Observations of the 7-day Kelvin Wave in the Tropical Atmosphere During the CPEA Campaign

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Abstract

Radiosonde observations of winds and temperature over several sites in Southeast Asia during the CPEA radiosonde observation period (10 April–9 May, 2004) reveal the presence of a 7-day wave in the upper troposphere and lower stratosphere (UTLS), especially during the first half of the radiosonde observation period. Many of the characteristics of the wave resemble those of Kelvin waves. The wave amplitude peak is observed at altitudes of 20–21 km. The vertical phase structure of the wave is consistent with altitude over the radiosonde sites considered. The vertical wavelength of the wave is found to be in the range of 5.5–6.5 km. The correlative analysis among the different radiosonde sites and analysis of TIMED-SABER data sets reveals that the wave is more active in the longitude band of 0–180°E and has a zonal wave number of 3. A wave of similar periodicity and zonal structure observed in OLR suggests that tropical convection could be a source for these waves. A slight shift is observed in the peak of wave amplitude toward the northern hemisphere. Moreover, the latitudinal width of the wave is narrower than that predicted by theory. This is discussed based on the existing model results, which indicate that the latitudinal structure of the wave may be affected by strong vertical shear in zonal wind, such as that reported in the present work.

1. Introduction

Factors such as a decrease in Coriolis frequency and the change of the sign of the Coriolis frequency across the equator, in addition to the deep convection and associated release of latent heat, result in the equatorial atmosphere
being characterized by a special type of wave, namely eastward propagating equatorially trapped planetary-scale Kelvin waves with periods ranging from a few days to a few tens of days. The theoretical study initiated by Matsuno (1966) showed that eastward propagating Kelvin waves is a possible solution to the perturbation equations of shallow water model on an equatorial β plane, where β is the meridional gradient of the Coriolis parameter. Wallace and Kousky (1968) discovered the existence of these waves in the real atmosphere. The basic characteristics and theory of these waves are reviewed by Andrews et al. (1987). A number of numerical studies have reported the role of these waves in driving the eastward phase of quasi-biennial oscillation (QBO) of zonal winds prevailing in the lower stratosphere (Holton and Lindzen 1972; Plumb 1982; Coy and Hitchman 1984). In addition to planetary-scale Kelvin waves, it has been shown that the combination of the flux in all vertically propagating gravity waves must be considered and that this combination is sufficient to fully explain the behaviour of QBO (Dunkerton 1997).

Observations of Kelvin waves in the real atmosphere began with radiosonde and rocketsonde measurements. Slow Kelvin waves with periods in the range of 10–20 days with zonal wave numbers of 1–2 in the lower stratosphere were observed in radiosonde measurements (Wallace and Kousky 1968). Fast Kelvin waves with periods in the range of 6–10 days in the upper stratosphere were observed in rocketsonde measurements (Hirot 1978). However, in order to study the global behaviour and horizontal propagation characteristics of these waves, satellite measurements are more useful because they offer global coverage (Hirot 1979), compared to radiosondes and rocketsondes, which offer sparse coverage of globe. The advent of limb viewing satellite instruments having relatively good vertical resolution, namely, LIMS, MLS, CLAES, and CRISTA, has led to important developments in the study of stratospheric Kelvin waves (Salby et al. 1984; Canziani et al. 1994; Shiotani et al. 1997; Smith et al. 2002). These satellite-based studies indicate that most Kelvin wave variability in the middle atmosphere is contained in the zonal wave number range of 2–3. Highly accurate and relatively better vertical resolution (~100 m) of temperature measurements in the troposphere and lower stratosphere have become possible with the advent of the GPS radio occultation technique. Using the GPS measurements, Tsai et al. (2004) showed evidence of Kelvin waves spanning the upper troposphere and lower stratosphere (UTLS) region. Randel and Wu (2005) further extended the analysis and observed long-period (~20 days) waves with short vertical wavelengths of 4–8 km. The temperature data acquired by the Sounding of Atmosphere using Broadband Emission Radiometry (SABER) instrument (an infrared multispectral radiometer) aboard the TIMED satellite launched on 7 December 2001 (Russell et al. 1999) is expected to provide further insights into the global structure and vertical propagation of the wave from the lower atmosphere to the MLT region. The SABER experiment is described in detail by Mlynczak (1997).

Although satellite measurements have the advantage of global coverage, they suffer from poor time resolution. Studies based on high vertical and temporal resolution radiosondes have shown the existence of short period and short vertical wavelength Kelvin waves. For example, high-vertical-resolution radiosonde measurements of winds and temperature have revealed the presence of Kelvin waves in the lower stratosphere having periods of approximately 7 days (Tsuda et al. 1994) and 10 days (Sato et al. 1994). Waves having an even shorter period of approximately two days and a short vertical wavelength of approximately 5 km were observed in radiosonde measurements of temperatures and zonal winds (Maruyama 1994 and Sato et al. 1994). Wada et al. (1999) examined the horizontal structure of equatorial waves of periods shorter than approximately three days with vertical wavelengths of 3–5 km in radiosonde data collected over 10 stations and discussed the relationship between these waves and convective activity in the troposphere. Holton et al. (2001) observed short-vertical-wavelength Kelvin waves having periods of 9.5 days and 5 days with zonal wave numbers of 2 and 4, respectively.

The generating mechanism of the Kelvin waves appears to be forcing by unsteady convective heating in the tropical troposphere.
(Holton 1972). Salby and Garcia (1987) and Garcia and Salby (1987) studied transient response to localized episodic heating in the tropics and found that responses to fast heating, produced by daily fluctuations in convection, consist mainly of a spectrum of Kelvin waves. In the lower stratosphere, the response is centered at frequencies corresponding to twice the effective depth of the heating. The wave number-frequency scales of the convective coupled Kelvin waves, which can be identified in cloud-proxy data, is sometimes identical to that of some of the Kelvin waves identified in the lower stratosphere, which implies direct forcing (Wheeler et al. 2000, and the references therein).

To understand the dynamic and electrodynamic coupling of the equatorial atmosphere over the western Pacific region, known as a center of intense atmospheric motion, an intensive observation campaign was carried out during March 10–Apr 9, 2004 under a major project called the Coupling Processes in the Equatorial Atmosphere (CPEA) campaign. A comprehensive overview of the objectives of the project and various observations carried out during the campaign period are described by Fukao (2006). In the present study, the characteristics of Kelvin waves are examined using both radiosonde and satellite observations carried out during the campaign period. The present study also investigates the relationship between the waves observed in the troposphere and the lower stratosphere and the convective activity in the troposphere. In addition to the present study, this campaign of multiparameter observations has produced many interesting results on Kelvin waves and gravity waves (for example, Tsuda et al. 2006, Venkat Ratnam et al. 2006, Alexander et al. 2006).

2. Data used in the present study

2.1 Radiosonde data

As part of the CPEA campaign, an intensive radiosonde observation campaign was conducted from 10 April to 9 May, 2004. Though the entire CPEA campaign period runs from March 10 to May 9, 2004, in the present work, it refers to second part only (10 April to 9 May, 2004). The radiosonde campaign is described in detail by Tsuda et al. (2006) and is briefly summarized herein. Four radiosondes per day were launched from several sites, namely, Koto Tabang (0.2°S, 100.3°E), Kuching (1.5°N, 110.3°E), Jambi (1.6°S, 103.7°E), Kuala Lumpur (2.4°N, 101.4°E) and Bandung (0.9°S, 100.4°E), over Southeast Asia every 5 to 7 hours. Wind velocity, temperature, pressure and humidity were measured from the ground up to an altitude of approximately 35 km. On some days, radiosondes were launched every three hours (Tsuda et al. 2006). However, the present study examines only the data collected approximately every six hours (0, 6, 12, and 18 UT). In addition, routine radiosonde sounding data over 25 sites, chosen based on data quality and region of interest, are also used whenever required. Most of the radiosonde sites considered in the present study are located between 90°E–180°E. The names of the stations, their geographical locations and numbers of radiosonde launches per day are listed in Table 1. Figure 1 shows the locations of the routine radiosonde sites, which are denoted by numbers corresponding to Table 1, and sites over which radiosondes were launched during the CPEA campaign period, which are denoted by letters corresponding to Table 1. The raw radiosonde data are averaged for every 1 km. Considering the data quality, the maximum altitude for the analysis is restricted to 26 km, because more than 70% of the radiosondes launched during the above-mentioned time intervals reached this altitude. The data for the entire campaign period is averaged and removed from individual profiles. The resulting data, consisting of fluctuating components, are used to study the characteristics of the wave.

2.2 OLR data

In addition, interpolated daily Outgoing Longwave Radiation (OLR) data obtained by a NOAA satellite, which are readily available in the NOAA’s website for a 2.5° latitude-longitude grid, were used as a proxy for tropical convection. The data for the CPEA campaign period are used to determine the period and horizontal structure of the convectively generated waves.

2.3 TIMED-SABER temperature data

In the present study, equatorial (5°N–5°S) temperature data at the altitude layer of approximately 20–22 km obtained from the SABER experiment aboard the TIMED satel-
lite are also used to obtain a better picture of the horizontal structure of the wave considered herein. The SABER is a 10-channel broadband limb-viewing, infrared radiometer, which has been measuring stratospheric and mesospheric temperatures, mainly from the 15-μm radiation of CO₂, since the launch of TIMED satellite. The data retrieval and validation are described by Ramsberg et al. (2003).

3. Results and discussion

3.1 Mean winds and temperature

The mean profiles of temperature, zonal and meridional winds during the CPEA campaign (April 10–May 9, 2004) are shown in Fig. 2. The mean zonal wind is westward in the lower and middle troposphere. The mean zonal wind remains approximately −6 m/s above 5 km, and there is no strong shear below 15 km. Between 15 and 17 km, there is a westward shear of approximately 3 m/s/km, followed by relatively strong eastward shear of approximately 6–7 m/s/km between 18 and 22 km over the sites near the equator. Over Bandung, which is located at a latitude of 6.9°S, the vertical shear between the altitudes of 18 and 22 km decreases to approximately 3.5 m/s/km. The zonal wind reaches a maximum eastward speed of

<table>
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<th>No. of profiles per day</th>
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approximately 15 m/s at 22 km and remains eastward at higher altitudes, due to the eastward phase of quasi-biennial oscillation (QBO). The mean meridional wind is weakly northward in the lower troposphere and relatively strongly equatorward at around 15 km and weakly equatorward above the tropopause. The altitude profile of the mean temperature shows that the mean tropopause is located at 17.5 km (Tsuda et al. 2006).

3.2 Spectral analysis
First, radiosonde winds over the Jambi site were subjected to spectral analysis. This particular site was selected based on good data quality, because nearly 90% of the radiosondes launched at 0, 6, 12 and 18 UT during the CPEA campaign reached an altitude of 26 km. Figure 3 shows the altitude-frequency cross section of the periodogram estimate of the power spectrum of zonal winds over Jambi for altitudes of 1–26 km and for the observation period of April 10–May 9, 2004. Details concerning the periodogram estimate of the power spectrum are described in Press et al. (1992). In the figure, the winds at altitudes near the tropopause are modulated by oscillations of periods greater than 10 days (Tsuda et al. 2006). In addition, an approximately 6- to 8.5-day oscillation, which is the focus of the present paper, is observed at altitudes of approximately 17–25 km.

3.3 Filtered winds and temperature
The Fig. 4a shows the time-altitude structure of zonal wind over Jambi after removing the mean at each altitude. The vertical white bars denote data gaps. Above the tropopause (17–18 km), downward propagating signatures with periods of 120 to 216 hours (5 to 9 days) can be observed. Although these signatures persist throughout the observation period, their vertical extent extends to an altitude of 23–24 km during the first half of the observation period.
period, whereas it is limited to an altitude of 19–20 km during the latter half of the observation period. To isolate these signatures, a 5- to 9-day band-pass filter is applied to the time series of zonal wind, temperature, and meridional wind. The band-pass filtered winds and temperature are plotted in Figs. 4b, c and d as a function of time (April 10–May 9, 2004) and altitude (1–26 km). The filtered zonal wind velocities and temperatures are larger, especially during first half of the CPEA campaign (Apr 10–25, 2004). Individual profiles reach nearly 5 K in temperature and 15 m/s in zonal wind speed at altitudes of 20–21 km. The wave is almost damped out above 23 km. This wave damping may be due either to critical level absorption or radiative damping and will be discussed later in detail. The presence of the wave cannot be inferred from the meridional wind, which is consistent with the characteristics of the Kelvin wave. Downward phase propagation is observed above approximately 8–12 km, indicating that the active center of the generating mechanism of the wave could be located at around 10 km.

3.4 Period of the wave

Since the wave is more active during the first half of the CPEA campaign, the observation period April 10–25, 2004 is selected for further analysis. In order to study the characteristics of the wave in detail, the period of the wave must be determined accurately. Therefore, the time series of zonal wind and temperature are fitted with a sinusoidal curve having a period that changes systematically from 120 to 216 hours in 1-hour steps, and the period of the wave is obtained corresponding to that which produced the maximum response. Although the wave period varies slightly with altitude, it was found to be nearly 168 hours (7 days) for altitudes at which the wave amplitude is larger and is consistent with all of the stations considered in the present study. Thus, for further analysis, the period of the wave is taken to be approximately 7 days.
3.5 Amplitude and phase profiles

Although the radiosonde observations during the CPEA campaign period recorded only the two cycles of the 7-day wave event, in order to find time duration of the entire wave event, we analyzed the zonal wind measurements from twice-daily routine radiosondes over Kuching (1.5°N, 110.3°E) and Bintulu (3.2°N, 113.0°E) for the year 2004. Before estimating the amplitude of the 7-day wave, the daily dominant period of the wave in the range of 5–10 days is estimated as described in Section 3.4 for every twenty days by shifting the window by one day, and its time variation at 21 km is plotted in Fig. 5 for Kuching and Bintulu. The wave having a dominant period of around 7-days was found to appear frequently between March and September, particularly during the first half of March and during April, June and September. The time variation of 7-day wave amplitude for March–September 2004 is plotted in the bottom panel of Fig. 5. Corresponding peaks in the amplitude of the wave, when the dominant period falls between six and eight days, were found. Although the wave having a period of around 7 days frequently appears in the lower stratosphere, it appears as a transient phenomenon, lasting only for two to three cycles. Of these transient wave bursts, the most enhanced wave amplitude is observed during April, which is during the CPEA campaign.

With respect to the radiosonde observations over Jambi during the CPEA campaign, the wave amplitude and phase are estimated for each altitude using periodogram analysis by assuming the dominant wave period, and the profiles are plotted in Fig. 6. As seen earlier in the filtered wind data, the wave is predominantly observed in the zonal wind and temperature in the altitude range of 17–23 km and is damped above 23 km. The wave reaches a maximum amplitude of approximately 10 m/s at 20 km for zonal wind, although individual profiles may reach 15–18 m/s (Fig. 4). The wave amplitude for temperature reaches 3–4 K at altitudes of 18–21 km. The phase profile shows downward propagation for temperature and zonal wind above 12 km. The phase profile of
Figs. 4a–d. Time-altitude structure of mean removed zonal wind and 5- to 9-day band-pass filtered zonal wind, temperature, and meridional wind over Jambi.

Fig. 5. Temporal variability of the dominant period of the wave (top panel) and that of the 7-day wave amplitude around 21 km (bottom panel).
meridional wind is irregular, because the meridional wind amplitudes are smaller and so are not shown in the figure. The temperature and zonal wind phases are consistent with altitude above 17 km, with the former leading the latter, which is consistent with the characteristics of the Kelvin wave. The phase difference between temperature and zonal wind decreases from $-45^\circ$ to $-90^\circ$ (19–22 km) for altitudes at which the wave amplitudes are larger (rightmost panel of Fig. 6). Note that the theoretical Kelvin wave shows a quadrature phase relationship between temperature and zonal wind. In the real atmosphere, Kelvin waves have characteristics that are slightly different from those predicted by theory.

Sato and Dunkerton (1997) discussed the relation between temperature and zonal wind during eastward and westward vertical shear of zonal wind. In the present study, we extended the study of the phase relation between temperature and zonal wind component of the 7-day wave over other sites and examined the relation with vertical shear of zonal wind over those sites. Consistent with the results of Sato and Dunkerton (1997) and with the characteristics of Kelvin waves, the co-spectrum between the temperature and zonal wind values were larger over equatorial sites (1 m/s K, over Kuching) compared to that over Bandung (0.2 m/s K), where the eastward shear of zonal wind (6–7 m/s/km) over Kuching was larger than that over Bandung (~3.5 m/s/km). Similarly, the corresponding quadrature spectrum shows large negative values over equatorial sites (~1.6 m/s K, over Kuching) compared to that over Bandung (~0.6 m/s K).

The vertical structure of the amplitude and phase of the 7-day wave in zonal wind over radiosonde sites A-E (Table 1a) is obtained by carrying out an analysis similar to that for Jambi. Figure 7 shows the altitude profiles of the 7-day wave in zonal wind over sites in Southeast Asia. The amplitudes of the waves over sites located at latitudes of ±3° are approximately comparable (9–11 m/s) at 19–21 km and are larger than the amplitude of the wave over Bandung (6–7 m/s), which is lo-
cated at 6.9°S. The phase profiles of the wave over the sites considered here are consistent with altitude, which shows that the wave is not localized and is of at least regional extent. The downward phase propagation of the wave could be observed at altitudes above 12 km, which suggests that the wave is generated in the lower atmosphere. The vertical wavelength of the observed wave feature in the lower stratosphere is estimated by fitting a straight line to the computed phase of the wave at altitudes 18–22 km and is found to be in the range of 5.5–6.5 km. The background wind affects the vertical structure of the wave significantly, as, for Kelvin waves, the vertical wavelength is directly proportional to \((\bar{U} - c)/N\), where \(\bar{U}\) is the mean zonal wind, \(c\) is the phase speed of the wave and \(N\) is the buoyancy frequency. The vertical wavelength of the wave is approximately 5.5 km over Bandung, where the mean zonal wind and its vertical variation are less in the altitude range of 18–22 km, whereas it is approximately 6–6.5 km for the other sites located over the equator (±3°), where the mean zonal wind and vertical shear are larger (Fig. 2). However, satellite observations show longer vertical wavelength (>10 km) for Kelvin waves with periods of 5 to 10 days (for example, Smith et al. 2002). The term \((\bar{U} - c)\) is smaller during the eastward phase of stratospheric QBO than during its westward phase. The stratospheric QBO being in the eastward phase during the observation period might be the reason for the observed shorter vertical wavelength. Randel and Wu (2005) observed similar variation in the vertical wavelength, depending on the direction of the background wind.

3.6 Zonal wave number

Atmospheric Kelvin waves have the dispersion relation for eastward propagating hydrostatic gravity waves, as follows:

\[
L_x = \pi \left[ \bar{U} + NL_z(2\pi)^{-1} \right]
\]

where \(\pi\) is the wave period, \(L_x\) and \(L_z\) are the zonal and vertical wavelengths of the wave, \(N\)
is the buoyancy frequency for the stratosphere (0.02 sec\(^{-1}\)), and \(\bar{U}\) is the mean zonal wind. For \(L_z = 5.5–6.5\) km, \(N = 0.02\) sec\(^{-1}\), \(L_z\) is estimated at 21 km to be in the range of approximately 14,000–15,000 km over equatorial sites, corresponding to a zonal wave number \(k\) of 3, and is approximately 11,000 km over Bandung, corresponding to \(k = 3–4\). For \(k = 3–4\), the horizontal phase velocity of the wave with respect to the ground is estimated to be approximately 18–25 m/s. A wave of this phase speed may not encounter a critical level absorption with the stratospheric QBO winds, because the latter have a maximum speed of only 15 m/s. In the theoretical model of equatorial waves by Holton and Lindzen (1972), the wave induced forcing of the mean flow was attributed to radiative damping of Kelvin waves rather than to critical level absorption. Since the rate of damping increases rapidly as the Doppler shifted phase speed decreases, the Kelvin waves will be preferentially damped and will produce eastward accelerations in the eastward shear zones.

The zonal wave number of the wave can also be estimated from the phase difference of the wave among the sites considered herein by using the relationship \((360/\tau)(\Delta \tau/\Delta \phi)\), where \(\tau\) is the wave period, \(\Delta \tau\) is the phase difference between any two sites, which are located at approximately the same latitude, and \(\Delta \phi\) is the longitudinal difference between the sites in degrees. To avoid possible errors in the estimation of zonal wave number due to the mutual proximity of these sites, routine radiosonde data obtained from the NOAA website for different locations around the globe are used. However, the relationship for the estimation of \(k\) is based on the assumption that there is not much distortion in the wave structure. Thus, as the wave propagates around the globe, the structure of the wave over the entire longitude band must be examined. The temperature data acquired by SABER instrument aboard the TIMED satellite provide an opportunity to examine the wave structure around the globe. Figure 8 shows the 6.4- to 7.8-day filtered tem-

![Fig. 8. Time-Longitude cross-section of 6.5- to 7.8-day band-pass filtered temperature at 21 km obtained by SABER aboard TIMED satellite.](image)
perature data at an altitude of approximately 21 km averaged over the latitudinal band of 5°N to 5°S for the period from March 10 to May 10, 2004. The figure shows that the wave appears to be more active with larger amplitudes in the limited longitudinal band of 30°E–150°E centered around 60°E, which suggests that the wave might have been generated in this longitude band. The wave amplitude is enhanced just one week prior to the CPEA campaign. Of the two cycles of largest activity, one cycle occurs during first week of the CPEA campaign. The structure of the wave is distorted greatly in the longitudes 180°E–360°E. The wave takes nearly 7 days to propagate from 30°E to 150°E, indicating a zonal wave number of 3.

With respect to the radiosonde observations, since the radiosonde sites considered thus far are situated near each other, routine radiosonde sounding data were collected from stations located at longitudes at which the wave is more active in order to estimate the zonal wave number of the wave. The top panel of Fig. 9 shows the amplitude of the wave over the stations given in Table 1 at latitudes within ±10°. Consistent with the previous figure, the amplitude of the wave in the longitude range of 300°E–330°E is much smaller than that over Southeast Asia. For example, over Manaus and Belem, which are located at the equatorial latitudes of 1.4°S and 3.2°S, respectively, in the longitude range of 300°E–330°E, the amplitude of the wave is approximately 6–7 m/s, whereas over Bintulu, which is located at 3.2°N in Southeast Asia, the wave amplitude is approximately 13 m/s. Even over Southeast Asia, the wave amplitude decreases from 100° toward the east. However, the structure of the wave is not distorted significantly (Fig. 8). Thus, for the estimation of zonal wave number, we focus on the longitudes from 100°E to 140°E. The bottom panel of Fig. 9 shows the cross section of longitude-phase of the 7-day wave over radiosonde stations situated over the range of latitudes of 0°–10°N. The best-fit line is plotted for the points, and from the slope \( m \) of the best-fit line \( (m = 1.38 \text{ hour/degree}) \), the zonal wave number \( k = 360 \times m/\pi \) is estimated to be 2.96 (~3), which again suggests that the wave has a zonal wave number of 3.

3.7 Correlation with OLR
The tropical convection has been considered as a generating mechanism of Kelvin waves (Holton 1972). The Outgoing Longwave Radiation (OLR) data have been used as a proxy for deep tropical convection and have yielded useful information about the dominant periodicitites present in the temporal variation of convective activity over the tropical sites. In order to identify any oscillations and their dominant scales of variability, the OLR data for the period of March–May, 2004 (90 days), which are a function of time and longitude, are subjected to two-dimensional spectral analysis in order to obtain an output spectrum as a function of both zonal wave number and period. The data for the period of March–May, 2004, which includes the CPEA campaign, are obtained in order to improve the frequency resolution. Before calculating the spectra, the data are separated into antisymmetric and symmetric components.
about the equator. The power calculated for the latitudes of 15°N and 15°S are summed and plotted in Fig. 10 in contour form as a function of zonal wave number and period for symmetric OLR (top panel) and antisymmetric OLR (bottom panel). Note that positive (negative) periods correspond to eastward (westward) propagating oscillations. The plot of the symmetric OLR spectrum shows the presence of approximately 20-day oscillation with zonal wave numbers of 1–2, 11- to 14-day oscillation with zonal wave numbers of 1 and 2, 9-day oscillation with zonal wave numbers of 1–4, and 5- to 10-day oscillation, centered around 7 days with zonal wave numbers of 3–4, on the eastward propagating side. The westward propagating side shows 15-day oscillation with zonal wave numbers of 2–4. The antisymmetric spectrum shows long-period oscillations (of approximately 20 days) with high zonal wave numbers, centered around $k = 8$, on both the eastward and westward propagating sides. The 7-day oscillation is present only in the symmetric OLR spectrum and not in the antisymmetric spectrum, revealing that the oscillation is convectively coupled. It is possible that the oscillation can become free from convection, propagate upward and be observed in the measurements at higher altitudes. This implies that the wave is directly forced from the lower atmosphere.

In order to consider the tropical convection as a generating mechanism for the wave, it is essential to investigate how the convectively active region is related to maximum temperature at the source level of the waves, since, theoretically, the convective heating has a quadrature relationship with temperature at the source level. In the filtered zonal winds shown in Fig. 4b, downward phase propagation can only be observed above 8–12 km. Hence, the altitude of approximately 10 km can be taken as the center of the source level. Figure 11 shows the comparison of 5- to 9-day bandpass filtered OLR of the $k = 3$ component (bottom panel) and the 5- to 9-day band pass filtered zonal wind (dashed curve) and temperature (solid curve) over Jambi at altitudes of 14, 10 and 6 km (first three panels from top).
Figure 11 shows that during days four to eight, an approximate quadrature phase difference exists between the time variation of temperature at the source level (~10 km) and convective heating (negative OLR), as there is a phase difference of one to two days between negative OLR and maximum temperature at the source level. The negative OLR, which corresponds to an increase in latent heating, coincides with a decrease in temperature at 6 and 10 km, suggesting that most of the troposphere is cool, which could be due to the result of enhanced upward motion in the troposphere (adiabatic cooling). This indicates that the latent heating of the Kelvin wave moist convection is not sufficient to overcome the adiabatic cooling of the vertical motion, which is consistent with the behavior of the convectively coupled Kelvin wave (Fig. 9 of Wheeler et al. 2000). In addition, the negative OLR coinciding with the decrease in temperature also coincides with the change of zonal wind direction from westward to eastward. These results are consistent with plates 1, 3 and 4 presented by Shimizu and Tsuda (1997). Like 7-day wave at ~20 km, the longitude-time plot of filtered 7-day oscillation in OLR also shows larger amplitudes concentrated only in the eastern hemisphere with the phase propagating eastward (not shown). From these results, it can be inferred that the 7-day Kelvin wave can be generated due to tropical convection of similar scale and period.

3.8 Latitudinal structure

The amplitude of the spectral component corresponding to $\tau = 7$ days and $k = 3$ is plotted as a function of latitude in the bottom panel of Fig. 12. Similarly, the 7-day wave amplitude
computed around 21 km over the radiosonde sites distributed in the latitudes over Southeast Asia is plotted in the top panel of the figure for comparison. The latitudinal structure of Kelvin waves computed from the expression \( u(y) = u_0 \exp(-\beta ky^2/2v) \), given in Holton (1992), where \( u_0 \) is the amplitude of the wave over the equator (here, the largest amplitude of the wave at 21 km among the radiosonde sites considered herein (14.5 m/s) is taken as the value of \( u_0 \)), \( v \) is the Doppler shifted frequency of the wave, \( y \) is the distance from the equator, and \( \beta = 2\Omega/a \), where \( \Omega \) is the angular frequency of rotation of the earth and \( a \) is the radius of the earth, is also plotted in the top panel corresponding to \( k = 2-4 \). In the figure, the solid squares show the amplitude of the waves in the longitude band 100°E–140°E and the hollow squares show the amplitude of the wave corresponding to the longitudes other than 100°E–140°E. Over 100°E–140°E, the latitude structure of the wave is regular and the wave amplitude generally decreases with latitude. The latitude structure of the wave is close to the model values corresponding to Kelvin waves of \( k = 3 \) and 4 over equatorial latitudes and at relatively higher latitudes (7°N–10°N), respectively. However, the latitude structure of the wave shows an irregular structure over longitudes other than 100°E–140°E. This is due to the decrease in the wave amplitude and the distorted structure of the wave in these longitudes.

In the bottom panel, a broad maximum OLR amplitude exists around the equator and the wave amplitude decreases with latitude. This is consistent with the characteristic of Kelvin wave. However, the 7-day wave amplitude at 21 km shows a relatively narrow maximum around the equator. The maximum amplitude in OLR can be observed slightly north of the equator. A similar feature is also observed at 21 km in radiosonde observations of winds. We also observed a similar shift of the peak towards the northern hemisphere in the longitude-latitude cross section of the 6.4- to 7.8-day filtered SABER temperatures (not shown). Canziani et al. (1994) also noted the displacement of the Kelvin wave peak, off the equator in MLS measurements, more often toward the summer hemisphere. Boyd (1978) used analytical and numerical methods to show that only the latitude structure of Rossby-gravity waves is affected by the presence of meridional shear in the background zonal wind and that the latitude structure of Kelvin waves of low zonal wave number is not affected by even strong shear. However, it is well established theoretically and experimentally that vertical shears have a strong influence on these waves (Coy and Hitchman 1984). In the present study, the observed strong vertical shear of approximately 6 m/s/km in zonal wind at altitudes 17–22 km over equatorial sites is consistent with the results reported by Coy and Hitchman (1984).

The e-folding decay width is estimated using the relation \( Y_k = \sqrt{(2c/\beta)} \), where \( c \) is the phase speed of the wave with respect to the mean wind and \( \beta = 2\Omega/a \). For the 7-day wave at 21 km, \( Y_k \) is found to be approximately 1,000 km, which corresponds to a latitude of around 9.6°. The 1/e of maximum amplitude of 14.5 m/s is nearly 5.5 m/s. This means that the amplitude of the wave must decrease to approximately 5.5 m/s at a latitude of around 9.6°. However, the observation shows that the decrease occurs at a latitude of 7°. These estimates show that the latitudinal structure of the wave is affected by a number of factors. As seen in Fig. 2, the vertical shear in zonal wind at heights of 18–22 km is larger over equatorial sites than over Bandung, which is located at 6.9°S. Due to the large vertical shear in zonal winds over equatorial sites, the vertical group velocity of the eastward propagating wave decreases when propagating through the eastward wind shear. It is followed by a convergence of wave flux in the region and this leads to the enhancement of the observed wave amplitude over equatorial sites (Alexander and Holton 1997; Alexander et al. 2002). This explains the narrower maximum in the latitudinal structure of the wave at 21 km.

4. Conclusions

Radiosonde observations of winds and temperature over several sites in Southeast Asia during the CPEA campaign (10 April–9 May, 2004) show the presence of the 7-day wave in the UTLS region during the first half of the CPEA campaign (April 10–25, 2004). The wave is predominantly observed in the zonal wind and temperature in the altitude range of 17–
23 km and is damped above 23 km. Temperature perturbations lead zonal wind perturbations. The phase profiles over the various sites suggest that the wave may be an eastward propagating wave. These characteristics reveal the presence of a Kelvin wave at these altitudes. The vertical wavelength of the observed wave feature is estimated to be in the range of 5.5–6.5 km and is consistent with that of equatorial waves excited by convective heating. The predominant planetary zonal wave number of the wave estimated from the phase differences among the stations is 3. The space-time Fourier spectrum of the symmetric component of OLR also shows the presence of the 7-day wave with zonal wave number of 3. The $e$-folding decay latitude of the 7-day wave at 21 km is approximately $10\degree$. However, theory predicts a larger width in the latitudinal structure of the wave. There is a slight displacement of the wave peak toward the northern hemisphere, which is consistent with the few earlier observations (for example, Canziani et al. 1994). These differences between the observations and theory can be explained by vertical shear in the zonal wind, which can affect the structure of the wave. Finally, the observations of waves of similar periodicity and zonal structure are observed in the UTLS region and in OLR suggest that tropical convection may be a generating mechanism for these waves.

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