Intraseasonal Perturbations in Sea Surface Temperatures of the
Equatorial Eastern Pacific and Their Association with the
Madden–Julian Oscillation*

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ABSTRACT

A particular pattern of intraseasonal perturbations in sea surface temperature (SST) is observed in the eastern Pacific Ocean following events of strong surface winds associated with the Madden–Julian oscillation (MJO). This intraseasonal SST pattern straddles at the equator with its longitudinal scales of 2–5 × 10^3 km and meridional scales of about 500 km. The amplitude of the perturbations is 0.5°C or greater. Positive and negative perturbations sometimes follow one another. They show tendencies of both eastward and westward movement. Such equatorially elongated perturbations in SST in the eastern Pacific are hypothesized to be caused by intraseasonal oceanic Kelvin waves forced by the MJO over the western/central Pacific. As the Kelvin waves propagate eastward, changes in the vertical temperature gradient in the upper ocean due to the fluctuations in the depth of the thermocline modify the thermal effect of the equatorial upwelling. As a result, mixed layer and surface temperatures may fluctuate. The observational basis for this hypothesis is presented through an empirical analysis of intraseasonal perturbations in SST, surface wind forcing, the depth of the thermocline, and the vertical temperature gradient of the upper ocean along the equator. The intraseasonal components of these fields fluctuate in coherence on interannual timescales. A possible implication of the observations to the interannual variability in the Pacific is proposed.

1. Introduction

Intraseasonal perturbations in sea surface temperature (SST) of the equatorial eastern Pacific are often associated with the tropical instability waves (e.g., Legeckis 1977; Pullen et al. 1987). The spatial scales of those perturbations are roughly 800–2000 km and their periods 20–40 days. Their maximum amplitudes, about 0.5°C, are often found near the mean SST front north of the equator. An example of such perturbations in SST is given in Fig. 1a.

Intraseasonal perturbations in SST in the same region sometimes exhibit a quite different spatial structure: They tend to straddle at the equator with their amplitudes of also 0.5°C or greater; their longitudinal scales (2–5 × 10^3 km) are much greater than their meridional scales (≤500 km). An example of such equatorially elongated intraseasonal perturbations in SST is given in Fig. 1b. SST perturbations associated with the tropical instability waves are often superimposed on this equatorially elongated pattern.

The equatorially elongated intraseasonal perturbations in SST in the eastern Pacific are unlikely to be caused by local atmospheric forcing. No intraseasonal perturbation in surface winds and latent/sensible heat fluxes of the similar zonal and meridional scales can be found in the region. No fluctuation in cloud is expected to exist in the region that may generate the equatorially elongated intraseasonal perturbations in SST by changing surface radiation fluxes. There is no known local oceanic phenomenon that can explain this perturbation pattern in SST.

The purpose of this study is to demonstrate that, in observations, the equatorially elongated intraseasonal perturbations in SST can be related to the Madden–Julian oscillation (Madden and Julian 1971, 1972), or simply the MJO, over the western Pacific.

The MJO is the dominant component of the atmospheric intraseasonal variability in the Tropics. In the western Pacific, it exerts substantial forcing to the underlying ocean through perturbations in surface fluxes of momentum, heat, and freshwater. There, responses of the ocean have been observed in temperature, salinity, and current (e.g., Kessler et al. 1995; Zhang 1996, 1997;
Hendon and Glick 1997; Ralph et al. 1998; Cronin and McPhaden 1998; Zhang and McPhaden 2000). One of the strongest signatures of the oceanic response to the MJO is the intraseasonal Kelvin wave (Kessler et al. 1995; Hendon et al. 1998). The Kelvin wave propagates at the phase speed of the first-mode Kelvin wave (2.4 m s$^{-1}$ from observations) with high zonal coherence over 10 000 km and dominant periods of 60–100 days. The perturbations in the thermocline depth associated with the intraseasonal Kelvin wave are of 20–60 m in the equatorial eastern Pacific.

It can be hypothesized that, as a result of the MJO-related perturbations in the depth of the thermocline, the vertical temperature gradient in the upper ocean also fluctuates. This in turn may modify the thermal effect of the equatorial upwelling in the eastern Pacific. At the end of this chain of actions, mixed layer temperature and SST in the equatorial eastern Pacific may fluctuate following MJO activities over the equatorial western and central Pacific. The observational basis of this hypothesis can be obtained by examining the statistical coherence among the intraseasonal perturbations in SST, surface wind forcing, the depth of the thermocline, and the vertical temperature gradient of the upper ocean along the equator. Results from such an examination are summarized in this article.

Observational data and analysis methods are described in section 2. In section 3, an observed case is first shown, in which strong intraseasonal perturbations in surface zonal wind over the central Pacific led to the equatorially elongated intraseasonal perturbation in SST in the eastern Pacific seen in Fig. 1b. A “Kelvin wave forcing index” (or simply “Kelvin wave forcing”) of surface winds is then introduced as a measure of atmospheric forcing of the oceanic intraseasonal Kelvin wave. Next, observed long-term (7-yr) time series of both the total fields and intraseasonal perturbations in Kelvin wave forcing, the depth of the equatorial thermocline, the vertical temperature gradient, and SST are compared. Relationships among these fields are further quantified through coherence analyses. Statistically reconstructed coherent patterns of these fields are presented. These analyses demonstrate that, out of all intraseasonal (5–90 days) variability in SST, the equatorially elongated pattern seen in Fig. 1b emerges as the one that is the most coherent with Kelvin wave forcing due to the MJO. The results, which serve as the observational basis for the hypothesis proposed earlier, are further discussed in section 4.

The coherence between intraseasonal perturbations in SST in the equatorial eastern Pacific and MJO activities over the western Pacific is of interest because of the debate on possible influences of the MJO on ENSO. It has been proposed that the MJO might influence ENSO either as a source of stochastic forcing (e.g., Lau 1985; Moore and Kleeman 1999) or more deterministically through interaction with the ocean in the western/central Pacific (e.g., Kessler et al. 1995; McPhaden 1999; Kessler and Kleeman 2000). Whether such influences exist or not is an extremely controversial issue. While a thorough discussion on this issue is beyond the scope of this study, it suffices to point out that SST perturbations in the eastern Pacific induced by the MJO are highly relevant to this issue. Particularly, perturbations with large zonal scales (as those shown in Fig. 1b) would be more likely than those with small zonal scales (as those shown in Fig. 1a) to have any effect on the basin-scale air–sea interaction. Interestingly, the equatorially elongated intraseasonal perturbations in SST bear similarities to positive interannual anomalies in SST during the early stages of ENSO warm events.

2. Data and method

The SST dataset used in this study is the weekly mean, 1° × 1°, optimal interpolation SST (OISST) of Reynolds and Smith (1994). A daily dataset of surface and subsurface temperatures observed by the Tropical Atmosphere–Ocean (TAO) mooring array (Hayes et al. 1991; McPhaden et al. 1998) was used to calculate the vertical temperature gradient of the upper ocean and the depth of the 20°C isotherm, which is often used as a
measure of the depth of the equatorial thermocline (e.g., Kessler et al. 1995). The temperatures from 10 moorings were used, which are located at the equator and 147°E, 156°E, 165°E, 180°W, 170°W, 155°W, 140°W, 125°W, 110°W, and 95°W. Daily means (based on measurements with sampling intervals of 15 min.) are available from 16 levels at 1, 3, 5, 10, 25, 30, 50, 75, 100, 125, 150, 175, 200, 225, 250, and 300 m. Missing data at a mooring were filled first by linear interpolation if data were available from its immediate neighboring moorings to east and west and otherwise by averaging data over 2°N and 2°S at the same longitude. Remaining missing data, about 6% of the total, do not obscure the analysis.

The surface wind data are gridded (1° × 1°) weekly mean surface wind vectors retrieved from measurements of space-borne scatterometers of the European Remote Sensing (ERS) satellites (Bentamy et al. 1996). The data used here are composed of retrievals from identical instruments onboard two polar-orbiting satellites, ERS-1 (launched July 1991) and ERS-2 (launched April 1995). The ERS scatterometers are active microwave C-band (5.3 GHz) radars, which measure the ratio of backscatter to transmitted signal power. The data are sampled into cells of 50 km × 50 km over a 500-km-wide swath. Wind speed and direction are estimated at 10-m height for neutral stratification. Comparing with in situ 10-m measurements from the TAO array, the mean bias in speed is ∼0.36 m s⁻¹ and the standard deviation is 1.46 m s⁻¹ within a 1° × 1° area around the buoy location. The discrepancies are mainly for TAO wind speed less than 2 m s⁻¹ or greater than 10 m s⁻¹. Correlation coefficients for weekly time series of ERS and TAO winds are, averaged over different TAO buoys, 0.82 for the zonal wind component and 0.72 for the meridional component. Detailed information of the ERS wind products and their comparisons with in situ and other remote sensing wind measurements can be found from Bentamy et al. (1996), Bentamy et al. (1999), and Grima et al. (1999).

The three datasets overlap from August 1991 through December 1998. Their time series of pentad means were created (using a bilinear interpolation for OISST and ERS winds), only for computational convenience. Intraseasonal anomalies were isolated by removing low-frequency signals using a high-pass filter whose half-power frequency is (90 day)⁻¹. It should be pointed out that signals of the tropical instability waves are preserved in the intraseasonal anomalous time series of SST. This is an intentional choice. It has been suggested that interaction between the tropical instability waves and eastward propagating current pulse forced by surface westerly wind bursts in the western Pacific can lead to surface warming in the equatorial eastern Pacific (Harrison and Giese 1988; Giese and Harrison 1991). It would be interesting to explore whether activities of the tropical instability waves are related to the MJO.

Different versions of singular value decomposition (SVD) analysis were used to explore the coherence among the fields of interest. The regular SVD analysis, described in detail in Bretherton et al. (1992) and Wallace et al. (1992), calculates coherent patterns of two given fields. A Hilbert SVD (HSVD) analysis can be used to detect propagating signals of a given field. HSVD is the same as conventional SVD except the second field is a Hilbert transfer of the first. Dominant propagating signals are represented by HSVD as pairs of leading modes. In each pair, the two modes are in quadrature in both time and space. This HSVD method is an efficient way of isolating zonally propagating components of a field. For example, the first two HSVD modes of the zonal wind field can be considered as a representation of the MJO (Zhang and Hendon 1997). Another version of the SVD analysis is extended SVD (ESVD). As in extended Empirical Orthogonal Function (EOF) (e.g., Weare and Nasstrom 1982; Lau and Chan 1985), the time series of a given field is first combined with a number of time series of the same field lagging each other by a time interval m; A = (A, A, . . ., A, . . ., A), where A, spans over time 1 + i × m to N + i × m; N being the length of the time series. Two such combined fields are then used in calculating the covariance matrix for the SVD analysis. For a given mode from the ESVD analysis, its singular vectors describe time sequences (i = 0, 1, . . ., I) of coherent spatial patterns of the two fields. The significance of a given mode from any of these SVD analyses can be judged using the same criterion for EOF suggested by North et al. (1982). This criterion states that a given mode can be considered having a physical meaning by itself only if the difference between the singular value of this mode and its neighboring mode is larger than the sampling error of the singular value of this mode. This criterion can be equally applied to a group of modes. When this criterion is satisfied, we will refer the mode (or a group of modes) to be separable from others and thus significant.

3. Results

a. SST

Figure 2 shows an example of time sequences in high-passed SST and surface winds observed from 7 March–15 May 1992. At the beginning of this period (7–11 March, Fig. 2a), strong westerly perturbations with a maximum amplitude near 7 m s⁻¹ are seen over the central Pacific, which was related to an MJO event penetrating farther eastward than usual during the warm ENSO event at the time; no impressive intraseasonal SST perturbation exists in the equatorial region except a local positive anomaly near the eastern boundary of the analysis domain. About a month and a half later (21–25 April, Fig. 2b), an equatorially elongated perturbation in SST emerged in the eastern Pacific with its maximum of 0.6°C. This equatorially elongated perturbation in SST grew into the pattern seen in Fig. 1b.
within 10 days by quickly expanding westward and increasing its amplitude to $1^\circ$C (Fig. 2c). During the next 10 days, the perturbations kept expanding westward into the central Pacific (at a speed of roughly 3 m s$^{-1}$) while its maximum remained in the eastern Pacific (Fig. 2d).

Many similar events can be found during the analysis period. The perturbations can be cyclic with both positive and negative amplitudes. During these events, signals of the tropical instability waves are sometime completely suppressed as seen in Fig. 2 but other times superimpose upon the equatorially elongated SST pattern. Intraseasonal perturbations in SST of large zonal scales can be clearly seen in the eastern Pacific from even the total fields of the TAO observations (Fig. 3d), whose low zonal resolution serves as a natural filter removing signals of the tropical instability waves. The questions are then to what degree the equatorially elongated intraseasonal perturbations in SST can be related to the oceanic Kelvin wave activity and whether they can be isolated from other types of intraseasonal perturbations in SST. The rest of this section will be devoted to addressing these questions.

b. Kelvin wave forcing

The hypothesis proposed in section 1 emphasizes that the association of the equatorially elongated intraseasonal perturbations in SST in the eastern Pacific with the MJO, if it exists, must be through oceanic intraseasonal Kelvin waves. The oceanic Kelvin waves respond to surface zonal wind stress integrated along their characteristic lines (Kessler et al. 1995). Using “pseudo zonal wind stress” $\tau_x = uV$, where $u$ and $V$ are, respectively, surface zonal wind and total wind speed, a “Kelvin wave forcing index,” $K$, is defined as integrated $\tau_x$ near the equator ($5^\circ$N–$5^\circ$S) along a Kelvin wave characteristic. At a given longitude $x_0$ and time $t_0$, $K$ is

$$K(x_0, t_0) = \int_{x_0}^{c} \tau_x \left( x, t_0 - \frac{x - x_0}{c} \right) dx,$$

where $x = 0$ is the western boundary of the ocean and $c = 2.4$ m s$^{-1}$ is the observed phase speed of the first-mode Kelvin wave. A complete calculation of wind-forcing projection on the Kelvin wave should include the drag coefficient and the meridional structure of the Kelvin wave (e.g., see Boulanger and Menkes 1995). Because only the dominant (first-mode) Kelvin wave is considered here, the magnitude of the Kelvin wave forcing index $K$ is proportional to the wind-forcing projection on the Kelvin wave. The magnitude of the oceanic Kelvin wave responding to wind forcing is therefore proportional to this index. Hereinafter, $K$ will be simply referred to as “Kelvin wave forcing.”

Kelvin wave forcing was calculated using the ERS surface wind data over the Pacific ocean ($135^\circ$–$270^\circ$E). Its total field is shown in Fig. 3a. Positive values indicate that accumulative effects of westerlies dominate. West-
erlies are responsible for the excitation of downwelling Kelvin waves, which, according to the proposed hypothesis, induce positive SST perturbations in the equatorial eastern Pacific. Intraseasonal signals in Kelvin wave forcing are clearly shown even in the total field. Although intraseasonal Kelvin wave forcing appears to exist all the time, its amplitudes vary interannually, especially over the eastern Pacific. Particularly interesting in the figure are two periods during which intraseasonal Kelvin wave forcing is stronger than usual: the northern winter of 1991/92 and the spring of 1997. The first period coincided with the peak of the 1991–92 ENSO warm event. The second coincided with the beginning of the onset of the 1997–98 ENSO warm event. Equally interesting is the period of 1995–97 when positive amplitudes of intraseasonal Kelvin wave forcing are abnormally weak over the eastern Pacific. An ENSO cold event occurred during this period. These observations do not suggest any cause-effect relationship between ENSO and Kelvin wave forcing but indicate that they might be related.

The dominant intraseasonal frequencies of Kelvin wave forcing are near $(90 \text{ day})^{-1}$, lower than the dominant intraseasonal frequencies of the zonal wind field $(50 \text{ day})^{-1}$. This discrepancy between the dominant intraseasonal frequencies of surface zonal winds and its Kelvin wave forcing explains the difference between the dominant intraseasonal frequencies of surface zonal winds and the oceanic Kelvin wave responses (Kessler et al. 1995; Hendon et al. 1998). The intraseasonal component of Kelvin wave forcing ($K_I$) was isolated by high passing the total $K$ with a filter whose half-power frequency is $(110 \text{ day})^{-1}$. As defined in (1), the eastward-propagating speed of $K_I$ is about 2.5 m s$^{-1}$ (Fig. 4a), same as that of the first-mode Kelvin wave. Notice that only in early 1997, at the dawn of the onset of the super

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**Fig. 3.** Time–longitude diagrams of the total fields along the equator: (a) Kelvin wave forcing (m$^3$ s$^{-2}$), (b) the depth of the 20°C isotherm (m), (c) the vertical temperature gradient in the upper ocean (10$^{-2}$ °C m$^{-1}$), and (d) SST (°C).
1997–98 ENSO warm event, is strong intraseasonal Kelvin wave forcing seen over the western Pacific.

Kelvin wave forcing does not exclusively depend on zonal propagation of the zonal wind $u$. However, its intraseasonal variability is dominated by $u$ associated with the eastward propagating MJO. The MJO component of $u$ can be isolated from total $u$. Using a high-pass filter with its half-power frequency at $(90$ day$)^{-1}$, a high-frequency or intraseasonal component, referred to as $u_I$, and a low-frequency component, $u_L = u - u_I$, were first calculated. An HSVD analysis was then applied to $u_I$ as briefly described in section 2. The first two modes of this HSVD analysis as a pair are significant according to the North et al. (1982) criterion and in combination are regarded as the MJO component, $u_{MJO}$. Because of the nonlinearity in $K$, the MJO component of $K$ should not be calculated using $u_{MJO}$. Instead, $u_{MJO}$ is combined with $u_I$ to create a zonal wind field whose only high-frequency component is $u_{LMJO} = u_I + u_{MJO}$. Kelvin wave forcing was calculated using $u_{LMJO}$ and the total meridional wind field. Its intraseasonal component ($K_{MJO}$) is very similar to $K_I$ (Fig. 4b).

In comparison, a high-frequency residual zonal wind $u_R = u_T - u_{MJO}$ was combined with $u_I$ to create another zonal wind field whose high-frequency component does not contain the MJO signal: $u_{LR} = u_I + u_R$. The intraseasonal component of Kelvin wave forcing calculated using $u_{LR}$ ($K_{NOMJO}$) is much weaker than $K_{MJO}$ (Fig. 4c). The zonal (135°–270°E) mean variance of $K_{NOMJO}$ is only 36% of $K_{MJO}$. The zonally averaged correlation coefficient for $K_I$ and $K_{MJO}$ is 0.8, whereas it is only 0.3 for $K_I$ and $K_{NOMJO}$. All these suggest that intraseasonal Kelvin wave forcing is mainly contributed by the MJO component of the zonal wind field.

c. Depth of the 20°C isotherm

The depth of the 20°C isotherm along the equator is often used as a measure of the depth of the equatorial
thermocline and its perturbations as a tracer of the oceanic Kelvin waves (Kessler et al. 1995; Hendon et al. 1998). The eastward propagation of the intraseasonal Kelvin waves, at a speed of about 2.5 m s$^{-1}$, can be clearly seen in the total field of the depth of the 20°C isotherm (Fig. 3b). The Kelvin wave signals appear to exist all the time, but their strength varies with that of Kelvin wave forcing, as expected. Unusually strong signals and unusual eastward penetration of the Kelvin waves during the 1991–92 and 1997–98 ENSO warm events and unusually weak Kelvin wave signals during the 1995–96 ENSO cold event are noticed. Also noticed is that the unusually strong Kelvin waves in the eastern Pacific are manifested as positive displacement of the total depth of the 20°C isotherm (i.e., deepening of the thermocline). This is so probably because westerly wind associated with the MJO are usually much stronger than their easterly counterparts (see, e.g., Fig. 3a in Lin and Johnson 1996). The depth of the 20°C isotherm fluctuates by about 20 m on intraseasonal timescales (Fig. 5c). Such fluctuations serve as a critical physical link between the observed perturbations in equatorial SST and Kelvin wave forcing, as will be illustrated in the rest of this section.

d. Vertical temperature gradient

In the equatorial eastern Pacific, vertical advection due to upwelling is a dominant component of the upper-ocean heat budget. The thermal effect of upwelling may vary because of two processes: the total upwelling ($w$) in the presence of the anomalous vertical temperature gradient ($\partial T'/\partial z$) and anomalous upwelling ($w'$) in the presence of the mean vertical temperature gradient ($\partial T/\partial z$) (Zebiak and Cane 1987; Battisti 1988), namely,

$$-\frac{w}{\bar{w}} \frac{\partial T'}{\partial z} = w' \frac{T'}{\partial z}. \quad (2)$$
Using long-term measurements of the TAO mooring array, the vertical temperature gradient can be better estimated than upwelling. Under an assumption that in the equatorial eastern Pacific the upper ocean above the thermocline is well mixed, \( \frac{\partial T}{\partial z} \) was estimated as \((T_e - T_s)/h\), where \(T_s\) is SST and \(T_e\) is temperature at the thermocline (i.e., the depth of the 20°C isotherm \(h\)). Intraseasonal perturbations in \(\partial T'/\partial z\) propagating eastward at similar speed as those in the depth of the 20°C isotherm can occasionally be identified even from the total field (Fig. 3c), for example, near the end of 1991 and the beginning of 1992. Obviously, the vertical temperature gradient undergoes other types of variability that are not all related to fluctuations in the depth of the thermocline. Intraseasonal fluctuations of the vertical temperature gradient (Fig. 5d) show that their largest amplitudes are mainly confined to the far eastern Pacific.

e. Coherence among different fields

Figure 5 compares the intraseasonal perturbations in the fields of interest along the equator. The MJO activities in zonal wind (Fig. 5a) are mainly in the western part of the Pacific. The intraseasonal perturbations in the vertical temperature gradient (Fig. 5d) and SST (Fig. 5e) are mainly in the eastern Pacific. Kelvin wave forcing (Fig. 5b) and the depth of the 20°C isotherm (Fig. 5c) tend to propagate across most of the Pacific basin, making the western and eastern Pacific connected. Also remarkable is the contrast between the fast eastward phase speed of the MJO signals in zonal wind and the slower eastward phase speed of the signals in the oceanic Kelvin wave (the depth of the 20°C isotherm) and its forcing. The intraseasonal perturbations in SST appear to be much more chaotic than the others. As mentioned earlier, signals in the tropical instability waves are included in the filtered SST data. Nevertheless, perturbations in SST with large zonal scales (>2000 km) can be easily identified in the eastern Pacific. These perturbations appear to move both eastward and westward. No doubt, not all variability in these fields can be related to the MJO and the oceanic Kelvin wave. The challenge is to isolate the part of the intraseasonal perturbations in these fields that is related to the MJO.

Intraseasonal perturbations in equatorial SST that are potentially associated with Kelvin wave forcing of the MJO were first extracted using an SVD analysis for these two fields with SST lagging Kelvin wave forcing. The first two modes cannot be separated from each other but as a pair are well separated from other modes according to the criterion of North et al. (1982). These two modes in combination account for 65% of the total covariance. Examples of the singular vectors of the first SVD modes for SST lagging by 5–20 pentads are given in Fig. 6. The equatorially elongated structures of these modes are remarkably similar to those seen from the case given in Fig. 2; the maximum amplitude centered at the equator with the zonal scale much larger than the meridional scale. There is a tendency of westward
TABLE 1. Statistics of the first four ESVD modes for Kelvin wave forcing and SST. Here $\lambda_n$ is the singular value, $\delta_{\lambda_n}$ is the sampling error of $\lambda_n$, $\Delta\lambda_n = \lambda_n - \lambda_{n-1}$ is the increment of the singular value (North et al. 1982), $\sigma_n$ is fractional covariance (%), $\Sigma\sigma_n$ is cumulative fractional covariance, and $C_{ab}$ is the correlation coefficient for the PCs of the left (SST) and right (Kelvin wave forcing) fields.

<table>
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</table>

movement or expansion of the equatorial SST perturbations as the lag increases. There are other modes that are also significant. Some of these modes show distinct structures of the tropical instability waves as seen in Fig. 1a. However, the explained covariance of these modes are much smaller than the first two modes and will not be discussed further.

The sole purpose of this SVD analysis is to demonstrate that, out of all intraseasonal signals including those of the tropical instability waves, it is the equatorially elongated SST perturbations that are most significantly related to Kelvin wave forcing, at least empirically. It should be pointed out, however, that the equatorially elongated SST modes can be extracted only from SVD (or combined EOF) analyses when the covariance of SST and Kelvin wave forcing is considered. No such mode can be obtained from an EOF analysis for only SST itself. The implication is that these modes should not be viewed as leading modes of SST for the wide intraseasonal band (5–90 days). They are only the leading modes of the SST component that are coherent with Kelvin wave forcing.

In order to systematically examine the influence of time lags on the coherence between SST and Kelvin wave forcing, an ESVD was applied to Kelvin wave forcing and equatorial SST with SST lagging Kelvin wave forcing by 1–25 pentads. The first four modes, in two pairs, can be separated from other modes (Table 1). They account for 54% of the total covariance. Time series of the principal components (PCs) of the two modes in each pair are in quadrature for both SST and Kelvin wave forcing (e.g., Fig. 7a). On interannual timescales the amplitudes of the PCs for SST and Kelvin wave forcing vary mostly in phase (Fig. 7b). No other separable modes can be identified.

The singular vectors of the first and third modes for Kelvin wave forcing and equatorial SST are plotted in Fig. 8. The singular vectors of the second (fourth) mode is in quadrature with the first (third). The singular vectors of Kelvin wave forcing (Figs. 8a,c) for all leading modes exhibit clear eastward propagation, as expected, at the phase speed of 2.7 m s$^{-1}$, roughly the same as that of the first-mode Kelvin wave. However, the behaviors of the singular vectors for SST are complicated. The first two modes show eastward propagation in most of the Pacific domain at about 2 m s$^{-1}$ (Fig. 8b), slightly
slower than the phase speed of the Kelvin wave. The third and fourth modes are mostly stationary with a slight tendency of westward movement in the central Pacific and eastward movement to the east (Fig. 8d).

To explore the coherence among all the fields of interest, the leading PCs from the ESVD analysis were used to reconstruct Kelvin wave forcing, the depth of the 20°C isotherm, the vertical temperature gradient, and SST. For each variable, the reconstructed field is a linear combination of regressions onto the PCs of the first four ESVD modes of Kelvin wave forcing. Their time–longitude diagrams are shown in Fig. 9. Many features previously discussed can be clearly seen here. While reconstructed perturbations in the vertical temperature gradient (Fig. 9c) and SST (Fig. 9d) are strong only in the eastern Pacific, reconstructed Kelvin wave forcing (Fig. 9b) and the depth of the 20°C isotherm (Fig. 9a) propagate eastward across most of the Pacific. The strongest perturbations in the vertical temperature gradient are mainly stationary. Reconstructed SST, on the other hand, appears to be predominantly stationary, with slight tendencies of both eastward and westward propagation. Many of the strongest perturbation signals seen in the reconstructed fields can also be identified from the original intraseasonal fields (Fig. 5). The amplitudes of all reconstructed fields vary seasonally and interannually. It is interesting that extreme events of these fields appear to occur simultaneously: the largest perturbations in the vertical temperature gradient and SST are found only during the periods when the amplitudes in reconstructed Kelvin wave forcing and depth of the 20°C isotherm are unusually large. During periods when the latter two show unusually small amplitudes, signals in the reconstructed vertical temperature gradient and SST are hardly identifiable. Time series of seasonal variance (within a 19-pentad running window) of these fields were calculated. Correlation coefficients for such time series of Kelvin wave forcing and the other three fields are 0.5 or greater in the eastern Pacific. If each season (19 pentads) is regarded as an independent sampling,
the degree of freedom for each time series of seasonal variance would be 31 and the correlation coefficients are significant at 99% level based on a Student’s t test.

The fractional variance of the reconstructed fields in comparison to the total intraseasonal perturbations is 45% for Kelvin wave forcing, 21% for the depth of the 20°C isotherm, 6% for the vertical temperature gradient, and 11% for SST. Again, there are other types of intraseasonal variability in the equatorial Pacific, such as the tropical instability waves, that are not closely related to Kelvin wave forcing.

4. Discussion

Perturbations in surface zonal wind associated with the MJO over the western/central Pacific generate the intraseasonal oceanic Kelvin waves, which propagate eastward into the eastern Pacific. There, the resulting perturbations in the depth of the thermocline lead to perturbations in the vertical temperature gradient. The thermal effect of the equatorial upwelling is thereby modified and as a result fluctuations in surface temperatures emerge that are narrowly concentrated at and elongated along the equator. The observational basis of this hypothesis has been presented in this study. The coherence between intraseasonal perturbations in equatorial SST, Kelvin wave forcing, the depth of the 20°C isotherm, and the vertical temperature gradient found in this study is robust and stable. It is sensitive to neither spatial resolutions and domain, period of the data, nor filtering methods. It can be obtained, only with slight modifications, using surface wind products from other satellite retrievals or global model analyses.

Intraseasonal oceanic Kelvin waves do not have to be generated by surface wind exclusively associated with the MJO. Using a global model analysis product and the same SST dataset used in this study, Vecchi and Harrison (2000) observe positive SST anomalies in excess of 0.5°C in the eastern Pacific following strong westerly wind bursts in the western Pacific. Those west-
erly wind bursts may or may not propagate eastward. Nonetheless, the dominant contribution to intraseasonal Kelvin wave forcing by the perturbations in surface zonal wind of the MJO makes the role of the MJO outstanding. It has been suggested that westerly wind bursts in the western Pacific may lead to perturbations in SST in the equatorial eastern Pacific due to an interaction between the resulting zonal current and the tropical instability waves (Harrison and Giese 1988; Giese and Harrison 1991). The analysis of the present study suggests that, as far as MJO forcing is concerned, the response of the tropical instability waves may exist but on average are much weaker than those of the equatorially elongated pattern.

The observational analysis in this study suggests a close relationship between the equatorially elongated perturbations in SST in the eastern Pacific and surface wind forcing associated with the MJO over the western/central Pacific. Numerical or theoretical models will have to be used to explore the exact dynamic mechanisms for this relationship and to formally test the hypothesis proposed in this study. A key process in the hypothesis that has been left unexplored in this study is the modification of the thermal effect of the equatorial upwelling by the intraseasonal perturbations in the vertical temperature gradient. If this process indeed plays a key role, then the minimum requirement for a model suitable for addressing the mechanisms involved would include, among others, adequate representations of perturbations in the depth of the thermocline, the vertical thermal stratification of the upper ocean, and equatorial upwelling. On the other hand, a capability of reproducing the observed relationship between the SST perturbations and MJO forcing can be viewed as a qualification of models designed for the study of the equatorial air–sea interaction and oceanic dynamics on the intraseasonal timescales.

The zonal movement of the observed intraseasonal perturbations in SST remains puzzling. Tendencies of both eastward and westward movements are observed. This reflects the existence of a competition and compensation between different dynamic and thermodynamic processes, possibly related to the first and second pairs of leading ESVD modes (Fig. 8). It is natural to expect the SST perturbations to propagate eastward, because all the other fields do and because the equatorial trapping of the perturbations is a strong indication of their association with the Kelvin waves. The reason for the tendency of the westward movement, however, is less obvious. There is no off-equatorial signal in SST that would suggest the involvement of reflecting Rossby waves. The oceanic zonal current near the surface is too weak to explain the westward movement of the perturbations in SST, which is at 3–4 m s\(^{-1}\). Westward motion is not observed in the depth of the thermocline and the vertical temperature gradient. The unexpected westward movement of the SST perturbations may reflect the complexity in the heat balance of the equatorial upper ocean. Zonal propagation of the Kelvin wave is not the only factor that may determine the zonal distribution of SST perturbations it induces. An analysis of TAO data (M. McPhaden 2000, personal communication) demonstrates that, on the intraseasonal timescales, the phase relationship between SST and the dynamic fields of the Kelvin wave may vary along the equator: In the central Pacific where the zonal gradient of the mixed layer temperature \(T\) is strong, the mixed layer heat balance is dominated by zonal thermal advection and the tendency of \(T\) is in phase with the zonal current \(u\) and the displacement of the thermocline \(h\) associated with the Kelvin wave. We refer to this region as the zonal advection regime. In the eastern Pacific where the zonal gradient of \(T\) is weak but the vertical temperature gradient strong, the mixed layer heat balance is dominated by vertical thermal advection and the tendency of \(T\) leads \(u\) and \(h\) by a quarter of cycle. This latter region is referred to as the vertical advection regime. If the separation of the two regimes is less than a quarter of the zonal wavelength of the Kelvin wave \(L (L \geq 10,000\ km)\), then SST at a point in the vertical advection regime to the east would start being affected before a point in the horizontal advection regime to the west as a Kelvin wave moves eastward through the Pacific. It has yet to be determined whether this actually does cause the observed westward movement of the equatorially elongated perturbations in SST within a realistic parameter regime.

It is not immediately clear what effects of the observed equatorially elongated intraseasonal perturbations in SST would have on the equatorial atmosphere–ocean coupled system on larger timescales. This cannot be adequately assessed solely based on observations. Here a speculation is made only for the purpose of keeping our minds open to even remote possibilities. The equatorially elongated intraseasonal perturbations in SST are of interest because of the possibility for the MJO to influence ENSO, as briefly mentioned in section 1. Influences of intraseasonal perturbations in SST on ENSO might exist only if these perturbations feed back to the atmosphere and rectify on lower-frequency variations. In one possible scenario of such rectifying feedback, easterly trade winds may relax or intensify as a result of changes in the zonal gradient of SST. The equatorially elongated pattern in intraseasonal anomalous SST in the eastern Pacific is more effective in modifying the basin-scale zonal gradient of SST than other patterns of intraseasonal perturbations in SST of smaller zonal scales. Relaxed trade winds reduce the equatorial upwelling and may encourage an eastward expansion of the western Pacific warm pool. An expanded warm pool would make a longer zonal fetch for surface westerlies associated with subsequent MJO events and consequently lead to stronger forcing of downwelling Kelvin waves. Such positive feedback might result in a slow but continuous relaxation of the trades and expansion of the warm pool. This highly simplified and speculative
feedback process is complementary to the scenario proposed by Kessler et al. (1995). They suggest that an eastward expansion of the warm pool might result from a local air–sea interaction associated with the MJO over the western Pacific. A common caveat in both scenarios is that MJO events occur every year but ENSO warm events do not. Apparently, the MJO cannot on its own cause an ENSO warm event through these feedback processes. What makes the MJO–ENSO problem interesting, however, is the effect that the MJO might introduce to the coupled system of the equatorial Pacific in addition to low-frequency (interannual) air–sea interaction. The similar spatial structures of the equatorially elongated intraseasonal perturbations in SST and the positive interannual SST anomalies during the early stages of ENSO warm events makes this additional effect of the MJO on ENSO particularly perceptible. When there is an initial warming in the equatorial eastern Pacific of 0.5°C at the early stage of a warm event, the MJO effect can enhance this warming to 1°C. Even though this additional warming due to the MJO is temporary (1–2 months), it is hard to imagine that it has no influence at all on the coupled system and on the development of the warm event. The potential importance of such an additional effect of the MJO on ENSO dynamics and predictability is worthy of investigation. Quantifying the MJO effect on ENSO would be a challenge.

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