Asymmetry in zonal phase propagation of ENSO sea surface temperature anomalies

Michael J. McPhaden\(^1\) and Xuebin Zhang\(^2\)

Received 19 April 2009; revised 27 May 2009; accepted 4 June 2009; published 3 July 2009.

[1] It is often emphasized in the literature that the phase propagation of El Niño sea surface temperature (SST) anomalies along the equator changed from westward to eastward after a mid- to late-1970s climate regime shift in the Pacific. Theories have been developed to explain this change in phase propagation in terms of changes in background state on which El Niño events develop. Those theories also suggest that the direction of La Niña anomaly phase propagation should have changed from westward to eastward as well. However, the direction of La Niña SST anomaly phase propagation did not change after the mid- to late-1970s. Instead, La Niña SST anomalies continued to exhibit westward phase propagation along the equator, a feature overlooked in both observational analyses and theories. This paper highlights the asymmetry in zonal phase propagation between El Niño and La Niña sea surface temperature anomalies since 1980 and discusses the implications of that asymmetry for understanding El Niño/Southern Oscillation (ENSO) dynamics. Citation: McPhaden, M. J., and X. Zhang (2009), Asymmetry in zonal phase propagation of ENSO sea surface temperature anomalies, Geophys. Res. Lett., 36, L13703, doi:10.1029/2009GL038774.

1. Introduction

[2] El Niño and the Southern Oscillation (ENSO) is the strongest year to year climate fluctuation on the planet. It originates in the tropical Pacific through coupled ocean-atmosphere interactions mediated by surface wind stress and sea surface temperature (SST) variations [McPhaden et al., 2006]. El Niño, or the warm phase of ENSO, is characterized by anomalously warm SST and weak trade winds while La Niña, or the cold phase of ENSO, is characterized by anomalously cold SST and strong trade winds. ENSO affects patterns of weather variability world-wide, shifting the probability for droughts, floods, heat waves and severe storms in many parts of the globe. The significant socio-economic impacts of ENSO have motivated efforts over the past 20 years to develop climate forecast models that exploit the predictability of ENSO at up to 3 season (9 month) lead times.

[3] It has been suggested that the character of ENSO changed in the mid- to late-1970s as part of a Pacific-wide climate “regime shift”. Manifestations of this shift include stronger El Niños in the 1980s and 1990s compared to the 1950s to 1970s, more El Niños than La Niñas since 1980, and a 4–6 year period for ENSO after the regime shift versus a 2–4 year period before [Fedorov and Philander, 2000]. The tendency for eastward propagation of El Niño SST anomalies along the equator after the mid-1970s compared to westward propagation before has also been viewed as a consequence of this regime shift. For example, Fedorov and Philander [2000] observe that “… descriptions of El Niño based on data from the 1960s and 1970s emphasize westward phase propagation… subsequently, eastward phase propagation… has been more common…” Similarly, Wang and An [2002a] state that “during the 1960s and 1970s the warm SST anomalies expanded westward from the South American coast into the central equatorial Pacific…after 1980, the warm SST anomalies propagated eastward across the basin from the central Pacific or developed concurrently in the central and eastern Pacific.” Trenberth et al. [2002] also note that, “For the 1979–98 period, El Niño-related SST warming occurs first in the western/equatorial Pacific and progresses eastward to develop later along the coast of South America.”

[4] Fedorov and Philander [2001] developed a theory for El Niño “whose properties—period, intensity, spatial structure, and direction of propagation—depend on the background climatic state…” In particular, they found that a deep mean thermocline and weak mean trade winds favor eastward anomaly propagation while a shallow mean thermocline and strong mean trade winds favor westward anomaly propagation. This theory offers an explanation for how coupled ocean-atmosphere interactions and oceanic processes affecting SST would produce eastward propagation of El Niño anomalies before the regime shift and eastward propagation of El Niño anomalies after the regime shift. In this theory however, there is no asymmetry between El Niño and La Niña in either anomaly amplitude or phase propagation. In a physical parameter space similar to that which prevailed before the late-1970s, their model ENSO warm and cold events both show a tendency for westward propagation while in a parameter space similar to that which prevailed since 1980, their model ENSO warm and cold events both show a tendency for eastward propagation.

[5] Almost universally overlooked in discussions of observations and theories for how the mid- to late-1970s regime shift affected the ENSO cycle is the clear asymmetry in zonal propagation along the equator of warm and cold phase ENSO SST anomalies after 1980: while El Niño events may at times show a tendency for eastward propagation, La Niña events show a very distinct westward propagation (Figure 1b). Theories have addressed the amplitude asymmetry between El Niños and La Niñas since 1980 in terms of nonlinear heating of the surface mixed layer [Jin et al., 2003; An and Jin, 2004]. However, there
has been no comparable discussion of the asymmetry in ENSO SST anomaly phase propagation. The purpose of this paper is to highlight this asymmetry and to discuss its implications for theories of the ENSO cycle.

2. Data Sets and Data Processing

We use the Reynolds et al. [2002] blended satellite/in situ monthly SST analysis available on a 1° latitude by 1° longitude grid for November 1981–December 2008 and the Smith et al. [2008] in situ SST analysis on a 2° latitude by 2° longitude grid for the period January 1950 to October 1981. Surface wind stress is computed from the 6-hourly European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalysis winds available from September 1957 to August 2002 on a 2.5° latitude × 2.5° longitude grid [Uppala et al., 2005]. After August 2002, we use the ECMWF operational product. We compute daily averaged zonal wind stress from wind velocities with a constant drag coefficient of $1.43 \times 10^{-3}$ and air density of $1.225 \text{ kg m}^{-3}$, then form monthly averages.

According to the NOAA oceanic Niño index (ONI, http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml), which is defined as a 3-month running mean of SST anomalies over 5 consecutive months in the Niño-3.4 region ($5^\circ$N–$5^\circ$S, 90–150$^\circ$W), eight El Niños and five La Niñas can be identified since 1980 (Table 1). Conversely, this index identifies seven El Niños and eight La Niñas during 1950–77. From these events we form composites as in Rasmusson and Carpenter [1982], Harrison and Larkin [1998] and Larkin and Harrison [2002]. We include the 1953–54 “El Niño” in our 1950–77 composite even though it does not qualify based on the ONI, since Rasmusson and Carpenter [1982], Harrison and Larkin [1998] and Larkin and Harrison [2002] included it in their composites. Our list of El Niño and La Niña years is very

Figure 1. Monthly anomalies of (a) zonal wind stress and (b) SST averaged between $2^\circ$N–$2^\circ$S beginning January 1980. Anomalies have been smoothed with a 1-2-1 filter in time. Contour Interval is $0.01 \text{ N m}^{-2}$ in Figure 1a and $0.5 ^\circ \text{C}$ in Figure 1b. White arrows are overlain on two El Niño events and two La Niña events in Figure 1b to illustrate the asymmetry in ENSO SST phase propagation. The arrows for the La Niña events are drawn to represent a westward phase speed of $0.95 \text{ m s}^{-1}$ as determined from analysis of the composite in Figure 2f.
similar to that of Larkin and Harrison [2002] for the 1950–77 period, but with one more warm event in 1963–64 and one more cold event in 1967–68. These events are weak and so do not have a significant influence on the structure of the composites. Monthly anomalies for 1950–77 and 1980–2008 are calculated relative to climatologies in their respective periods, then smoothed with 1-2-1 filter to remove intraseasonal variations.

The composites extend over two years centered on December, which is typically the month of maximum ENSO SST anomaly magnitude in the Niño3.4 region. For the post-1980 period, we form two El Niño composites, one for all events and one excluding the two largest events (1982–83 and 1997–98). We estimate uncertainties by computing standard errors for each grid point and month of the composite, using standard sampling theory [e.g., Emery and Thomson, 2001] under the assumption that individual events are independent and anomalies are normally distributed.

### Table 1. El Niño and La Niña Years Since 1950

<table>
<thead>
<tr>
<th>El Niño Years</th>
<th>La Niña Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1951</td>
<td>1950</td>
</tr>
<tr>
<td>1953</td>
<td>1954</td>
</tr>
<tr>
<td>1955</td>
<td>1955</td>
</tr>
<tr>
<td>1956</td>
<td>1964</td>
</tr>
<tr>
<td>1965</td>
<td>1967</td>
</tr>
<tr>
<td>1969</td>
<td>1970</td>
</tr>
<tr>
<td>1972</td>
<td>1973</td>
</tr>
<tr>
<td>1975</td>
<td>1975</td>
</tr>
<tr>
<td>1982</td>
<td>1984</td>
</tr>
<tr>
<td>1986</td>
<td>1988</td>
</tr>
<tr>
<td>1991</td>
<td>1991</td>
</tr>
<tr>
<td>1994</td>
<td>1995</td>
</tr>
<tr>
<td>1997</td>
<td>1998</td>
</tr>
<tr>
<td>2002</td>
<td>2002</td>
</tr>
<tr>
<td>2004</td>
<td>2004</td>
</tr>
<tr>
<td>2006</td>
<td>2007</td>
</tr>
</tbody>
</table>

Only the first year of the event is listed. All entries are based on the NOAA Oceanic Niño Index (ONI), except for the El Niño beginning in 1953, which is commonly included in composite El Niño analyses for the period before 1980.

Many of the features described above stand out more clearly in our composites (Figure 2) since event-to-event differences tend to average out. The composite SST and wind stress anomaly magnitudes are comparable for El Niño and La Niña, which peak near the end of the calendar year. Maximum wind anomalies are displaced to the west of the most significant SST anomalies, which emphasizes the importance of remote forcing and ocean wave dynamics in the eastern Pacific in combination with zonal advection in the central Pacific for generating ENSO SST anomalies [Wang and McPhaden, 2000]. For both El Niño and La Niña, zonal wind stress anomalies in the eastern Pacific tend to be opposite of those in the central Pacific, e.g., easterly in the case of El Niño and westerly in the case of La Niña. These eastern Pacific winds locally oppose the development of remotely forced SST anomalies and may account in part for the eastward decrease in ENSO SST anomaly amplitudes in the eastern basin [Zhang and McPhaden, 2006, 2008]. Similar features are evident in the composites of Harrison and Larkin [1998] and Larkin and Harrison [2002].

In the composite El Niño, SST anomalies exhibit eastward propagation west of and near the date line prior to and during the onset phase, followed by concurrent development of anomalies in the central and eastern Pacific (Figures 2b and 2d). Likewise zonal wind stress anomalies show clear eastward propagation, with first development in the western Pacific (Figures 2a and 2c). The features noted above are apparent whether one considers the composite based on all eight El Niños or just on the six weak-to-moderate amplitude El Niños.

The main difference between the two El Niño composites is that in the weak-to-moderate amplitude case, maximum SST anomalies are shifted westward by about 40° and amplitudes are weaker by about 0.5°C in the eastern Pacific compared to the all-inclusive composite. The tendency for maximum SSTs to occur near the date line for weak-to-moderate amplitude El Niños since 1980 has led some investigators to label these events as “date line El Niños” or “modoki El Niños” [Larkin and Harrison, 2005; Ashok et al., 2007]. There also is a suggestion of westward propagation of warm anomalies in the central and western Pacific during the termination phase of the weak-to-moderate strength composite El Niño (Figure 2d). However, this phase propagation is an artifact of the tendency for La Niña to follow El Niño since La Niñas are associated with not only unusually cold SST in the eastern basin but unusually warm SSTs in the far western Pacific (Figure 1b).

In contrast to the El Niño composites, the La Niña composite shows clear westward propagation of cold SST anomalies along the equator (Figure 2f). Zonal wind stress anomalies do not show as obvious westward propagation in the composite vis a vis individual events (Figure 2e). This is probably because the composite averages the tendency for the envelope of easterly wind stress anomalies to propagate eastward for some events with the tendency for the periods of strongest easterlies to propagate westward in tandem with SST. An interesting feature of the La Niña composite is the re-emergence of cold anomalies a year following main cold event development (Figure 2f). This feature in the composite is due to the tendency for some La Niña events to extend into a second year (Figure 1b).
For comparison with these post-1970s regime shift composites, we computed composite SST anomalies for the period 1950–77 as in Rasmusson and Carpenter [1982], Harrison and Larkin [1998], and Larkin and Harrison [2002]. Our composite El Niño for 1950–77 looks very similar to that of Rasmusson and Carpenter [1982] and Harrison and Larkin [1998]. Our La Niña composite also looks very similar to that of Larkin and Harrison [2002], though they included the 1988–89 La Niña in a composite of La Niña events from 1950–89. Composite SST anomalies for both warm and cold events appear first in the eastern Pacific and then propagate into the central Pacific (Figures 3a and 3b). The El Niño composite anomaly is 0.75°C greater in magnitude than for the La Niña composite, but otherwise the longitudinal development of the anomalies as a function of time is very similar. This similarity is in sharp contrast to the asymmetry between El Niño and La Niña phase propagation that exists after 1980.

There are differences between the pre- and post-regime shift La Niña composites. One is that the tendency after 1980 for cold anomalies to persist and re-emerge for a second year is not a consistent feature of La Niñas in the earlier period. Also, before the regime shift cold anomalies tend to propagate westward in the eastern Pacific then develop concurrently in the central Pacific while after the regime shift they show progressive westward propagation.
Figures 3b and 3d). Fitting a regression curve the minimum SST anomalies along the equator as a function of longitude for the 1980–2008 La Niña composite, we infer a westward phase speed of 0.95 m s$^{-1}$. We find a similar phase based on time/longitude cross-correlation analysis of the composite SST anomalies in Figure 2f using 110°W, 140°W, or 170°W as an index longitude. This phase speed is close to that expected for a first baroclinic mode, first meridional mode equatorial Rossby wave in the Pacific. Further investigation will be required to determine whether this is simply a coincidence resulting from the coupled dynamics of the ocean-atmosphere system, or whether it is indicative of some special role for Rossby wave processes in post-1980 La Niña events.

(16) The inference of contrasting eastward propagation for El Niño anomalies and westward propagation for La Niña anomalies after 1980 in the Reynolds et al. [2002] blended satellite/in situ SST product does not depend on the introduction of satellite SST measurements in 1981. Two independent in situ SST analyses, one based completely on data from the TAO/TRITON array of moored buoys (http://www.pmel.noaa.gov/tao/ [McPhaden et al., 1998]) and another based primarily on ship-of-opportunity expendable and mechanical bathythermograph profiles [White, 1995], exhibit essentially the same behavior for those parts of the records that overlap between 1980 and 2008. Thus, the asymmetry in ENSO SST anomaly phase propagation after 1980 is real and not an artifact of changes in the observing system.

4. Summary and Conclusions

(17) Results of this study illustrate the pronounced asymmetry in zonal phase propagation of ENSO SST anomalies along the equator since 1980. Specifically, El Niño anomalies tend to propagate eastward and La Niña anomalies westward. This asymmetry has not been documented systematically in the literature and yet westward propagation of cold phase ENSO SST anomalies was evident as early as 1984 (Figure 1b). What accounts for this oversight? La Niñas were less frequent than El Niños after 1980, which may have contributed to focusing more on the warm phase of ENSO. Also, the major El Niños of 1982–83 and 1997–98, with their intense anomalies and spectacular global climatic impacts, riveted attention of the research community on understanding these strong events. As such, they may have distracted attention from the subtleties of SST anomaly phase propagation between El Niño and La Niña.

(18) Whatever the reason, existing theories do not adequately provide an explanation for the asymmetry in zonal phase propagation of ENSO SST anomalies after 1980. For example, Wang [1995] and Fedorov and Philander [2000, 2001] assume a time scale separation between background state changes and ENSO in which prescribed changes in the
background state have an identical effect on the direction of phase propagation for El Niño and La Niña SST anomalies. However, as is evident from Figure 3, the changes in zonal phase propagation for El Niño SST anomalies are very different from those for La Niña anomalies after the mid-to late-1970s regime shift. The fact that zonal phase propagation of warm and cold SST anomalies differs in direction after 1980 indicates that either (a) the background state is not sole determinant of ENSO SST anomaly phase propagation or (b) that changes in the background state affect El Niño and La Niña differently. In either case, our results suggest the existence of a fundamental nonlinearity that favors eastward propagation of warm events and westward propagation of cold events after 1980. Likely sources of this nonlinearity, based on model results emphasizing ENSO amplitude asymmetries, are horizontal and vertical advection in the mixed layer temperature balance [Wang and An, 2002; Jin et al., 2003; An and Jin, 2004]. Wang and An [2002] in particular have suggested that nonlinearity involving enhanced vertical advection is associated with eastward propagation of anomalies while enhanced zonal advection is associated with westward propagation. Further research is required to address precisely how these processes act to produce the observed variability.

[10] Acknowledgments. The authors would like thank Fei-Fei Jin and Alexey Fedorov for helpful discussions. We also thank two anonymous reviewers whose valuable comments improved the final version of this manuscript. This work was supported by NOAA's Climate Program Office.

References


M. J. McPhaden, Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115, USA. (michael.j.mcphaden@noaa.gov)
X. Zhang, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92039, USA.