Observations of a Convectively Coupled Kelvin Wave in the Eastern Pacific ITCZ

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(Manuscript received 23 February 2001, in final form 4 July 2001)

ABSTRACT
A case study of a convectively coupled Kelvin wave in the eastern Pacific intertropical convergence zone (ITCZ) is presented, as observed during the 1997 Pan American Climate Studies (PACS) Tropical Eastern Pacific Process Study (TEPPS). The large-scale convective envelope associated with this disturbance, with a zonal scale of approximately 1000–2000 km, propagates eastward at 15 m s$^{-1}$ along the mean convective axis of the ITCZ. This envelope consists of many smaller-scale, westward-moving convective elements, with zonal scales on the order of 100–500 km.

As the convectively coupled Kelvin wave disturbance propagates eastward, it exerts a strong control on local convection. Radar and vertical profiler data collected aboard the NOAA R/V Ronald H. Brown during the wave passage show that convection deepens rapidly as the Kelvin wave approaches from the west, progressing from isolated, shallow cumuli to organized deep convective features within just 12 h. Initially, rainfall in the vicinity of the ship consists of a significant deep convective fraction, but as the large-scale envelope departs to the east, stratiform precipitation becomes dominant.

Radiosonde data collected during the Kelvin wave passage reveal dynamical perturbations in the troposphere and lower stratosphere that are consistent with linear equatorial Kelvin wave theory. The TEPPS radiosonde data also compare remarkably well with the vertical structure of a typical eastern Pacific Kelvin wave disturbance in the ECMWF reanalysis dataset, based on a 15-yr linear regression analysis. When this analysis is expanded to include all global grid points, it is shown that Kelvin waves in the eastern Pacific ITCZ have a dynamical structure that is nearly symmetric with respect to the equator, as would be expected based on linear Kelvin wave theory. However, the convective signal associated with these symmetric dynamical perturbations is itself primarily asymmetric with respect to the equator. The deepest convection is located significantly to the north of the equator, in the region of warmest sea surface temperatures. These observations present a somewhat different perspective on the dynamics of convectively coupled Kelvin waves, in that the symmetric dynamical fields and asymmetric convection interact to sustain the simultaneous eastward propagation of both fields.

1. Introduction
Zonally propagating convective activity represents a significant component of the total variability in the eastern Pacific intertropical convergence zone (ITCZ). Although this region is generally dominated by westward-propagating convective disturbances, observations often reveal the presence of eastward-propagating convective activity, especially during Northern Hemisphere summer and fall. The most frequently observed eastward-propagating disturbances in this region have phase speeds of approximately 17 m s$^{-1}$, and propagate along the mean convective axis of the ITCZ. The spatial and temporal scales of these disturbances suggest that they can be classified as convectively coupled Kelvin waves (Takayabu 1994; Wheeler and Kiladis 1999, hereafter WK99).

In this paper, we present a case study of a particular convectively coupled Kelvin wave in the eastern Pacific ITCZ, and then document the more general statistical structure of convectively coupled Kelvin waves in this region.

Convectively coupled Kelvin waves are eastward-propagating tropical convective disturbances with the dispersion characteristics of equatorially trapped shallow water Kelvin modes (Takayabu 1994; WK99). The convection in these waves is coherently coupled to significant dynamical perturbations in the upper troposphere and lower stratosphere, which are consistent with linear Kelvin wave theory (Takayabu and Murakami 1991; Wheeler et al. 2000, hereafter W2000).

Previous studies of convectively coupled Kelvin waves have focused on disturbances in the Indian Ocean and western Pacific regions (Takayabu and Murakami 1991; Dunkerton and Crum 1995; W2000). In these

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regions, both the convective and dynamical fields composing convectively coupled Kelvin waves are fairly symmetric with respect to the equator, as would be expected from linear theory (W2000). In the eastern Pacific, on the other hand, we will show that the observed eastward-propagating convective signals with Kelvin-like phase speeds and spatial scales exist primarily within the Northern Hemisphere, such that the convection is asymmetric with respect to the equator. Nevertheless, these eastern Pacific disturbances possess similar dynamical structures and dynamical symmetry with respect to the equator as the convectively coupled Kelvin waves in the Indian Ocean and western Pacific, especially in the upper troposphere and lower stratosphere. Since the convection in these eastern Pacific waves exists exclusively to the north of the equator, though, a somewhat different relationship between convection and dynamics is involved.

In order to more completely understand the detailed structure of a convectively coupled Kelvin wave in the eastern Pacific ITCZ, we present a case study of a single Kelvin wave passage based on data collected during the 1997 Pan American Climate Studies (PACS) Tropical Eastern Pacific Process Study (TEPPS; Yuter and Houze 2000). During TEPPS, an eastward-propagating Kelvin wave convective envelope passed directly over the program’s observational platform, the National Oceanic and Atmospheric Administration (NOAA) R/N Ronald H. Brown, which was stationed in the eastern Pacific ITCZ at 7.8°N, 125°W. Instrumentation aboard the Ronald H. Brown included a C-band Doppler radar, two vertical wind profilers, an upper-air sounding system, an optical disdrometer and rain gauge, and surface meteorological sensors. NOAA polar-orbiting and GOES-9 geostationary satellites also collected outgoing longwave radiation (OLR) and infrared (IR) measurements over the region. The extensive dataset collected during TEPPS thus provides an unprecedented view of the multiscale convective and dynamical fields composing a convectively coupled Kelvin wave in the eastern Pacific ITCZ.

Prior to this study, observations of the dynamical fields of convectively coupled Kelvin waves had been based on model analysis or reanalysis data of rather coarse horizontal resolution (Takayabu and Murakami 1991; W2000). The case study presented here includes data of a much finer temporal and spatial resolution, and is the first analysis based purely on direct field observations. These observations will provide a benchmark for assessing Kelvin wave structures in model datasets, to evaluate the models’ utility for further analysis of these waves.

This paper is organized as follows. Section 2 provides a brief background on convectively coupled waves. In section 3, observations of the convectively coupled Kelvin wave observed during TEPPS are presented. The convective and dynamical structure of this wave are analyzed using observations of global OLR, GOES-9 IR data, and the radar, profiler, rain rate, surface meteorology, and radiosonde data collected aboard the Ronald H. Brown during TEPPS. The radiosonde data are compared with the time–height structure of a “composite” Kelvin wave disturbance calculated from European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data. These composite results are then extended in section 4 to include all global reanalysis grid points, and the temporal and spatial evolution of a three-dimensional composite Kelvin wave disturbance in the eastern Pacific is discussed. Finally, a summary and conclusions are presented in section 5.

2. Background

The existence of convectively coupled equatorial waves has been known for some time (e.g., Sikdar et al. 1972; Gruber 1974; Zangvil 1975; Zangvil and Yanai 1980, 1981; Takayabu 1994; WK99). Kelvin and mixed Rossby–gravity waves are the most well-documented of all the wave types affecting the equatorial region (Nakazawa 1988; Hayashi and Nakazawa 1989; Liebmann and Hendon 1990; Hendon and Liebmann 1991; Lau et al. 1991; Takayabu and Murakami 1991; Dunkerton and Baldwin 1995; Dunkerton and Crum 1995; W2000). Inertio-gravity and equatorial Rossby waves have also been studied (Kiladis and Wheeler 1995; Takayabu et al. 1996; Haertel and Johnson 1998; W2000).

Convectively coupled equatorial waves can be identified in a power spectrum of many years of tropical cloudiness data (Takayabu 1994; WK99). Presented in Fig. 1 is an updated version of the symmetric OLR power spectrum shown in WK99 (see their Fig. 3b) for the years 1979–99. A smoothed red background spectrum has been removed from the raw power spectrum such that the contours in Fig. 1 represent statistically significant spectral peaks at greater than the 95% level (see WK99 for more details). These peaks fall along the dispersion curves for several of the equatorially trapped shallow water waves discussed by Matsuno (1966), including Kelvin, equatorial Rossby, mixed Rossby–gravity, and inertio-gravity waves. The implied equivalent depth of these waves is within the range of 10–100 m. Note the Kelvin wave spectral peak in the OLR spectrum, and the spectral gap separating it from the Madden–Julian oscillation (MJO) spectral peak directly beneath it (wavenumbers 0–5, period 30–70 days). This spectral gap suggests that Kelvin waves can be considered to be distinguishable from the MJO.

W2000 calculated the composite dynamical structures corresponding to each of these OLR modes, based on reanalysis data, and found remarkable similarities to the theoretical shallow water wave structures predicted by Matsuno (1966) and linear Kelvin wave theory (including vertical structure; e.g., Andrews et al. 1987), particularly in the upper troposphere and lower stratosphere, above the heating associated with deep convection. The coherence between convection and circulation in these equatorial waves, together with their resem-
Fig. 1. Wavenumber–frequency power spectrum of the symmetric component of OLR for 1979–99, summed from 15°N to 15°S, and plotted as the ratio of the raw OLR power to the power in a smoothed red noise background spectrum (see WK99 for details). Contour interval is 0.1, from 1.1 to 1.4. Shading begins at 1.1, where the signal is significant at greater than the 95% level. Dispersion curves for the Kelvin, $n=1$ equatorial Rossby (ER), and $n=1$ westward inertia-gravity (WIG) waves are plotted for equivalent depths of 8, 12, 25, 50, and 90 m. Heavy solid box represents region of Kelvin wave filtering.

Blance to the linear shallow water modes, suggests a coupling between deep convection and the linear, dry (or “free”) dynamical modes of the shallow water system. The shallow equivalent depths implied by the OLR power spectrum in Fig. 1 suggest an interplay between tropical convection and dynamics that may be responsible for slowing the phase speed of these waves from that of their dry counterparts (W2000).

3. Observations of the TEPPS Kelvin wave

The majority of this study is devoted to observations of the convectively coupled Kelvin wave that propagated across the eastern Pacific ITCZ during TEPPS. Our analysis begins with observations of the cloudiness field associated with this eastward-propagating wave. In section 3a, a spectral decomposition of global OLR data demonstrates that this particular disturbance is in fact consistent with a convectively coupled Kelvin wave, as defined by the methodology developed in WK99 and W2000. In section 3b, the spatial and temporal evolution of the small-scale cloud structures during this Kelvin wave event are analyzed using GOES-9 IR data. The radar and vertical profiler data collected aboard the Ronald H. Brown during TEPPS are presented in section 3c. The surface meteorology data are then used in section 3d to assess the local effects of convection on the boundary layer, and also to determine any lower-frequency variability that may be associated with the large-scale wave structure. Finally, in section 3e, the vertical structure of the dynamical and moisture fields associated with the TEPPS Kelvin wave are illustrated using radiosonde data from the Ronald H. Brown. These fields help to confirm that the wave observed during TEPPS is in fact a convectively coupled Kelvin wave.

a. Outgoing longwave radiation

OLR has been used successfully in many previous studies to identify large-scale convective disturbances with timescales of several days or longer (e.g., Kiladis and Weickmann 1992, 1997; WK99). In this section, the OLR signature of the eastward-propagating wave observed during TEPPS will be shown to fall into the
space–time region of the convectively coupled Kelvin waves (hereafter referred to as simply “Kelvin waves”) pictured in Fig. 1. Kelvin waves are identified using a filtered version of the interpolated, 2.5° gridded, global NOAA polar-orbiting satellite OLR dataset described by Liebmann and Smith (1996).

The technique used to isolate the OLR variability associated with Kelvin waves is fully detailed in WK99. In summary, the OLR data are filtered in wavenumber–frequency space such that only the variability on time- and space scales represented by the Kelvin wave “box” shown in Fig. 1 is retained. The resultant filtered OLR dataset is then used to identify specific Kelvin wave episodes in the raw OLR data. In this study, the Kelvin wave box drawn in WK99 is slightly modified by shifting the lower boundary upward in frequency from 1/30 cycles per day (cpd) to 1/17 cpd, as reflected in Fig. 1. This change provides a more distinct separation between Kelvin waves and the MJO, and is based on the pronounced spectral gap at a period of 17 days. It does not affect the phase speed of the filtered waves.

In WK99 and W2000, this filtering was performed only on the symmetric component of the OLR field, since Kelvin waves are defined in the symmetric portion of the OLR power spectrum. In this study, however, we take a slightly different approach and instead filter the data without first separating into symmetric and antisymmetric components. The motivation for this change is as follows. In the eastern Pacific, where this study is focused, convective disturbances tend to propagate along the latitude of the ITCZ, which for the majority of the year lies between approximately 5° and 15°N. Fast eastward-propagating convective signals with similar spatial scales and phase speeds to WK99’s symmetric Kelvin waves are often observed within this latitude band. These disturbances, with significant amplitudes present only in the Northern Hemisphere, will project onto both the symmetric and antisymmetric components of the OLR field. Thus the total OLR field is necessary to resolve these disturbances accurately. Correlation coefficients between the Kelvin wave filtered OLR and the total OLR are higher in the eastern Pacific with this filtering method than when only the symmetric data are used (not shown).

The average variance of the Kelvin wave filtered OLR for Northern Hemisphere summer [Jun–Jul–Aug (JJA)] for 1979–99 is shown in Fig. 2. The maximum variance tends to follow the latitude of the climatological ITCZ, with an equatorial maximum in the Indian Ocean region, and a maximum significantly to the north of the equator in the central and eastern Pacific and Atlantic regions. Figure 2 also illustrates the concentration of high Kelvin wave variance to the north of the equator in the central Pacific during JJA, with a maximum near 7.5°N, 180°.

The behavior of the tropical OLR field is now examined for the period encompassing the TEPPS cruise, during July and August 1997. Figure 3 is a Hovmöller diagram of the twice-daily total OLR (shading) and the Kelvin wave filtered OLR (contours, only negative values shown, representing enhanced deep convection in the Kelvin filtered band), averaged between 2.5° and 15°N, from 1 July to 31 August 1997. A number of strong eastward-propagating disturbances are visible in the eastern Pacific during this time period, the most noteworthy crossing 120°W on 13 July, 25 July, and 20 August. The Kelvin wave filtered OLR captures the timing and phase speed of these disturbances remarkably well.

The solid vertical line in Fig. 3 represents the time and location of TEPPS data collection while the Ronald H. Brown remained stationary in the ITCZ at 7.8°N, 125°W, from 8 to 23 August 1997. The location of the Ronald H. Brown is also marked on the Kelvin wave variance map in Fig. 2. Based on the Kelvin wave filtered OLR in Fig. 3, it can be seen that the eastward-propagating disturbance that passed over the ship during this period was in fact a convectively coupled Kelvin wave. The dynamical fields, to be shown in section 3e, confirm this. This disturbance is traceable in the OLR field from 160°E to 100°W, over a period of 9 days, giving an average phase speed of about 15 m s⁻¹. While the total OLR field suggests that the deepest convection associated with the Kelvin wave occurred as it passed over the Ronald H. Brown, the Kelvin wave filtered OLR shows that this component actually peaked to the west of the ship. The minimum OLR over the Ronald H. Brown on 18–19 August reflects both Kelvin wave variability and OLR variability unrelated to the Kelvin wave disturbance.
b. GOES-9 imagery

GOES-9 infrared (IR, 10.7 μm) data provide a much higher resolution (3 hourly, 0.1°) view of the cloudiness field associated with the Kelvin wave during TEPPS. An overview of the eastward propagation of the convective disturbance is presented in Fig. 4. Six IR images are shown, spanning a roughly 5-day period from 1500 UTC 14 August to 0000 UTC 20 August. The location of the Ronald H. Brown is indicated by an “x” in each image.

On 14 August, the deepest convection is located at the western edge of the domain, centered at approximately 10°N, 180°. By 15 August, this convective envelope has shifted eastward and southward to approximately 5°N, 160°W. At this stage, the overall envelope measures roughly 20° in longitude by 10° in latitude, or approximately 2000 km by 1000 km. The envelope continues to shift eastward over the next 4 days, passing almost directly over the ship on 18 August, and is centered around 10°N, 120°W on 20 August. The average phase speed over the period is approximately 15 m s⁻¹, which agrees with the speed determined from the more coarsely gridded OLR data in the previous section.

Within the larger eastward-propagating envelope of convection in Fig. 4, many smaller-scale features are evident. Although the large-scale cloudiness field appears to propagate to the east, higher temporal resolution images show distinct convective elements, with spatial scales on the order of 100–500 km, moving westward within this envelope. To illustrate the westward movement of these smaller-scale features, Fig. 5 is a Hovmöller diagram of the 3-hourly GOES-9 data, averaged from 2° to 12°N, for 13–22 August. Many westward-moving features are apparent within the eastward-propagating envelope of convection, most notably on 16–17 August near 140°W and on 20 August near 120°W. Of course, since this convective signal is averaged over a 10° latitude band, it illustrates only the largest and most intense of the westward-moving features, which appear to have widely varying westward phase speeds. Additional evidence of the westward movement of the smaller-scale embedded features is apparent in the 3-hourly maps of the GOES-9 data (not shown) as well as the radar data discussed in the next section. The hierarchical structure of convection shown here for the TEPPS Kelvin wave is also observed within other eastern Pacific Kelvin waves we have examined.
Nakazawa (1988) first detailed this hierarchy of convection in eastward-propagating “super clusters” within the MJO in the western Pacific, using OLR and Geostationary Meteorological Satellite (GMS) infrared data. Super clusters propagate eastward at 10–15 m s\(^{-1}\), and consist of smaller-scale “cloud clusters” that move westward within the envelope, in a similar manner to the observations presented in Fig. 5. In fact, the specific examples of super clusters illustrated in Nakazawa (1988) are identified in our Kelvin wave filtered OLR dataset as clear examples of convectively coupled Kelvin waves (not shown). Thus it is suggested in both Nakazawa (1988) and the present study that an eastward-propagating convectively coupled Kelvin wave envelope consists primarily of smaller-scale, westward-moving convective features.

**c. Radar and vertical profiler**

To further examine the small-scale structure of convection in the eastward-propagating Kelvin wave convective envelope during TEPPS, data are presented from the C-band Doppler radar and the 2835-MHz vertical profiler located aboard the Ronald H. Brown. These measurements provide a more complete picture of local convection in the vicinity of the ship during the Kelvin wave passage.
FIG. 5. Hovmöller diagram of 3-hourly GOES-9 IR data, averaged from 2° to 12°N, for 13–22 Aug 1997. Contours from 225 to 255 K by 10 K. Dark shading denotes temperatures less than 245 K, light shading between 245 and 255 K. Missing data were filled in by a linear interpolation in time if only one or two sequential observations were missing.

1) RADAR

The Massachusetts Institute of Technology (MIT) C-band Doppler radar collected three-dimensional reflectivity and velocity measurements every 15 min while the ship was on station in the eastern Pacific ITCZ. Maps of reflectivity at 0.5-km altitude will be analyzed in this section. To provide a broader context for these data, simultaneous GOES-9 IR images will also be presented.

At 0000 UTC 18 August (1700 LST), the Kelvin wave convective envelope is centered about 1000 km to the southwest of the ship, at approximately 3°N, 132°W (Fig. 6a). Convection in the vicinity of the ship, as observed by radar, is widely scattered, fairly small scale, and generally shallow, with most cells on the order of 5–10 km across (Fig. 6b). The low clouds in the area are noted in the ship’s cloud log as cumulus mediocris and humilis, with altocumulus the predominant cloud type at midlevels. These small convective cells generally move to the northwest, consistent with the mean flow in the lowest 3 km (3.9 m s⁻¹ from 112°, as calculated from radiosonde data), similar to observations by Wu and Lemone (1999) during TOGA COARE easterly wind periods. This relatively “suppressed” convective environment had been in place for at least the past 48 h. We note, however, that this suppressed environment does not preclude the development of isolated deep convective events, as can be inferred from occasional 40+ dBZ radar reflectivities and a waterspout sighting noted in the cloud log at 1900 UTC 17 August.

By 1300 UTC (0600 LST) 18 August, convection around the ship has increased in areal coverage and in intensity, as well as in its scale of organization (Fig. 6d). This general intensification of convection is associated with the eastward propagation of the large-scale Kelvin wave convective envelope toward the ship, as is evidenced by the eastward shift of the coldest cloud tops to 125°–130°W (Fig. 6c). Several linear features are apparent in the radar data, oriented from southwest to northeast and on the order of 50–100 km in horizontal extent, with maximum reflectivities at the 0.5-km level of 45 dBZ. These features generally move to the northwest, and have lifetimes on the order of several hours. Cloud observations at the ship over the time period from 0000 to 1300 UTC confirm the deepening of convection from cumulus to cumulonimbus. Lightning to the northwest of the ship is noted at 1100 UTC, suggesting that convection is deep and vigorous enough at this time to electrify through ice-phase processes (e.g., Williams
FIG. 6. GOES-9 IR images (left, in K) and MIT C-band Doppler radar reflectivity maps at 0.5-km elevation (right, in dBZ), for (a), (b) 0000 UTC 18 Aug; (c), (d) 1300 UTC 18 Aug; (e), (f) 2200 UTC 18 Aug; and (g), (h) 2300 UTC 19 Aug. Radar reflectivity maps are superimposed onto GOES-9 images; red icons represent locations of TAO buoys. Range rings in reflectivity maps are at 30-km intervals.
By 2200 UTC 18 August (1500 LST), the coldest cloud tops in the large-scale region are located to the southeast of the ship (Fig. 6e), with deep convection extending in a northwesterly direction into the southwestern quadrant of the radar coverage (Fig. 6f). These cells are organized on an even larger scale than at 1300 UTC, extending over 100 km in the horizontal. Less linear organization is apparent than at 1300 UTC, with larger regions of stratiform precipitation surrounding the expanding convective cores. These systems move westward and southward. The predominant cloud types observed at the ship during this period are towering cumulus and altocumulus. Rain begins to fall at the ship at 1800 UTC, and lasts until 0200 UTC 19 August, as is discussed further in the following section.

The large-scale convective envelope continues to shift eastward over the next 24 h. At 2300 UTC 19 August (1600 LST), the coldest cloud tops are located to the northeast of the ship, centered at approximately 10°N, 120°W (Fig. 6g). The ship is located at the western edge of the Kelvin wave envelope. A large percentage of the radar domain is now covered by lower reflectivities, signifying stratiform rainfall (Fig. 6h), with smaller embedded deep convective cores. To the southwest is a vigorous convective line, oriented from northwest to southeast and moving slowly to the northeast. The change in orientation and direction of motion of this line from that observed on 18 August may be related to the observed shift in the low-level wind direction, from southeasterly to southwesterly. As will be discussed further in section 3d, the low-level wind field of a theoretical Kelvin wave is expected to shift from easterly to westerly at a fixed point as enhanced convergence (and in the moist case, precipitation) propagates past.

Convection in the vicinity of the ship dissipates as rapidly as it initially grew, declining from widespread stratiform precipitation to very few scattered radar echoes within just 2–3 h on 20 August. The speed at which convection intensifies and dissipates suggests the presence of strong large-scale forcing in the vertical motion and/or stability fields, which effectively turns deep convection on and off.

In summary, the radar data collected aboard the Ronald H. Brown suggest a rapid buildup of convection as the Kelvin wave convective envelope approaches from the west. Initially, convection consists of small, isolated cells that move to the northwest, in the direction of the mean low-level wind. Linear features build from these small cells, and convective elements in general become more interconnected. Large stratiform regions then develop, while deep convection continues to consolidate into larger systems. As the large-scale envelope moves to the east, stratiform features become progressively more predominant, and finally, all convection rapidly dissipates within just a few hours. The total duration of convection observed at the Ronald H. Brown during this Kelvin wave event is approximately 48 h.

2) VERTICAL PROFILER

Two NOAA Aeronomy Laboratory vertical profilers (915 and 2835 MHz) collected data on the vertical structure of convection directly above the Ronald H. Brown. The 2835 MHz (or “S band”) data are analyzed here, because of this instrument’s higher sensitivity to rain compared to the 915-MHz profiler. However, the qualitative aspects of the data from the two profilers are very similar. The data have a temporal sampling interval of approximately 1 min.

Measurements of rain rate taken at the ship are presented with the profiler data. Rain rates were calculated based on measurements from the Institut fuer Meereskunde (IfM) optical disdrometer located aboard the Ronald H. Brown. These measurements were also generally taken every minute.

Figures 7a and 7b show the S-band profiler data and the IfM rain-rate data for the 48-h period from 1200 UTC 18 August to 1200 UTC 20 August, which covers the period of significant rainfall at the ship associated with the Kelvin wave passage. In general, the timing of the reflectivity signal in the profiler data and the rain-rate signal match very well.

As was shown in the radar data in Fig. 6, convection in the vicinity of the Ronald H. Brown builds rapidly on 18 August. The first rain signal at the ship associated with the Kelvin wave passage occurs as convection is just beginning to intensify, at 0500 UTC 18 August, and is associated with a very isolated, shallow convective event (not shown). By 1500 UTC, convection near the Ronald H. Brown has intensified substantially, and the first deep convective signal is observed by the profiler, with echo top heights reaching at least 13 km. The most intense rainfall event of the 3-day period from 18 to 20 August then begins at 1800 UTC 18 August. This event is primarily convective in nature, with little evidence of a stratiform bright band. Rain rates reach a maximum of 35 mm h⁻¹ at 1818 UTC. The cumulative rainfall total for the 12-h period from 1500 UTC 18 August to 0300 UTC 19 August is 23.77 mm.

After this initial convective event, the remainder of the rainfall signal at the ship appears to be primarily stratiform in nature, as identified by the prominent bright band in the reflectivity data at 4.5 km. Rain rates during this stratiform precipitation are very light, generally less than 0.2 mm h⁻¹, and the total accumulation at the ship is 0.44 mm. The initial deep convective precipitation event thus accounts for the majority of the rainfall measured at the Ronald H. Brown (92% of the total) during the Kelvin wave passage.

The disdrometer rainfall data collected aboard the Ronald H. Brown, however, represent only one point measurement of rainfall, and thus may not accurately portray the large-scale environment surrounding the
ship. Presented in Fig. 8 is a time series of the stratiform fraction of the total precipitation area as observed by the C-band Doppler radar, from 0000 UTC 18 August to 0600 UTC 20 August. [For details on the analysis procedure, see Steiner et al. (1995) and Yuter and Houze (1997)]. As convection initially intensifies on 18 August (see Fig. 6), the stratiform area fraction decreases rapidly, corresponding to an increase in deep convective rainfall. The total area covered by precipitating echo also increases during this period (not shown), again suggesting the rapid growth of deep convection in the vicinity of the ship. As the cloud systems organize onto larger scales, during the latter half of 18 August and into 19 August, the stratiform fraction steadily increases, reaching a value of 1.0 at approximately 0800 UTC 19 August. The stratiform fraction then decreases again between approximately 1300 and 2100 UTC 19 August, corresponding to the deep convective signal observed by the vertical profiler at the ship at 2000 UTC 19 August (Fig. 7). Finally, as the Kelvin wave envelope departs to the east on 20 August, the stratiform fraction increases once again to values approaching 1.0. Interestingly, during the entire TEPPS ITCZ cruise (8–23 Aug 1997), the stratiform fractional area remains higher than 0.5 at all times (not shown). This suggests that stratiform rainfall is predominant during active periods in the eastern Pacific ITCZ region.

In summary, during the Kelvin wave passage, the stratiform fractional area initially decreases rapidly, then generally increases as a function of time, punctuated by several distinct periods of more active deep convection. Based on both the vertical profiler data and the stratiform area fraction data, it appears that the highest rainfall rates and the largest deep convective fraction occur in the initial stages of this Kelvin wave passage. As the envelope propagates eastward across the observational domain, the stratiform area fraction increases, associated with smaller rain rates over a proportionally larger area.

3) DISCUSSION

The radar and profiler data imply a clear sequence of events at a fixed point as the Kelvin wave convective envelope passes by. As the large-scale envelope approaches the ship from the west, the rainfall has a substantial convective component, with echo top heights generally above 10 km. These convective cells increase in intensity, size, and organization with time as the large-scale envelope approaches, beginning with small-scale, unorganized cells and progressing to larger-scale, more intense features. These features generally move with the mean low-level wind. As the convective envelope propagates to the east of the ship, the convective portion of the rainfall gradually decreases and the stratiform component increases. The cloud systems that produce the stratiform rainfall tend to be large in horizontal extent, covering a larger portion of the total domain, and the rainfall at a single point lasts for a significant time period. While the interpretation of the disdrometer rainfall data might suggest that the total rainfall accumulation during the Kelvin wave passage is dominated by its deep convective component, the area-averaged
radar data in Fig. 8 show that it is instead dominated by the stratiform component.

These measurements suggest that the Kelvin wave envelope consists of deeper convection on its eastern side, and predominantly stratiform precipitation to the west. This is consistent with observations of large-scale features within the envelope moving westward with time, as shown in Fig. 5. New convection appears to be initiated to the east of the existing envelope, and is organized into deep, intense convective cells. These cells then mature into stratiform-dominated systems as they move westward.

d. Surface meteorology

Surface meteorology and sea surface temperature (SST) measurements were continuously recorded aboard the Ronald H. Brown during the Kelvin wave passage. Presented in Fig. 9 are time series of total shortwave radiation; anomalous temperature, SST, specific humidity, and pressure; and total wind speed and direction, for 16–22 August. Data were reported at 1-s intervals and averaged to 1-h intervals. Anomaly time series were created by subtracting the 16-day average daily cycle (8–23 Aug 1997, at hourly resolution). A slight warming trend (0.042° day⁻¹) was removed from the SST time series by a least squares fit. The mean values of the surface variables are shown in Table 1.

Evidence of the cloudiness signal associated with the Kelvin wave passage can be seen in the shortwave radiation time series (Fig. 9a). Prior to and subsequent to the disturbance passage, the daily cycle of shortwave radiation is quite evident, with a maximum insolation of approximately 1050 W m⁻². During the Kelvin wave passage, however, the shortwave radiation at the ship is very low, with an average daytime value of approximately 150 W m⁻² (calculated from 1200 UTC 18 Aug to 1200 UTC 20 Aug). One day before the Kelvin wave begins to affect conditions in the vicinity of the ship, on 17 August, there is cloud over the ship in early afternoon, around 1900 UTC (1200 LT). However, the profiler and rain-rate data for this time period show no associated rainfall. On the two most convectively active days, 18 and 19 August, there appears to be little cloudiness over the ship for the first 3–4 h after sunrise, followed by a sharp drop in shortwave radiation as cloudiness builds. The maximum drop occurs at approximately 1800–2000 UTC each day (1100–1300 LT). The lowest overall insolation occurs on 18 August, when the deepest convective signal and highest rain rates are observed at the ship.

Figure 9b shows the surface temperature and SST anomaly time series at the ship. Corresponding to the large rain events seen in the profiler and rain rate data are sharp drops in surface temperature (e.g., 1900 UTC.
18 Aug; 0000 UTC 19 Aug; 2000 UTC 19 Aug), presumably associated with the evaporative cooling of rainfall in convective downdrafts. Typically, the surface temperature drops 1°–2°C during a strong rain event. This is consistent with observations in the western Pacific of a 1.1°C surface temperature difference between convectively disturbed and undisturbed periods (Young et al. 1992).

The SST anomaly time series generally follows the surface temperature series, with a maximum correlation between the two series of 0.67 when SST lags air temperature by 3 h. Prior to the Kelvin wave passage, the
SST is anomalously warm. As the convection passes over the ship, SST gradually decreases, reaching its lowest value at approximately 0000 UTC 20 August, during the last stratiform rainfall event of the wave passage. After the Kelvin wave convection ends, the SST rises to as high as 0.7°C above average, most notably at 0000 UTC 21 August. This sharp rise in SST, combined with the coincident increase in shortwave radiation, suggests a quiescent, cloud-free, subsident environment following the Kelvin wave passage. Cloud photos taken from the ship on 21 August show only widely scattered shallow cumuli and thin cirrus clouds at this time.

Figure 9c illustrates the surface specific humidity and pressure anomalies at the ship. Prior to the Kelvin wave passage, specific humidity increases to a maximum of approximately 1.5 g kg⁻¹ above the mean. This maximum occurs at 1000 UTC 18 August, as convection is rapidly building near the ship. As convection becomes more widespread, specific humidity generally decreases, with two intense negative anomalies apparent at 0900 UTC on 19 August and 0100 UTC on 20 August. These rapid drops in specific humidity are coincident with sharp increases in temperature, suggesting the presence of unsaturated downdrafts in the wake of organized mesoscale convective systems (Zipser 1977). Specific humidity finally climbs back to its average value on 22 August, just prior to the outbreak of the next convective event.

In a theoretical Kelvin wave, pressure and zonal wind should be positively correlated; that is, low pressure should occur during easterlies and high pressure during westerlies, with convergence (and perhaps precipitation, if this structure is observed in the boundary layer of a moist atmosphere) between the easterlies and westerlies (see Fig. 6 in W2000). The surface observations recorded during the TEPPS Kelvin wave passage are consistent with this theoretical model. Initially, pressure is anomalously low and winds are easterly (Figs. 9c,d). As convection begins to build, on 18 August, pressure rises rapidly, and winds veer to southwesterly. This wind shift can also be detected in the direction of motion of large convective elements, as described in section 3c. Wind speed and direction become more variable during the deep convective events, as might be expected. Subsequent to the Kelvin wave convection, pressure falls rapidly (3 hPa drop on 20 Aug), and winds return to easterly.

In summary, the surface meteorological data collected aboard the Ronald H. Brown during the Kelvin wave passage agree well with the expected structure of a large-scale, eastward-propagating convective disturbance. Temperature, SST, and specific humidity exhibit positively correlated low-frequency variations tied to the development and decay of deep convection. Surface pressure and winds agree well with the theoretical structure of a linear Kelvin wave disturbance. These observations suggest that large-scale Kelvin wave dynamics play a role in constraining the shorter-timescale fluctuations at the surface.

e. Radiosondes and ECMWF reanalysis

In this section, the 4-hourly radiosonde data collected aboard the Ronald H. Brown during the TEPPS Kelvin wave passage are analyzed. These data provide a high-resolution time series describing the upper-air dynamical features of the passing Kelvin wave.

The radiosonde data have been linearly interpolated in pressure to regular 10-hPa intervals. Single missing points in time (4%–8% of data) were then filled in by a subsequent linear interpolation. Anomalies were created by subtracting from each individual interpolated sounding the average value at each vertical level for the entire ITCZ portion of TEPPS (8–23 Aug 1997).

For comparison purposes, vertical structure plots based on ECMWF reanalysis dynamical fields are also presented. Rather than directly comparing the vertical structures for the TEPPS time period, however, we instead create a statistical composite Kelvin wave disturbance from the ECMWF reanalysis data to compare with the TEPPS radiosonde data. This is done to reduce the impact of any inherent model bias or random errors that would be apparent in the comparison of a single episode from the reanalysis with simultaneous radiosonde measurements. In addition, since the ECMWF reanalysis dataset extends only from 1979 to 1993, a comparison with the 1997 TEPPS data preserves the independence of the two samples.

The “composite” Kelvin wave fields are calculated by linearly correlating and regressing the reanalysis dynamical fields (e.g., temperature, wind) against the Kelvin wave filtered OLR at the closest grid point to the location of the Ronald H. Brown during TEPPS (7.5°N, 125°W), for the 15 Northern Hemisphere summers (JJA) from 1979 to 1993. This technique is more thoroughly described in W2000. The daily ECMWF reanalysis fields include 16 pressure levels in the vertical, from 1000 to 10 hPa. The regressions are calculated at successive temporal lags, such that time–height vertical sections at the TEPPS base point can be created to compare with the TEPPS radiosonde data.

1) TEMPERATURE

Time–height plots of temperature from the TEPPS radiosonde data and the ECMWF reanalysis regression

<table>
<thead>
<tr>
<th>Table 1. Average surface observations at the Ronald H. Brown for 8–23 Aug 1997.</th>
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<tbody>
<tr>
<td>Shortwave radiation (daytime)</td>
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<tr>
<td>Air temperature</td>
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<tr>
<td>Sea surface temperature (SST)</td>
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<td>Wind speed</td>
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are presented in this section. Figure 10a shows the TEPPS radiosonde temperature anomalies for 16–21 August 1997. The plot includes a total of 6 days of data (37 soundings), centered around 1800 UTC 18 August, when the OLR at the grid point closest to the ship (7.5°N, 125°W) reached its minimum value. The data series has been smoothed 3 times each in time and height with a 1-2-1 filter.

Figure 10b is the corresponding regressed temperature plot from the ECMWF reanalysis. The regressed values are scaled to a −125 W m⁻² anomaly in OLR on day 0, which represents the lowest observed value of OLR (110 W m⁻²) during the TEPPS Kelvin wave passage relative to the long-term mean at that grid point (235 W m⁻²). This OLR anomaly represents both the Kelvin and non-Kelvin components of convection observed at the Ronald H. Brown during TEPPS. The regressions are scaled to this value so as to provide a realistic comparison with the radiosonde data, in which the temperature anomalies are presumably influenced by the total convection, not just that associated with the Kelvin wave.¹

The regressed temperature plot extends from day −3 to day +3, spanning the same time interval as the radiosonde plot (6 days). In a similar manner to the radiosonde plot, the reanalysis plot is centered around the time of lowest OLR at the base point (which is defined as day 0 in the regression). Because of the statistical reduction of noise achieved by including many events in the regression, there is no need to smooth this plot.

The radiosonde and reanalysis plots have many important features in common. As will be discussed throughout the remainder of this paper, a number of these features resemble the theoretical structure of a linear, dry, vertically propagating Kelvin wave (Andrews et al. 1987). Beginning in the stratosphere and upper troposphere, above about 250 hPa, there is a downward phase propagation of temperature in both plots, with alternating warm and cold anomalies in the vertical. This structure is predicted by linear theory for a vertically propagating Kelvin wave, where phase lines tilt upward and eastward, parallel to the direction of energy dispersion (Andrews et al. 1987). At a fixed point, then, one would expect a downward propagation of phase with time as a Kelvin wave propagated past, which is seen in Figs. 10a and 10b. This suggests that the upper troposphere and lower stratosphere are responding in a linear, dry dynamical fashion to the presumed upper-tropospheric heat source associated with the Kelvin wave convection. The observed vertical wavelength of temperature perturbations in the stratosphere during the TEPPS Kelvin wave is approximately 4–5 km, which is consistent with the theoretical 3–6-km vertical wavelength for dry Kelvin waves of equivalent depth 12–50 m, based on typical stratospheric values of scale height (6.1 km) and lapse rate (+2.5 K km⁻¹), as discussed in W2000. The close correspondence of the radiosonde and reanalysis plots to one another in this region further suggests that the ECMWF global model is realistically capturing both the heating associated with these fast-moving Kelvin waves and the dynamical response associated with this heating.

A significant warm anomaly is centered at approximately 250 hPa in both the radiosonde and reanalysis plots, around the time of minimum OLR. This timing strongly suggests that the warm anomaly is caused by upper-tropospheric latent heating in the Kelvin wave convective envelope. In the radiosonde data (Fig. 10a), the warm anomaly stretches from approximately 0000 UTC 18 August to 0400 UTC 20 August, the same time period when convection is active near the Ronald H. Brown. The maximum anomaly occurs around 0000 UTC 19 August, during the strongest convective rain event of the Kelvin wave passage (see Fig. 7).

The overall warm anomaly lasts for approximately 2 days in both the radiosonde and reanalysis data, with a peak amplitude of at least 1.2 K. However, the warm anomaly is centered about a day later in the reanalysis than in the radiosonde data. This result is somewhat surprising, since the regressed vertical motion (not shown) is maximized in the upward direction on day 0, coincident with the minimum OLR. This suggests that an additional diabatic or dynamical mechanism is contributing to the upper-tropospheric warming in the composite ECMWF Kelvin wave.

In the lower troposphere, the observed vertical structure of temperature is not as clearly related to the predicted linear response as in the upper troposphere and stratosphere. This is most likely caused by interactions between the Kelvin wave convective heating and dynamics. However, there is still a good correspondence between the radiosonde and reanalysis temperature structures in the lower troposphere, with warm anomalies preceding the convective maximum, and cold anomalies following it. This agreement suggests that the reanalysis is realistically capturing the large-scale structure resulting from these interactions.

¹ The amplitude of the regressed temperature anomalies would be reduced by a factor of 2.5 if they were scaled to the observed Kelvin wave filtered OLR anomaly (50 W m⁻²) instead of the total OLR anomaly (125 W m⁻²). In this case, the amplitudes of the reanalysis and radiosonde data in Figs. 9 and 10 would not agree quite as favorably. However, considering that there are no regularly reported radiosonde data near the location of the Ronald H. Brown that are assimilated into the ECMWF reanalysis, we feel that even an agreement within a factor of 2.5 is noteworthy.

2) ZONAL WIND

Figures 11a and 11b show the zonal wind anomaly for the TEPPS radiosonde data and the ECMWF reanalysis composite, respectively. As in the temperature analyses, the correspondence between the two structures is excellent. In the stratosphere and upper troposphere, an easterly zonal wind anomaly propagates downward over the 6-day period from 50 to 200 hPa. In the re-
Fig. 10. (a) TEPPS 4-hourly radiosonde temperature anomalies for 16–21 Aug 1997, from 1000 to 50 hPa. (b) Regressed daily ECMWF temperatures from day −3 to day +3, based on a −125 W m⁻² anomaly in OLR at the TEPPS base point on day 0. Contour interval in both plots is 0.3 K, with zero contour omitted. Dark shading represents positive anomalies.

Fig. 11. As in Fig. 10 except for zonal wind. Contour interval is 1.0 m s⁻¹.
and timing of the westerly wind maxima in Fig. 12 are smoothly eastward-propagating features; instead, they ever, the zonal wind anomalies do not appear to be the convection. These wind anomalies propagate east-
OLR minimum to westerly anomalies during and after the changeover from easterly anomalies prior to the Kelvin wave filtered OLR, also shown in Fig. 3. Note wave passage. The dark solid contours represent the anomalies from the TAO array during the TEPPS Kelvin 8±23 August mean at each longitude.

Figure 12 is a Hovmöller diagram of zonal wind anomalies from the TAO array during the TEPPS Kelvin wave passage. The solid contours represent the Kelvin wave filtered OLR, also shown in Fig. 3. Note the changeover from easterly anomalies prior to the OLR minimum to westerly anomalies during and after the convection. These wind anomalies propagate eastward with the same phase speed as the convection. However, the zonal wind anomalies do not appear to be smoothly eastward-propagating features; instead, they are more localized in space and time. When the location and timing of the westerly wind maxima in Fig. 12 are compared with the total OLR minima in Fig. 3, the correspondence is good, suggesting a strong relationship between the deepest convection and anomalous surface westerlies.

For comparison, Fig. 13 is a Hovmöller diagram of 1000-hPa zonal wind from the ECMWF composite Kelvin wave. This composite structure was calculated in the same manner as in Fig. 11b, by regressing zonal wind at all ECMWF reanalysis grid points against the Kelvin wave filtered OLR at the TEPPS base point, again for the 15 Northern Hemisphere summers (JJA) from 1979 to 1993. Figure 13 shows the 1000-hPa zonal wind averaged for 0° to 10°N, for day −11 to day +5 and 155°E to 95°W. Since the regression is calculated such that the minimum OLR occurs on day 0, the timing of this minimum is plotted so as to correspond with the minimum OLR at the ship on 19 August in the TAO plot (Fig. 12). The solid contours in Fig. 13 represent the regressed total OLR anomaly, calculated in the same manner as the zonal wind. Note the clear eastward propagation of both OLR and 1000-hPa zonal wind in the regressed fields, at a slightly faster speed than in the TAO data, about 17 m s⁻¹. In a similar manner to Fig. 12, easterlies precede the convective signal. As the convective anomaly intensifies in time, the 1000-hPa wind anomaly shifts to westerly, and remains westerly while the convection peaks and then dissipates.

3) SPECIFIC HUMIDITY

We now return to a comparison of the TEPPS radiosonde data with the time–height reanalysis composite for the specific humidity field. Relative humidity data were converted to specific humidity so that the large temperature changes associated with the Kelvin wave (see Fig. 10a) do not mask changes in total moisture.

Figures 14a and 14b show the radiosonde and re-analysis specific humidity, respectively, for the 6-day period surrounding the Kelvin wave passage (shown only to 300 hPa). In the radiosonde data (Fig. 14a), there appears to be a quasi periodicity in the specific humidity variations of around 4 days, which is apparent throughout the entire 16-day radiosonde dataset, as also shown by Serra and Houze (2001, manuscript submitted to J. Atmos. Sci.). These variations are not seen in the re-analysis plot (Fig. 14b), most likely because they are due to modes that are not present in the Kelvin filtered dataset.

In the radiosonde data, specific humidity increases in the lower troposphere, below 700 hPa, for about 24 h prior to the OLR minimum. This moistening of the lower troposphere occurs concurrently with the deepening cumulus observed in the radar and profiler data on 18 August. The maximum specific humidity anomaly of 2.3 g kg⁻¹ occurs near 850 hPa at 2000 UTC 18 August, during the deepest convective event of the Kelvin wave passage. After this event, starting at approximately 0400 UTC 19 August, there is a pronounced shift in the spe-
specific humidity profile, with a sharp decrease in low-level humidity and a more gradual increase in humidity above 700 hPa. The lower-tropospheric specific humidity anomaly reaches its minimum value, a $-3.3 \, \text{g kg}^{-1}$ anomaly at 930 hPa, at 1200 UTC 20 August, after all convection associated with the Kelvin wave convective envelope has dissipated, and conditions have returned to a suppressed regime. The specific humidity in the midtroposphere (at approximately 450 hPa), on the other hand, reaches its maximum value ($\alpha + 1.2 \, \text{g kg}^{-1}$ anomaly) just prior to this low-level minimum, at approximately 0400 UTC 20 August. This suggests that the midtropospheric moist anomaly arises either locally, as a result of the pervasive stratiform convection in the region on 19 and 20 August, or else is advected westward from convection developing to the east of the ship by the midlevel easterlies.

The ECMWF reanalysis composite captures only the grossest features of the specific humidity changes apparent in the radiosonde data. In the lower troposphere, the composite shows a weak moist anomaly beginning 3 days prior to the peak in convection, and lasting until after the OLR minimum on day 0. This differs sharply from the rapid buildup of specific humidity in the lower troposphere in the radiosonde data. The reanalysis composite does, however, capture the upward propagation of positive specific humidity anomalies after the peak in convection, and the development of negative anomalies in the lower troposphere several days after this peak.

4) CAPE

The radiosonde temperature and humidity profiles allow a calculation of the convective available potential energy (CAPE) as a function of time. In this study, CAPE is defined as the net positive area on a thermodynamic diagram, between the observed temperature sounding and the temperature of a parcel lifted moist pseudoadiabatically from the lifting condensation level to the level of neutral buoyancy (Emanuel 1994).

Figure 15 is a time series of CAPE at the ship from...
16–23 August. Prior to the Kelvin wave passage, on 16–17 August, CAPE fluctuates around its cruise mean of 650 J kg⁻¹. CAPE then increases dramatically on 18 August, reaching a maximum of nearly 2300 J kg⁻¹ at 1200 UTC. This buildup of CAPE coincides with the rapid intensification of deep convection on 18 August as observed in the radar data (Fig. 6). The maximum CAPE at 1200 UTC precedes by approximately 3 h the outbreak of deep convection at the ship as observed by the vertical profiler (Fig. 7). The radiosonde data in Figs. 10a and 14a suggest that this increase in CAPE is due to a substantial warming and moistening of the boundary layer air, and not a cooling aloft.

CAPE decreases rapidly after 1200 UTC 18 August, then intensifies to another maximum at 0400 UTC 19 August. By 0000 UTC 20 August, when stratiform rainfall is dominant near the ship, CAPE has fallen to nearly zero. This gradual decline can be attributed to a cooling and drying at the surface, as observed in Figs. 10a and 14a.

The time series of CAPE at the Ronald H. Brown illustrates the local effect of the Kelvin wave passage on the potential for deep convection. CAPE builds rapidly as warm, moist boundary layer air is advected westward toward the ship by the low-level easterlies. Deep convection is able to quickly decrease CAPE by both transporting moisture upward and also cooling the boundary layer air via convective downdrafts. In addition, the lower-frequency decline in CAPE can be attributed to the advection of cooler, drier boundary layer air from the west as the Kelvin wave propagates eastward.

4. Large-scale wave structure

The similarities between the ECMWF reanalysis Kelvin wave structures and the TEPPS radiosonde data in Figs. 10, 11, and 14 give us confidence that the reanalysis is realistically capturing the dynamics of convectively coupled Kelvin waves. To further investigate
these dynamics, the ECMWF regressions are expanded to include all grid points on the globe and all vertical levels. In this manner, the three-dimensional structure of a typical Kelvin wave in the eastern Pacific ITCZ can be assessed.

To give a general overview of the eastward propagation of the Kelvin wave fields, Fig. 16 shows the regressed OLR (shading) and 150-hPa temperature (contours) and winds (vectors) on days \(-3\), 0, and \(+3\), based on a \(-50\) W m\(^{-2}\) anomaly in OLR on day 0 at the TEPPS base point. This OLR anomaly corresponds to a typical perturbation during a strong Kelvin wave event, and represents only the Kelvin wave filtered portion of the total OLR anomaly. As shown in Fig. 16, the regressed OLR, temperature, and wind signals propagate together to the east at approximately 17 m s\(^{-1}\), which is quite close to the phase speed of the TEPPS Kelvin wave (15 m s\(^{-1}\)).

The 150-hPa temperature perturbations are fairly symmetric with respect to the equator in the vicinity of the OLR signal. The zonal component of the wind perturbations is also quite symmetric near the equator at this level (Fig. 16; note that winds are plotted as vectors only at a significance level of 95% or greater), although significant off-equatorial, asymmetric wind signals can also be seen. The symmetry in the temperature and zonal wind fields, as well as the geopotential height field, becomes much more pronounced in the lower stratosphere (not shown). The symmetry above 150 hPa is consistent with the structure of a dry, linear, upward-propagating Kelvin wave, as might be forced by an upper-tropospheric heat source (Holton 1972). We consid-

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Fig. 14. As in Fig. 10 except for specific humidity. Contour interval is 0.3 g kg\(^{-1}\).

Fig. 15. CAPE (J kg\(^{-1}\)) at the Ronald H. Brown from 16 to 23 Aug 1997, calculated from 4-hourly radiosonde data.
Fig. 16. Regressed OLR (shading, dark negative, ±10 and 30 W m$^{-2}$) and 150-hPa temperature (contours, solid positive, contour interval 0.1 K, zero contour omitted) and winds (vectors, maximum 10 m s$^{-1}$, shown only where 95% significant) for (a) day -3, (b) day 0, and (c) day +3, based on a $-50$ W m$^{-2}$ OLR anomaly at the TEPPS base point on day 0.

er this signal to be the coherent Kelvin wave response to the upper-tropospheric heating associated with the eastward-propagating convective envelope. The temperature response propagates eastward at approximately the same phase speed as the OLR signal most likely because it is being continually forced by the convection. Faster vertically propagating Kelvin waves may also be excited by this convective heat source (Salby and Garcia 1987); however, these waves are filtered out by the technique used to produce Fig. 16, since they radiate away at faster phase speeds and thus are not coherent with the Kelvin filtered OLR signal.

While the regressed 150-hPa winds are predominantly zonal near the equator, they do include a nonnegligible meridional component, especially in the vicinity of the enhanced deep convection, for example, at $10^\circ$N, $160^\circ$W in Fig. 16a. Although a theoretical Kelvin wave is comprised of purely zonal flow, one might expect a moist Kelvin wave in the real atmosphere to contain Rossby-like components associated with the mass circulation due to deep convection. These meridional winds are primarily associated with the off-equatorial location of the divergence signal at 150 hPa, which is collocated with the lowest OLR (not shown). The fact that the winds at 150 hPa do contain these signatures supports the hypothesized coupling between convection and circulation in this wave.

The near symmetry of the upper-tropospheric and lower-stratospheric perturbations associated with the eastward-propagating deep convection agrees well with linear equatorial Kelvin wave theory. The structure in the lower troposphere, on the other hand, is not as well accounted for by simple dry linear dynamics, since active convection most likely interacts with the low-level circulation. Interestingly, though, the dynamical symmetry observed above 150 hPa is also apparent throughout the majority of the troposphere, above 850 hPa. The near symmetry of these regressed dynamical fields in the troposphere is somewhat surprising, considering that the convective portion of the wave (as signified by the OLR perturbations) is significantly off-equatorial, especially eastward of $140^\circ$W.
At 1000 hPa, however, the temperature and zonal wind fields are centered to the north of the equator, between 5° and 10°N (not shown). As can be inferred from Figs. 10 and 11, the warmest temperatures and strongest easterly winds are located directly to the east of the lowest OLR signal. Moisture convergence is also strongest to the east of the existing convection. This is consistent with the fact that the OLR signal propagates eastward with time, as new convection is preferentially initiated to the east of existing convection, in the region of strongest low-level moisture convergence. This region of convergence to the east of the heating may simply be the low-level Kelvin response to the tropospheric heat source, as illustrated by Mapes (1998) in a linear vertical spectral band model. Thus it appears that both convection and dynamics play a role in setting the phase speed of the wave structure as a whole.

We note here that the asymmetry in the convective field is not dependent on either the Northern Hemisphere location of the OLR base point or the choice of OLR as the filtered variable. Additional regressions were calculated using a base point on the equator (0°N, 125°W), based on both Kelvin filtered OLR and Kelvin filtered 100-hPa zonal wind (not shown). Both regressions depict a similar evolution of the OLR signal to Fig. 16, with low OLR propagating eastward at 17 m s⁻¹ along the ITCZ, consistent with the maximum in Kelvin wave OLR variability to the north of the equator in the eastern Pacific, as shown in Fig. 2.

These results illustrate that the free tropospheric dynamical structure of a Kelvin wave in the eastern Pacific ITCZ may be largely symmetric about the equator, as predicted by theory, while the convection and boundary layer signals maximize to the north of the equator. The off-equatorial location of convection is most likely due to the warm SSTs to the north of the equator in this region, which provide the necessary boundary layer moist static energy to fuel deep convection. Near the equator itself, climatologically cold SSTs in the eastern Pacific cold tongue prevent deep convection from occurring.

While the relationship between convection and dynamics in Fig. 16 may be surprising in light of the theoretical Kelvin wave structure, it must be remembered that the theoretical shallow water modes are dry modes of the atmosphere; these modes account for the structure of the divergence field without moisture, but not necessarily the associated precipitation field. Given equatorially asymmetric lower-boundary conditions (i.e., SST), it seems reasonable that equatorially symmetric dynamical forcing (e.g., upward motion, wind, or pressure fields) may result in an equatorially asymmetric OLR distribution. We suggest that this is the case in the eastern Pacific ITCZ. This hypothesis is further supported by observations of a systematic shift in Kelvin wave convection toward the equator during warm ENSO events, when the eastern Pacific equatorial cold tongue is significantly weakened (not shown).

The vertical structure of the eastern Pacific composite Kelvin wave also shows many similarities to the theoretically predicted Kelvin wave structure, particularly in the upper troposphere and lower stratosphere, above the heating associated with deep convection. Shown in Fig. 17 is a longitude–height cross section of temperature along the equator on day 0 (bottom), and an OLR cross section along 7.5°N (top), where the convective signal is maximized. The temperature phase lines tilt eastward with height in the stratosphere and upper troposphere, and westward with height below about 250 hPa. Note that the stratospheric temperature structure in Fig. 17 is similar to that in Fig. 10b, but with the x axis reversed, consistent with a propagating structure. The stratospheric signals are consistent with a vertically propagating Kelvin wave, where energy travels upward and eastward, parallel to lines of constant phase. The phase lines themselves propagate downward and eastward with time. This structure is consistent with forcing by an upper-tropospheric convective energy source, namely, the deep convective heating associated with the Kelvin wave.

The Kelvin wave horizontal and vertical structures in the eastern Pacific ITCZ shown in Figs. 16 and 17 are similar to those calculated for a Kelvin wave in the Indian Ocean region by W2000 (see their Figs. 5 and 7). This suggests that the Kelvin wave dynamical structures are not strongly affected by differences in basic-state winds between the Indian Ocean and eastern Pacific. The horizontal distribution of convection changes from region to region, however, most likely due to changes in the underlying thermal boundary conditions.

5. Summary and conclusions

In this study, observations are presented of a convectively coupled Kelvin wave that propagated eastward within the eastern Pacific ITCZ during the 1997 TEPPS field program. These observations represent a unique high-resolution, in situ, multiparameter dataset detailing the convective and dynamical structure of this type of convectively coupled wave. The large-scale convective envelope of the TEPPS Kelvin wave moves eastward at approximately 15 m s⁻¹, and consists of smaller-scale westward-moving convective elements, similar to observations of “super clusters” within the MJO by Nakazawa (1988). Radar and vertical profiler data show that the large-scale Kelvin wave envelope significantly affects local convection. Convective activity increases rapidly from small-scale, shallow cumulus to deep cumulonimbus within 24 h, organizing into linear features that move with the mean low-level wind. Much larger-scale convective and stratiform regions then develop, with stratiform rainfall becoming predominant within the next 24 h. Convection then dissipates rapidly, within 2–3 h. The evolution of convection as observed at the Ronald H. Brown suggests that a Kelvin wave envelope is much more convectively
active on its eastern side, with widespread stratiform precipitation composing the trailing western region.

The dynamical properties of the TEPPS Kelvin wave in the upper troposphere and lower stratosphere are largely consistent with linear equatorial Kelvin wave theory. Locally downward-propagating temperature and zonal wind signals are observed, as would be expected for an upward-propagating Kelvin wave forced by upper-tropospheric latent heating. At the surface, there is a significant wind shift from easterly to westerly anomalies at the time of deepest convection, which is also observed as a coincident shift in the direction of movement of convective elements.

The TEPPS radiosonde data compare very well with a composite Kelvin wave disturbance calculated from 15 yr of ECMWF reanalysis data, suggesting that the reanalysis is accurately capturing Kelvin wave convective variability and its dynamical manifestations. When this composite Kelvin wave structure is expanded to three dimensions, its dynamical structure looks similar to the Kelvin waves in the Indian Ocean studied by W2000, with wind and temperature anomalies fairly symmetric with respect to the equator. However, the OLR signal in the eastern Pacific Kelvin wave is strongly asymmetric, existing only in the Northern Hemisphere, where SSTs are warm enough to support deep convection. It is thus hypothesized that the dry dynamical structure of Kelvin waves remains intact as these waves propagate eastward into the eastern Pacific ITCZ, but that their convective signal shifts latitudinally into the region of warmest SSTs. Apparently the maximum in latent heating to the north of the equator is still able to project onto the equatorially symmetric Kelvin wave dynamical mode as the entire structure propagates eastward.

The reanalysis data used in constructing the composite Kelvin wave should continue to be very useful in further diagnosing the full three-dimensional structure of Kelvin waves in the eastern Pacific ITCZ. In addition, we plan to incorporate data from several other field programs in which convectively coupled Kelvin waves were observed [e.g., South China Sea Monsoon Experiment (SCSMEX) and Nauru99] to determine whether the structure we observe in the eastern Pacific

Fig. 17. Longitude–height cross section of regressed temperature along the equator on day 0 (bottom), and regressed OLR along 7.5°N (top), based on a −50 W m⁻² OLR anomaly at the TEPPS base point on day 0. Contour interval is 0.2 K, with zero contour omitted. Regions of 95% or greater statistical significance are shaded, with dark shading denoting positive correlations.
ITCZ is truly a global signature. In addition, reanalysis and in situ data will allow the analysis of other equatorially trapped waves, such as mixed Rossby–gravity and equatorial Rossby waves, as well as the modulation of these waves by longer-timescale variability such as the MJO and ENSO.

Acknowledgments. Many thanks to Sandra Yuter at the University of Washington for providing the TEPPS radiosonde, surface meteorology, and radar data used in this study. Thanks also to Christopher Williams at the NOAA Aeronomy Laboratory, who provided the vertical profiler data. The rain-rate measurements were calculated by Martin Grossklaus and Lutz Hasse of the Institut fuer Meereskunde, Kiel, Germany, and were provided by Sandra Yuter. Thanks to Xin Lin at Colorado State University for providing the code used to calculate CAPE, which is based on code originally written by Kerry Emanuel. We also thank Robert Houze, Richard Johnson, David Randall, Wayne Schubert, Ian Watterson, Klaus Weickmann, Matthew Wheeler, and two anonymous reviewers for providing helpful comments on earlier versions of this paper. The ECMWF reanalysis fields and the NOAA OLR data were obtained from the NOAA–Cires Climate Diagnostics Center. Wesley Berg at the NOAA Environmental Technology Laboratory provided the GOES-9 data. The TAO buoy data were downloaded from the Pacific Marine Environmental Laboratory’s TAO project Web page (http://www.pmel.noaa.gov/tao/). This work was supported by the Pan American Climate Studies program of the NOAa Office of Global Programs under Project GC98-627.

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