2b and all but hopeless in coarser monthly observations (Figure S2) is the fact that every El Niño—even the most notoriously "EP" events (1982–1983 or 1997–1998)—involves a distinct and geographically separated SST anomaly that develops and evolves in the central Pacific as described above. Likewise, El Niños that might be judged "CP" by various objective or subjective criteria (e.g., 1994–1995) involve clear and separate SST anomaly development in the eastern Pacific. It is more often the case, and well illustrated by the 2006–2007 event, that a given El Niño is a mixture of SST anomalies developing (and likely interacting through large-scale coupled processes) in both the central and eastern equatorial Pacific. The remaining analysis is aimed at understanding whether the geographically separable SST anomalies appearing in all El Niños, which seem to vary by event only in their magnitude relative to each other, are also mechanistically separable.

[9] Three cases spanning the range of events shown in Figure 3 are selected for further mechanistic analysis using

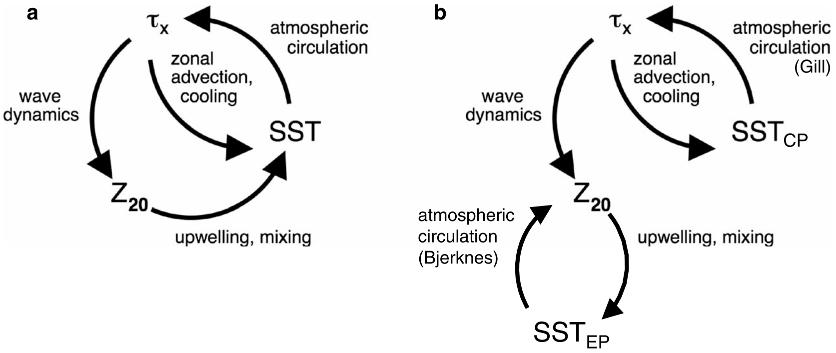

Figure 5. (a) Diagram illustrating the major ENSO feedbacks. Reproduced from *Zelle et al.* [2004], ©American Meteorological Society (used with permission). (b) A modified diagram based on the findings herein. SST anomalies geographically located in the central and eastern equatorial Pacific Ocean (and potentially the observed diversity of El Niño events) are better understood when the dynamics governing them (i.e., local versus remote processes) are considered separately.

a broad suite of fields documenting the state and evolution of the coupled system (1994–1995, 2006–2007, and 1997–1998; Figure 4). The following analysis procedure was adhered to for each event: (1) identify and mark Kelvin waves as coherent, positive, eastward propagating SSH anomalies; (2) identify and mark westerly wind bursts as positive τ_x anomalies found near the leading edge of each Kelvin wave; and (3) identify and mark coherent warm SST anomalies that develop during the first year and persist into the second. Upon completion of each step, all markings resulting from that step are replicated and translated to all other fields for comparison.

[10] Despite large differences in the timing and spatial distribution of the peak warm anomalies, each event unfolded in a remarkably similar way. Intermittent westerly wind bursts occurring at the beginning of the first year (or end of the previous year) either drove or reinforced an anomalously eastward position of the warm pool edge through a combination of (reduced) latent heat flux and zonal temperature advection. Simultaneously, the westerly wind bursts initiated positive (downwelling) Kelvin waves propagating eastward, where they eventually depressed the thermocline in the far eastern Pacific. Hence, both local and remote SST anomalies can be identified in each event. In all three cases, latent heat flux was a positive feedback on both the locally and remotely driven SST anomalies.

[11] What made these three events different was the strength (and likely timing) of the westerly wind bursts. The wind bursts at the beginning of the 1997–1998 El Niño were earlier and roughly twice as strong as those associated with 1994–1995 and 2006–2007, and so were the Kelvin waves and thermocline depth anomalies. As the strong Kelvin waves reached the eastern Pacific in early 1997 and began depressing the thermocline by up to 100 m, SST anomalies in excess of 5°C developed, initiating a strong Bjerknes feedback which led the patch of westerly wind anomalies and thus warm pool edge to continue propagating eastward, further reinforcing the thermocline and SST anomalies [see *Gebbie et al.*, 2007, and references therein]. Despite the overwhelming amplitude of the remotely forced SST anomalies in the eastern Pacific during 1997–1998, locally forced SST anomalies associated primarily with anomalous zonal temperature advection remained distinguishable in the central Pacific well into 1998 (Figure 4c). Likewise, despite the relatively strong locally driven SST anomalies in the central Pacific during 1994–1995 (Figure 4a), weaker eastern Pacific SST anomalies developed during late 1994 in concert with a ~40 m deepening of the thermocline—a clearly remote response to the arrival of Kelvin waves initiated by weaker and later wind bursts in 1994.

4. Discussion and Conclusions

[12] To summarize, nature exhibits a rich diversity of El Niños composed of a mixture of SST anomalies initially developing in the central and eastern Pacific. The results presented herein suggest that CP and EP El Niños are, in theory, mechanistically distinct (i.e., CP SST anomalies are a local response to wind forcing, whereas EP SST anomalies emerge as a remote response). However, the obvious potential for interaction between wind forcing and SST anomalies at opposite ends of the basin explains why, upon closer examination with suitable observations, they occur simultaneously more often than not. The usual view of feedbacks involved in ENSO, summarized in Figure 5a [from *Zelle et al.*, 2004], contains all of the fundamental dynamics to explain SST anomalies without geographic variation. Separating the local from remote processes and explicitly invoking basin-scale atmospheric feedbacks (à la Bjerknes) enables one to envision how the known dynamics already account for simultaneous mixtures of distinctly CP and EP SST anomalies in every El Niño (Figure 5b). It should not be too surprising that the observed diversity of La Niña is different than that of El Niño. El Niño and La Niña are known to be asymmetric and so, too, may be aspects of their dynamics including triggers. Many of these insights would be difficult to tease from discrete monthly data with limited degrees of freedom (or empirical modes). Moreover, the often-subtle zonal propagation and frequent overlap with EP anomalies would confound stationary box average indices designed to isolate CP events.

[13] Much of the controversy surrounding Modoki concerns whether it is a new phenomenon or at least increasing in frequency and/or amplitude. There is hope for distinguishing El Niño blends based on their evolution in time-longitude space at submonthly temporal resolution, but the amount of overlap and interaction precludes the clean separation needed for impact and trend studies as commonly formulated. While CP SST anomalies appear to be distinguishable from those in the east, it is unlikely that Modoki is a new phenomenon.

Rather, its detection is enhanced by observations that are higher temporal resolution and methods that are unreliant on assumptions of linearity, stationarity, and symmetry.

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