The Association of the Evolution of Intraseasonal Oscillations to ENSO Phase

PAUL E. ROUNDY AND JOSEPH R. KRAVITZ
University at Albany, State University of New York, Albany, New York

(Manuscript received 19 December 2007, in final form 25 July 2008)

ABSTRACT

The Pacific Ocean intraseasonal Kelvin wave is a leading oceanic mode that links intraseasonal tropical atmospheric variations with interannual variations in the coupled ocean–atmosphere system. This study considers the premise that these waves may evolve differently with their associated weather patterns during different phases of El Niño–Southern Oscillation (ENSO). If atmospheric and oceanic intraseasonal modes interact and evolve differently during various stages of ENSO, this result may provide useful information with regard to the role of these intraseasonal processes in ENSO evolution. This work utilizes signals of the oceanic Kelvin wave as a statistical basis for a simple composite averaging technique that is applied during different phases of ENSO to objectively analyze the evolution of oceanic and the associated portions of atmospheric intraseasonal oscillations. Results confirm the above premise and suggest that coupling between Kelvin waves and atmospheric convection evolves differently during different stages of ENSO. Further, intraseasonal zonal wind anomalies across the east Pacific timed with oceanic Kelvin waves are stronger during adjustment toward El Niño than during adjustment away from El Niño. These and other patterns in the composites suggest the possibility that systematic changes in the evolution of intraseasonal variations over the course of ENSO might feed back upon this interannual mode to influence the evolution of ENSO itself.

1. Introduction

El Niño–Southern Oscillation (e.g., Wyrtki 1975; Neelin et al. 1998) comprises a vast system of interactions between the ocean and atmosphere as well as between modes of weather and climate that span time scales of days to decades or longer. Although ENSO exists largely on interannual time scales through interactions between oceanic and atmospheric dynamics (e.g., Bjerknes 1969; Battisti 1988; Schopf and Suarez 1988; Kessler 2002), it strongly modulates and responds to the weather (e.g., Penland and Sardeshmukh 1995; Vecchi and Harrison 2000; Yu et al. 2003; Eisenman et al. 2005). Objective analyses suggest that the Madden–Julian oscillation (MJO) (Madden and Julian 1994; Hendon and Salby 1994; Wheeler and Kiladis 1999; Roundy and Frank 2004a,b; Kiladis et al. 2005; Zhang 2005; etc.) might influence the development of El Niño more than any other weather process (Enfield 1987; Hendon et al. 1998, 1999; Bergman et al. 2001; Moore and Kleeman 1999; Kessler and Kleeman 2000; Zhang 2001; Kutsuwada and McPhaden 2002; Zhang and Gottschalck 2002; Shinoda and Hendon 2002; Roundy and Kiladis 2006, 2007).

Since there is no consensus about the dynamics of the MJO, there is no consistently accepted definition for it. For the purposes of this work, the MJO is loosely defined as a planetary-scale disturbance of winds and moist deep convection characterized by a local period of 30–80 days and eastward phase speeds between 3 and 8 m s⁻¹ in the deep tropics of the Eastern Hemisphere. The MJO comprises planetary-scale envelopes of alternating anomalously active and suppressed moist deep convection. However, the MJO also modulates activity associated with smaller-scale modes that are coupled to convection. These disturbances include equatorial Rossby waves (Roundy and Frank 2004b,c), convectively coupled atmospheric Kelvin waves (Nakazawa 1988; Dunkerton and Crum 1995; Straub and Kiladis 2003; Roundy 2008), and synoptic- and subsynoptic-scale features such as westerly wind bursts (e.g., Harrison and Giese 1991; Hartten 1996; Seiki and Takayabu 2007a,b) and tropical cyclones (e.g., Frank and Roundy 2006). As...
such, there is enhanced activity associated with these smaller-scale disturbances within the larger, planetary-scale envelopes of anomalous convection. Each of these elements may be integral to the multiscale structure and development of the MJO (e.g., Majda et al. 2004; Kiladis et al. 2005). In addition to these convective anomalies, the MJO is also associated with global wind patterns. These include intraseasonal westerly wind bursts as well as zonally broad surges in the equatorial trade winds. Both of these wind patterns may influence ENSO.

Intraseasonal weather events influence the ocean through modulating fluxes of momentum, heat, and moisture across the ocean surface. It is well established that intraseasonal westerly wind stress on the equatorial west Pacific triggers downwelling intraseasonal oceanic Kelvin waves (hereafter simply “Kelvin waves”) that might influence the development of El Niño by pushing the thermocline of the central and east Pacific downward and/or by moving warm water eastward (e.g., Harrison and Schopf 1984; Federov and Melville 2000; Roundy and Kiladis 2006; and many others). Nearly every intraseasonal downwelling Kelvin wave can be traced back to eastward-moving active convective anomalies associated with the MJO (Hendon et al. 1998; Roundy and Kiladis 2006). Active moist deep convection associated with the MJO also reduces west Pacific SST (e.g., Hendon et al. 1998), thus acting to make SST more uniform across the equatorial basin. The synoptic-scale westerly wind bursts (e.g., Harrison and Giese 1991; Hartten 1996; Seiki and Takayabu 2007a,b), which many authors have also shown to be associated with the development of Kelvin waves, are not necessarily independent from the MJO as evidenced by the clear association of both processes to the Kelvin waves. Since the Kelvin waves are a leading response of the equatorial ocean to changes in zonal wind stress (regardless of its source), their signals offer a convenient statistical basis for analysis of associated atmospheric disturbances without making assumptions about whether the most relevant atmospheric mode is a synoptic-scale process or an active MJO event.

Even though the MJO is clearly involved in the development of some El Niño events, debate about the specific relationship between the MJO and ENSO is far from settled. Some indices of MJO activity are uncorrelated with indices of ENSO (Slingo et al. 1999; Hendon et al. 1999). This finding is sensitive to the MJO indices chosen (e.g., Kessler 2001) and to the seasons analyzed (Hendon et al. 2007). Bergman et al. (2001) noted that, although the MJO was very active preceding the major El Niño of 1997–98, it was apparently not abnormally active prior to the major 1982–83 El Niño. Bergman et al. therefore concluded that the MJO might be relevant to the timing and initial growth of El Niño rather than responsible for the event itself. However, Roundy and Kiladis (2007) showed that a Kelvin wave triggered by a MJO event during June 1982 was directly associated with a dramatic 25-cm increase in sea surface height at Christmas Island that was then sustained for more than seven months. This finding suggests that the MJO helped trigger the rapid onset of El Niño conditions during July–August 1982 [consistent with the timing noted by Harrison and Schopf (1984)]. Most MJO events are not associated with such dramatic changes in the oceanic background state. The background state may help determine whether an individual MJO event can be associated with such changes.

It is well established that some aspects of the MJO change with ENSO. As oceanic conditions adjust toward El Niño, the zonal “fetch” of surface westerly winds associated with the MJO extends farther to the east of the date line [e.g., Hendon et al. (1998), and consistent with the discussion of westerly wind bursts by Eisenman et al. (2005)], enhancing the amplification of the associated downwelling Kelvin waves. In addition, Roundy and Kiladis (2006) showed that anomalies of atmospheric convection, sea surface temperature, and sea surface dynamic height linked to Kelvin waves occasionally move eastward together at phase speeds much slower than the average MJO. They also showed that subsequent similar anomalies tend to move eastward progressively more slowly with time during periods of enhanced Kelvin wave activity. These periods of enhanced Kelvin wave activity and transient phase speed decline tend to occur in conjunction with increases in regional SST as the ocean adjusts toward El Niño conditions.

Roundy and Kiladis (2006) suggest that this pattern is consistent with coupling between the oceanic long waves and atmospheric convection. Their findings also indicate that the pattern of transient phase deceleration across groups of high-amplitude waves is in large part responsible for the frequency difference between the east Pacific Kelvin waves (~70 days) and the west Pacific MJO (~40–50 days). In the absence of the coupling process, westerly wind anomalies associated with the MJO tend to move eastward more quickly than the Kelvin waves, limiting Kelvin wave amplification farther east (although a very strong MJO event can still excite a high amplitude Kelvin wave without the coupling effects). The coupling process apparently allows wind stress to amplify Kelvin waves more effectively than the MJO would without the coupling effects. The coupling process is most effective during the onset phase of El Niño. The pattern of transient phase speed reduction is more strongly linked to changes in basinwide
wind stress than to changes in the stratification of the ocean (Shinoda et al. 2008). This pattern is consistent in some respects with the “advective mode” of Lau and Shen (1988), in which anomalies of SST associated with Kelvin waves and active atmospheric convection move eastward together more slowly as regional mean SST increases.

Many studies that examine the potential relationship between atmospheric intraseasonal variability and ENSO have simply evaluated correlations between indices of MJO variance and indices of ENSO (e.g., Zhang and Gottschalck 2002; Hendon et al. 1999; Slingo et al. 1999). Since the structures of intraseasonal oscillations might evolve differently during different ENSO phases, it is possible that some intraseasonal patterns could favor adjustment toward El Niño, whereas other patterns might favor adjustment toward La Niña. In other words, it may be the specific pattern of evolution of intraseasonal weather and not just the amount of MJO activity in any given season that influences the advance or decline of ENSO anomalies. If so, analysis of correlations of ENSO with MJO variance alone might be insufficient to diagnose the general relevance of the MJO to ENSO.

The present work advances analysis of the connection of intraseasonal variations to ENSO by objectively compositing how intraseasonal patterns of wind and convection linked with oceanic Kelvin waves and ENSO tend to change with ENSO phase. The methods applied here diagnose the relevant wind patterns without assuming the form of the MJO or any other process. Since this is an observational study designed to diagnose in general terms how intraseasonal patterns change with ENSO, the causes of the many changes we diagnose are beyond the scope of the paper and will need to be addressed elsewhere for brevity. However, if the composite wind stress patterns vary with ENSO phase, the relevant composite structures could serve to focus the direction of future research toward determining whether the intraseasonal patterns might enhance the evolution of the changing oceanic background state either toward or away from El Niño. The present analysis is limited to the longitude–time domain for brevity. Corresponding plan-view maps will be summarized in a subsequent paper.

2. Data

Interpolated outgoing longwave radiation (OLR) data (Liebmann and Smith 1996) were obtained from the NOAA/Earth System Research Laboratory (ESRL) (formerly Climate Diagnostics Center) Web site. OLR is a relatively good proxy for moist deep convection in the tropics. This analysis includes the period 1 June 1974 through December 2006. It is important to point out that different satellite platforms were used to obtain these data over the years. Equatorial crossing times varied between satellites and over time for individual satellites because of orbital decay, thus examination of long-term trends in these data is difficult. However, structures associated with the temporal evolution of observed intraseasonal convective events would not be significantly influenced by these irregularities. Wind data at 1000 hPa were obtained from the National Centers for Environmental Prediction (NCEP) reanalysis (e.g., Kalnay et al. 1996). The mean and four primary harmonics of the seasonal cycle were subtracted to generate anomalies, and the data were then filtered for periods from 10 to 120 days by means of a Fourier transform. This filter is sufficiently broad to render Gibbs ringing phenomena inconsequential. Optimum interpolated SST data (e.g., Reynolds et al. 2002) were obtained from the ESRL Web site. These data were interpolated to a 2.5° grid, and anomalies were obtained by removing the first four harmonics of the seasonal cycle. These SST data begin in 1982.

Dynamic height data from the Tropical Atmosphere Ocean (TAO) (McPhaden 1995) array of buoys moored in the tropical Pacific are temporally filtered for 20–120-day periods (to include mainly the signals of intraseasonal Kelvin waves) by applying the least squares fits of sine and cosine waves characterized by those periods. This filtering method is identical to the Fourier transform, but was more convenient to apply in a manner that ignores missing data. Since these data are only available in sufficient quantities to analyze oceanic Kelvin waves after ~1990, regression relationships between the buoy data and sea level gauge observations from island and coastal sites are applied to reconstruct missing data [see Roundy and Kiladis (2007) for details of the reconstruction method]. This reconstruction method is applied here to both 20–120-day periods (to help diagnose Kelvin waves) and to 120-day low-pass filtered dynamic height data (to estimate the background ENSO dynamic height signal), averaged over the Niño-3.4 region. The first time finite difference of the ENSO index is applied as an index for the time rate of change of ENSO. These two indices are applied together to obtain ranges of dates consistent with different phases of ENSO. Dynamic height is applied here because it responds relatively more directly to forcing by wind stress than does SST. Work done by wind stress is manifest directly by redistribution of mass (more consistent with dynamic height), whereas SST is comparatively more sensitive to other factors such as fluxes of radiation and sensible and latent heat across the ocean surface. Dynamic height anomalies tend to lead SST anomalies on interannual time scales. For example,
during the end phases of strong El Niño events, dynamic height tends to decline during December–January, whereas SST anomalies may decline months later. Although signals of tropical instability waves extend into the 20–120-day Kelvin wave band, these waves are usually characterized along the equator at the date line by amplitudes much smaller than those of Kelvin waves.

3. Compositing method

Composite averages of multiple events are applied to discern patterns of atmospheric intraseasonal variability that tend to occur in association with oceanic Kelvin waves during specific stages of ENSO. These composites are made by averaging reconstructed dynamic height, 10–120-day band OLR and zonal wind data, and unfiltered SST anomalies at each grid point over sets of dates and time lags from those dates, following a variation on the method Roundy (2008) applied to diagnose MJO modulation of the evolution of atmospheric convectively coupled Kelvin waves. Dates for averaging are obtained from the set of all local maxima greater than 0.5 standard deviation (SD) in the observed or reconstructed 20–120-day bandpass filtered dynamic height at a base buoy (e.g., Roundy and Kiladis 2006). To reduce the contributions of higher frequency processes to the composites, all dates from six days before to six days after each dynamic height maximum are included. We then eliminated all events in which the dynamic height was not greater than 0.5 SD five days previous at the buoy to the west and 0.5 SD five days later at the next buoy to the east. This elimination increases the likelihood that retained events are associated with eastward-moving anomalies, consistent with Kelvin waves. The remaining dates correspond to the times of Kelvin wave crests at the base buoys. Subsets of the list of dates were obtained by selecting only those events that occurred during specific ranges of ENSO phase determined from analysis of the ENSO dynamic height indices. Composites presented here are averaged over these subsets. The date line was applied as the base longitude during most phases of ENSO, except the buoy at 156°E was applied during advancing La Niña conditions (since many waves attenuate before reaching the date line during La Niña). This analysis was repeated based on neighboring buoys to confirm the patterns seen in the first set of composites.

The ENSO index ranges selected for the ENSO-based composites (shown in Table 1) were chosen to diagnose intraseasonal patterns that tend to occur during periods of rapid adjustment toward warmer or colder ENSO conditions, when the ENSO state was either cold, neutral, or warm. Thus six states are analyzed. We decided to focus on periods of rapid change in ENSO since preliminary results (not shown here) suggest that intraseasonal events might catalyze rapid changes in ENSO. The range of standard deviations for some phases were expanded relative to the others to improve the balance in the number of Kelvin wave events per composite (e.g., rapid changes in ENSO do not frequently occur during La Niña conditions).

Although a family of events included in a composite during a particular phase of ENSO might have many factors in common, there is likely to be large spread in the values of atmospheric signals averaged over dates associated with oceanic Kelvin waves. Although inclusion of the additional six days both before and after each event would average out much of the high frequency, more random variations, some further variation between events is still anticipated. The purpose of this analysis is to discern whether certain patterns are favored over other patterns during specific phases of ENSO. Statistical significance was evaluated by applying 1000 bootstrap experiments at each grid point and time lag to assess the probability that the composite anomalies are different from zero (e.g., Roundy 2008). Each experiment was performed by randomly selecting new samples of Kelvin wave crossing dates from the original sample. After selecting the event, a date was selected at random from the period six days before to six days after the event. The process was then repeated to construct a sample of dates the same length as the original sample, then, a new composite was generated by averaging data fields over those dates. Any individual event was allowed to be drawn any number of times when selecting a new sample. This process results in a distribution of 1000 composite values at each grid point and time lag. The probability that each composite anomaly is significantly different from zero is determined by locating the zero anomaly line within the distribution, assuming the null hypothesis that the actual mean value is zero. A 95% confidence level means that 95% of the random draw composites for a given

<table>
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<th>1</th>
<th>2</th>
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<td>Maximum dynamic height index</td>
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<td>−0.5</td>
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<td>Minimum dynamic height trend</td>
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<td>+0.5</td>
<td>−4</td>
<td>−4</td>
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<tr>
<td>Maximum dynamic height trend</td>
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<td>+4</td>
<td>+4</td>
<td>−0.5</td>
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location and time lag were distributed on the same side of zero. Depending on the frequency of outliers and on the stationarity of the intraseasonal processes over time (e.g., Roundy and Kiladis 2007), this may be sufficient for clear assessment. Since the distributions vary at each grid point and time lag, there is no specific amplitude that can be considered significant everywhere. Further similar tests were applied to determine the significance of the differences between specific pairs of composites by comparing the two relevant bootstrap distributions and assuming the null hypothesis that the two means are the same (Wilks 2006). A t test for the difference of two means was also applied for comparison. We discuss composite patterns only when similar patterns were also significant in each of the composites based on neighboring buoys. Unless otherwise noted, a value reported as significant is so at the 95% level.

It is important to consider that, since different phases of ENSO tend to occur during specific phases of the seasonal cycle, the seasonal cycle may actually be responsible for some of the differences between the composite patterns. To address this issue, we generated a second set of composites based on averaging over data corresponding to the set of dates of Kelvin wave crossings at the date line, further sorted by calendar month but not according to the phase of ENSO in which they occurred. As above, all dates 6 days before to 6 days after each dynamic height maximum were included. We then tabulated the Kelvin wave events included in the ENSO-based composites according to the month in which they occurred. New composites were then constructed for each ENSO phase by combining the monthly averages with weighting by the number of events per month that occurred for each phase of ENSO. These monthly average-based composites were then utilized to diagnose the contribution of the seasonal cycle to the ENSO-based composites.

4. Results

a. Overview

Figures 1a–f show composite average OLR, 1000-hPa zonal wind, and reconstructed 20–120-day dynamic height for each of six phases of ENSO dynamic height anomalies: (a) negative and increasing, (b) neutral and increasing, (c) positive and increasing, (d) positive and declining, (e) neutral and declining, and (f) negative and declining. OLR and wind anomalies are averaged over 2.5°S–2.5°N and dynamic height is averaged from 2°S to 2°N. For reference, Fig. 2 shows the composite OLR with a single contour added, representing the 95% confidence level for difference from zero, for comparison with the corresponding panels of Fig. 1. Figure 3 shows the same for the composite zonal wind. Table 1 shows the ranges of the ENSO dynamic height and ENSO trend indices assigned to each of these phases. Corresponding composites of SST anomalies are shown for reference in Fig. 4. Note that the SST data are limited to the period since 1 January 1982, whereas the other products extend back to 1974. These SST composites confirm the presence of La Niña conditions during Phase 1 (Fig. 4a), neutral but warming during Phase 2 (Fig. 4b), El Niño onset during Phase 3 (Fig. 4c), mature El Niño during Phase 4 (Fig. 4d), declining El Niño during Phase 5 (Fig. 4e), and developing La Niña during Phase 6 (Fig. 4f). Figure 5 indicates the number of events during each phase that occurred by month of the year. Figure 5a shows an enhanced concentration of Phase 1 events during late northern winter through early summer, consistent with Hendon et al. (2007). Phase 2 events are most prevalent during boreal summer. Phase 3 events concentrate during summer and fall. Phase 4 events concentrate during December through March. Phase 5 events are most frequent during January through March, and Phase 6 events cluster during December and February through April. As more data are collected during future years, these seasonal patterns will likely become better defined. The seasonal cycle of SST might be relevant to changes in the evolution of intraseasonal patterns in the composites in Fig. 1. Phases 2 and 3 tend to occur during months when seasonal SST declines with time in the east Pacific, whereas Phase 4 through 6 events (which occur during adjustment away from El Niño) tend to occur during months when seasonal SST increases in the east Pacific.

Although there are significant differences between the composites in Fig. 1, some general structures are common to each. Near the center of each composite, a positive dynamic height anomaly moves eastward across the base point at the date line and the 0-day time lag (consistent with a downwelling Kelvin wave). This dynamic height anomaly is preceded farther west by negative OLR anomalies and anomalous westerly wind stress. Subsequent negative OLR and westerly wind anomalies occur from 40 to 60 days later. These wind and OLR anomaly patterns are evident during each ENSO phase and are consistent with the MJO.

b. Phase 1

Greater spread exists between events during Phases 1 and 6 than during the other phases; nevertheless, some patterns were found to be significantly different from zero. Figure 1a and the corresponding analyses at neighboring buoys (not shown) show an upwelling...
Kelvin wave developing in a region of easterly winds across the west Pacific near lag $-45$ days. Negative OLR anomalies are associated with westerly wind anomalies over the west Pacific between lag $-30$ and lag $-15$ days.

These westerly wind anomalies reach maximum intensity across the west Pacific near lag $-20$ days, then rapidly spread eastward across the central basin, coincident with attenuation of the negative dynamic height anomaly mentioned above. A second local maximum in these westerlies occurs near lag $-10$ days near $135^\circ W$. The west Pacific westerly wind anomaly is associated with development of a downwelling Kelvin wave (suggested by the solid black contours of positive dynamic height). Comparison of Fig. 1a with Fig. 4a suggests that a small eastward excursion of less negative equatorial SST anomalies occurs in the vicinity of this downwelling Kelvin wave.

Also at lag $-20$ days, a region of suppressed convection is suggested over the Indian Ocean (Fig. 1a), then over the west Pacific following lag $-10$ days. Easterly wind anomalies are collocated with these positive OLR anomalies, and these easterly anomalies redevelop over the west Pacific near lag 0 days. The central Pacific wind anomalies (both easterly and westerly) spread eastward more quickly than the dynamic height anomalies and there is a resultant switch in wind anomaly sign along the dynamic height anomaly trajectories. When intersected by the Pacific easterly wind anomalies, the positive dynamic height anomalies weaken, suggesting attenuation of the oceanic waves by
the intraseasonal wind stress. This pattern of alternating zonal wind stress likely also facilitates the slight westward return of isotherms following the downwelling Kelvin wave passage (Fig. 4a).

In comparison with Phases 2–5 (shown in Figs. 1b–e), Fig. 1a suggests that intraseasonal anomalies of wind and dynamic height tend to be weaker or less organized in the Pacific basin during the cold phase of ENSO than during other phases, consistent with the previous results of many others (e.g., Hendon et al. 1998).

c. Phase 2

Figure 1b shows the composite intraseasonal pattern during Phase 2 of ENSO. Enhanced moist deep convection and westerly wind anomalies over the Indian Ocean (near lag \(-35\) days) develop over the west Pacific, then progress slowly eastward at approximately the same phase speed as the developing positive dynamic height anomaly. This pattern is consistent with coupling between downwelling Kelvin waves and westerly wind stress over the west Pacific (Roundy and Kiladis 2006), but the apparent coupling pattern is confined to the far western Pacific. The west Pacific negative OLR and westerly wind anomalies taper to zero near lag \(-10\) days. However, the westerly wind anomaly subsequently amplifies again across the east Pacific centered near \(135^\circ W\) near lag \(-10\) days. A negative dynamic height anomaly that is moving eastward across the eastern basin at the same time appears to attenuate in the vicinity of these westerly wind anomalies. In contrast, the previously described positive dynamic height anomaly (crossing lag 0 days) maintains its amplitude farther to the east. This maintenance may be in response to these westerly wind anomalies. The positive dynamic height anomaly subsequently attenuates after la +10 days upon encountering an easterly wind anomaly near \(135^\circ W\). This intraseasonal pattern might favor extended surface warming of the equatorial

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**Fig. 2.** Composite 20–120-day OLR anomalies plotted as in Fig. 1 but with an additional contour representing the 95% confidence level for the difference from zero (based on the bootstrap test described in the text). Negative anomalies are shaded and positive anomalies are not.
east Pacific because of the apparent attenuation of the upwelling Kelvin wave and amplification of the downwelling wave. Composite SST anomalies increase in association with the downwelling Kelvin near the center of the composite (Fig. 4b).

**d. Phase 3**

Figure 1c shows the composite intraseasonal pattern during Phase 3. Negative OLR and westerly wind anomalies are centered near lag $\approx 40$ days over the Indian Ocean. These anomalies progress eastward to the west Pacific. The westerly wind anomaly apparently triggers development of a positive dynamic height anomaly near lag $\approx 20$ days. The westerly wind anomaly over the west Pacific moves gradually eastward at about the same phase speed as this downwelling Kelvin wave until it reaches the date line where the convection dissipates and the wind anomaly extends eastward across the basin. The simultaneous slow progression of negative OLR, westerly wind, and positive dynamic height anomalies suggest coupling between the oceanic Kelvin wave and atmospheric convection, as suggested by Roundy and Kiladis (2006). Around lag $-15$ days, westerly wind anomalies extend rapidly across the remainder of the basin, where they remain for about two weeks. Dramatic increases in anomalous SST appear in the vicinity of the downwelling Kelvin wave (Fig. 4c), and SST remains anomalously high following passage of the wave.

Two convectively suppressed phases of the MJO are also apparent in the composite, but they evolve differently. The first occurs between lag $-50$ and lag $-30$ days, and appears to follow roughly the same pattern as the convectively active phase at the center of the composite, but with opposite sign. The second event begins with positive OLR and easterly wind anomalies developing over the Indian Ocean near lag $-20$ days. A region of easterly wind and positive OLR anomalies then develops across the west Pacific following lag 0 days. This pattern is associated with the development of a
new upwelling Kelvin wave but, unlike the earlier event, the associated easterly anomalies do not extend across the downwelling Kelvin wave until after lag \(120\) days, giving the downwelling wave an opportunity to cross most of the basin largely unimpeded by easterly wind-stress-induced attenuation.

e. Phase 4

Figure 1d shows the composite intraseasonal pattern observed during Phase 4. Composite OLR, wind, and dynamic height anomalies are characterized by significantly higher amplitudes during Phase 4 than during all other phases. A negative OLR anomaly develops over the Indian Ocean prior to lag \(230\) days, moves eastward, and amplifies over the west Pacific. Westerly wind anomalies of \(2\) m s\(^{-1}\) develop within this region of active convection west of the date line, then move to the east along the trajectory of the positive dynamic height anomaly, suggesting coupling between the oceanic wave and atmospheric convection. This narrow region of westerly anomalies is significantly different from zero at the 90\% level to the west of the dynamic height anomaly all the way to 135\(^\circ\)E. The downwelling Kelvin wave at the center of Fig. 1d is coincident with the maximum central and east Pacific SST anomaly of the composite El Niño (Fig. 4d).

Anomalies of positive OLR and easterly wind develop over the western Indian basin after lag \(225\) days and move eastward together and amplify as a coherent structure over the west Pacific. This pattern is consistent with the suppressed convective phase of the MJO. Associated easterly wind anomalies that develop near lag \(110\) days west of the date line are significantly more intense than the comparable anomaly observed during Phase 3 (Fig. 1c). This pattern suggests a much stronger suppressed convective phase of the MJO during adjustment away from El Niño than during adjustment toward El Niño, given the same range of values in the ENSO index. Another similarly significant difference between Figs. 1c and 1d is that the region of westerly wind anomalies across the eastern basin prior to lag 0 is stronger and of longer duration during Phase 3 than during Phase 4. Although causality cannot be assured from these analyses, and other factors might also be...
relevant, this result is consistent with the possibility that anomalous intraseasonal westerly winds across the east Pacific favor amplification of El Niño conditions, whereas an unusually strong suppressed convective phase of the MJO following an active MJO event associated with weaker westerlies across the east Pacific favors the beginning of El Niño decline.

f. Phase 5

Figure 1e shows the composite intraseasonal pattern during Phase 5 of ENSO, corresponding with a period of adjustment away from El Niño conditions toward neutral ENSO. An active convective phase of the MJO (suggested by both westerly wind and negative OLR anomalies moving eastward across the Indian and west Pacific Oceans) precedes a downwelling Kelvin wave that then crosses the date line near lag 0 days. However, the negative OLR and westerly wind anomalies weaken west of the date line. Unlike during Phase 2 (Fig. 1b), when ENSO dynamic height anomalies are similar, there is only a small signal of a second westerly anomaly developing farther east. The westerly anomalies across the east Pacific in Figs. 1e and 1b are significantly different from each other above the 95% level in a bootstrap test and a student’s t test. Figure 4e suggests that rapid SST decline tends to occur across the east Pacific during Phase 5, with the most rapid declines occurring after the local passage of the positive dynamic height anomaly.

g. Phase 6

Figure 1f shows the composite intraseasonal pattern during Phase 6 of ENSO (when ENSO dynamic height values are most consistent with strengthening La Niña conditions—see Fig. 4f for the corresponding evolution of SST anomalies). A pattern of zonal wind and OLR...
anomalies is apparent across the Eastern Hemisphere, consistent with the MJO. However, the amplitude of the negative OLR anomaly at negative lags is higher across the Indian Ocean than across the Pacific, in spite of the location of the base point in the west Pacific. The negative and positive dynamic height anomalies throughout the composite are characterized by smaller amplitudes than during Phases 2–5. Further, the secondary development of westerly anomalies east of the date line is significantly weaker during Phase 6 than during Phase 1. Rapid surface cooling is indicated in Fig. 4f east of the date line.

h. Seasonal cycle of intraseasonal evolution

Figure 6 shows the evolution of intraseasonal variations associated with Kelvin waves during different stages of the seasonal cycle based on the averaging technique discussed in section 3 for Kelvin waves during specific months of the year. Results are shown averaged by pairs of months (e.g., Fig. 6a shows the result for January and February, Fig. 6b for March and April, and so forth). As with Kelvin waves throughout the ENSO cycle, the MJO pattern of eastward-moving anomalies of zonal wind and convection is apparent in association with Kelvin waves throughout the seasonal cycle. These results also suggest that Kelvin wave amplitudes tend to be highest during January and February. Close examination of Fig. 6 reveals that Kelvin waves apparently propagate more slowly during January through March than other months, and most quickly during May–June. Westward-moving anomalies of active convection are
most apparent during January through February, suggestive of convectively coupled atmospheric equatorial Rossby waves linked to the MJO (e.g., Roundy and Frank 2004b). Secondary westerly wind events develop east of the date line in association with downwelling Kelvin waves, mainly during April–October. These results suggest that the intraseasonal westerly wind anomalies associated with Kelvin waves appear to be most coherent with positive dynamic height anomalies during November and December. This finding suggests that the coupling process discussed by Roundy and Kiladis (2006) tends to be most prevalent during these two months.

Figure 7 shows the weighted averages of the individual monthly composites based on the monthly distribution of events (Fig. 5) included in the ENSO-based composites, for comparison with Fig. 1. If the seasonal cycle generates the leading distinctions between the different panels in Fig. 1, then Fig. 7 would show similar patterns to those in Fig. 1. The patterns in Figs. 7a–c and Figs. 7d–f are similar to each other. Distinctions are most easily made between the wind anomalies. Figures 1a–c suggest that during months consistent with Phases 1–3, secondary westerly anomalies develop east of the date line, to the east of positive dynamic height anomalies. These westerly anomalies are largely absent from Figs. 1d–f. This pattern suggests that the seasonal cycle and ENSO may both play some roles in the evolution of intraseasonal westerly wind events east of the date line that are timed with Kelvin waves during adjustment toward El Niño. The amplitudes of these secondary wind events are significantly greater in the
ENSO composites than in the composites based on the seasonal cycle during Phases 2–3. The other major differences between the panels in Fig. 1 are not apparent in Fig. 7, suggesting that the differences between the panels of Fig. 1 are attributable to ENSO phase directly and are not determined by the seasonal cycle.

5. Discussion

Composite equatorial intraseasonal OLR, zonal wind, SST, and dynamic height (Figs. 1, 4) indicate that weather patterns tend to evolve differently in association with oceanic Kelvin waves during different phases of ENSO. These intraseasonal patterns include differences in the favored longitudes and intensities of westerly wind bursts (e.g., Gebbie et al. 2007; Seiki and Takayabu 2007a), variations in the intensities of intraseasonal wind anomalies east of the date line that are timed with Kelvin waves (e.g., Shinoda et al. 2008), and differences in the amplitudes and phase speeds of anomalies of atmospheric convection and zonal winds in the immediate vicinity of the positive dynamic height anomalies [suggesting variations in coupling between oceanic waves and atmospheric convection; Roundy and Kiladis (2006)]. Since these patterns favor specific phases of ENSO, they might influence the evolution of the oceanic background state differently among the different ENSO phases. Any modulation of interannual variations by these intraseasonal processes would be superimposed upon and potentially interact with the internal dynamics of ENSO.

These results, together with those of Eisenman et al. (2005), Gebbie et al. (2007), and Sieki and Takayabu (2008a,b), suggest that stochastic forcing theories for ENSO should be modified to account for the influence of ENSO on the stochastic forcing—that is, if intraseasonal weather processes associated with oceanic Kelvin waves evolve differently during different stages of ENSO, the weather forcing cannot be considered purely stochastic since evolution changes systematically with ENSO. Eisenman et al. showed that westerly wind bursts evolve systematically eastward with the development of El Niño, and they went so far as to conclude that these weather events are internal to ENSO. However, Kessler (2002) showed that ENSO has been known to remain in a neutral state for up to two years before westerly wind events initiate a new cycle. Additionally, most intraseasonal wind stress events can be traced back to regions of active convection moving eastward from the Indian Ocean (Hendon et al. 1998). These planetary-scale active convective events develop away from the centers of action of ENSO, and occur during all phases of ENSO (e.g., Hendon et al. 1998).

Thus, ENSO does not determine the specific timing of these intraseasonal events, suggesting that, although the behavior of individual intraseasonal events already present might be modulated by ENSO, the events themselves are not internal to ENSO (e.g., Gebbie et al. 2007). Our results and those of Seiki and Takayabu (2007a,b) suggest that the cooperative evolution of oceanic Kelvin waves and their associated weather processes is consistent with nonlinear modulation of these intraseasonal processes by ENSO. In other words, the intraseasonal patterns do not develop at times predetermined by ENSO, but rather ENSO affects how they evolve in time and space when they happen to occur.

An alternative perspective that may be consistent with some of our results is that the sensitivity of the oceanic Kelvin waves to particular patterns of atmospheric forcing might change with ENSO, causing the composites to favor those patterns. For example, changes in the stability of the ocean might dictate that oceanic Kelvin waves would be more responsive to different speeds of eastward propagation in the atmosphere. In other words, even if the population of forcing events remained the same, changes in Kelvin wave phase speeds in response to the forcing would be possible. Our analysis of the individual events that were included in the composites suggests that the forcing patterns do, in fact, change with ENSO since most of the individual events included in a given composite include the same patterns that were shown to be significant in the composites. Nevertheless, this alternative mechanism might contribute to some observed ocean–atmosphere interactions.

Coupling between the intraseasonal Kelvin waves and atmospheric convection (e.g., Roundy and Kiladis 2006) provides one mechanism whereby ENSO might influence the development of intraseasonal weather events since the evolution of the coupled Kelvin wave events depends on SST (Lau and Shen 1988). Our results also show that secondary westerly wind anomalies develop east of the date line in association with Kelvin waves, especially during July through October. Adjustment toward El Niño apparently amplifies these wind anomalies. Further study is necessary to diagnose the relevance of these secondary westerly anomalies to ENSO. Further analysis of composite patterns, including plan-view maps and a census of processes seen in individual events included in the composites, will be summarized in a subsequent paper.

Acknowledgments. This work was financed by startup funds for new faculty from the University at Albany. TAO data were provided by the Pacific Marine Environment Laboratory. Sea level height observations were
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