Characteristics of 10-day Kelvin Wave Observed with Radiosondes and CHAMP/GPS Occultation during the CPEA Campaign (April–May, 2004)

Toshitaka TSUDA, M. VENKAT RATNAM

Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Uji, Japan

Toshiaki KOZU

Faculty of Science and Engineering, Shimane University, Matsue, Japan

and

Shuichi MORI

Institute of Observational Research for Global Change (IORGC), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan

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Abstract

As a part of the Coupling Processes in Equatorial Atmosphere (CPEA) program, an intensive radiosonde sounding was conducted for 30 days from April 10 to May 9, 2004, coinciding with the eastward phase of QBO, at seven stations over the Indonesian maritime-continent, including the Equatorial Atmosphere Radar (EAR) site at Koto Tabang (0.2°S, 100.32°E), west Sumatra. Using radiosonde profiles, we studied the behavior of equatorial Kelvin waves with periods of 10–12 days and vertical wavelengths of 6–7 km. The global feature of the Kelvin wave was also analyzed with simultaneous CHAMP/GPS (CHAllenging Mini satellite Payload/Global Positioning System) radio occultation (RO) data. The Kelvin wave characteristics delineated by the GPS RO analysis, assuming only zonal wave number 1 and 2 components, shows good agreement with radiosonde results in the stratosphere, although the wave amplitudes were estimated to be somewhat smaller for GPS RO. However, a discrepancy in the Kelvin wave characteristics was recognized around and below the tropopause. This discrepancy is likely due to higher zonal wave number (>2) components being dominant in the troposphere. The Kelvin wave amplitudes were enhanced around the tropopause and in the lower stratosphere between 17 and 25 km and dissipated above approximately 25 km, which is consistent with earlier results. GPS RO results show eastward phase propagation of wave number 1 during the first half of the CPEA campaign, while a mixture of wave numbers 1 and 2 appeared during the second half of the campaign. We also report the modulation of the tropopause structure by these Kelvin waves.

1. Introduction

In the tropics, the Kelvin wave is one of the most dominant atmospheric waves with a planetary scale variation (Wallace and Kousky 1968), which is characterized by eastward propagation (Matsuno 1966) and periods ranging from three to 20 days with vertical wavelengths of 5 to 12 km, and the Kelvin wave is limited to
within the 15° of equator (Andrews et al. 1987; Tsuda et al. 1994; Shiotani et al. 1997; Holton et al. 2001; Mote et al. 2002). Remarkable progress has been made in connecting Kelvin waves with the perturbations in cloud convection inferred from outgoing long-wave radiation (OLR), and these waves are often referred to as ‘convectively coupled’ Kelvin waves (e.g., Takayabu 1994; Wheeler et al. 2000). Upward propagating Kelvin waves are of significant importance in stratospheric circulation and gravity wave effects (Hitchman and Leovy 1988).

In recent decades, considerable efforts have been devoted in characterizing Kelvin waves by ground-based measurements. In particular, a number of studies have been conducted using radiosonde soundings (Wallace and Kousky 1968; Tsuda et al. 1994; Sato et al. 1994; Holton et al. 2001; Shimizu and Tsuda 1997; Fujiwara et al. 1998). Although these studies clarified the time-height structure of Kelvin waves and their impact on the tropopause structure, the horizontal structure of the waves remains to be clarified.

The global feature of Kelvin waves was investigated by satellite observations, including observations by Nimbus-7 (Salby et al. 1984), Microwave Limb Sounder (MLS) measurements with a vertical resolution of approximately 2.7 km (Canziani et al. 1995; Srikanth and Orland 1998; Mote et al. 2002) and observations by the cryogenic limb array etalon spectrometer (CLAES), having a vertical resolution of 2.5 km (Shiotani et al. 1997). All of these observations are of coarse height resolution and are not well suited in retaining the fine structures of Kelvin waves, which are sometimes confined within the narrow layer near the tropopause.

The novel GPS radio occultation (RO) technique is characterized by high accuracy (0.5–1 K) and vertical resolution (0.4–1.5 km) (e.g., Rocken et al. 1997). Tsuda et al. (2000) showed that the temperature fluctuations observed by GPS/Meteorology (GPS/MET) RO are appropriate for a study on the global distribution of atmospheric gravity waves in the stratosphere. Furthermore, Randel et al. (2003) studied temperature perturbations around the tropical tropopause and found an eastward phase-tilt with height below and around the cold-point tropopause. However, the observations by GPS/MET were restricted to limited times (prime times). Using one-year GPS RO data with German (CHAMP) and Argentine (SAC-C) satellites, Tsai et al. (2004) reported evidence of Kelvin waves in the lower stratosphere. Randel and Wu (2005) extended the study with special emphasis on how these Kelvin waves are influenced by background stratospheric winds and their relation to tropical deep convection.

Although GPS RO can provide information globally, verification by ground-based measurements as to whether this information provides a sufficiently detailed vertical structure, for example, in order to study the wave effects on the tropopause, has not yet been accomplished. An intensive observation campaign of Coupling Processes in Equatorial Atmosphere (CPEA) (Fukao et al. 2006) was conducted over Indonesia during April–May, 2004, which provided a good opportunity to study Kelvin waves simultaneously through both ground-based and satellite observations.

The primary focus of the present study is the comparison of Kelvin waves observed with GPS RO and radiosondes. In addition, we also presents statistics of the balloon soundings during the CPEA campaign and the background conditions prevailing over the observation sites, which will serve as basic reference for further analysis. Finally, modulation of the tropopause structure by these Kelvin waves is presented in detail using both radiosonde campaign and CHAMP/GPS RO measurements.

2. Data

2.1 CPEA radiosonde campaign of April–May, 2004

In order to understand the vertical coupling processes between different atmospheric layers, a coordinated experiment was carried out from April 10 to May 9, 2004 in collaborative effort between Japan and Indonesia. The participating parties included the CPEA group, the Institute of Observational Research for Global Change (IORGC), 21st Kyoto University Active Geosphere Investigations (KAGI21), the Indonesian National Institute of Aeronautics and Space (LAPAN), the Indonesian Meteorological and Geophysical Agency (BMG), and the Indonesian Agency for the Assessment and Application of Technology (BPPT). Collaboration was also extended to the Singapore Meteorological Office and the Malaysian Meteorological Ser-
vice, by increasing the number of launches in addition to the routine soundings, and by using a larger balloon (800 grams instead of 350 grams) in order to cover a greater height range.

Figure 1 shows the locations of the balloon sites. The height profiles of temperature, horizontal wind velocities and humidity were measured through Väisälä RS-80 radiosonde soundings at Kuala Lumpur (KL, 2.73°N, 101.70°E), Kuching (KU, 1.49°N, 110.34°E), Singapore (SG, 1.34°N, 103.89°E), Padang (PD, 0.88°S, 100.35°E), and Bandung (BD, 6.89°S, 107.59°E), and a Väisälä RS-92 radiosonde was used at Koto Tabang (KT, 0.20°S, 100.32°E), except during the period from April 20–25, 2004, and at Jambi (JB, 1.63°S, 103.64°E).

Figure 2 shows the maximum height (balloon burst height) reached by each balloon at the seven sites during the CPEA campaign sorted according to the latitude. Note that balloons were released four times a day over all of the stations except PD and SG, where balloons were released twice and three times a day, respectively. In addition, balloons were released eight times a day for five days during the intensive observation period (IOP) of April 18–23, 2004 over KL, KT, PD and JB and for three days during the IOP of April 29 to May 1, 2004 over KT, PD and JB.

Table 1 also summarizes the balloon burst height at each site. On average, 98% (834) reached the tropical tropopause at approximately 17 km, and 86% (739) and 65% (552) ascended higher than 25 km and 30 km, respectively. Consistent with earlier balloon studies (e.g., Tsuda et al. 2004), the balloons generally reached higher altitudes (by approximately 2 km on average) during the daytime compared to the nighttime, with the maximum difference at PD (4.1 km). However, at KL and SG, balloon burst occurred at lower altitudes during the daytime, as shown in Table 2.

All of the atmospheric parameters were recorded every two seconds during the balloon ascent (~10 m height resolution), and the results were then averaged for every 100 m of height resolution. Later, quality checks were employed in order to remove outliers arising for various reasons. Firstly, the median and standard deviation (s.d.) were calculated for the first three days (one to three days), and each profile was checked as to whether the deviation of individual observations from the median value was within a threshold. For example, if the observed value shows an excursion more than one s.d. from the median value, the data is excluded as an outlier. Next, we proceeded to the next three-day period (two to four days), and so on, until the end of the campaign. For one s.d., many gaps still appeared. With two s.d., although we obtained better results, a few important features were missing. Finally, we empirically determined the threshold as one s.d. plus 1.5 (K, m/s) and found a good fit to the present data set.

2.2 CHAMP/GPS RO observations

CHAMP/GPS RO measurements (temperature profiles) were also used to study the large-scale variability of the Kelvin waves. The CHAMP satellite was launched on July 15, 2000 into an approximately circular, near-polar orbit (with an inclination of 87°) with an initial altitude of 454 km. See Reigber et al. (2000) for the system details. The first occultation measurement was performed on February 11, 2001, and since then approximately 150–200 RO measurements per day have been recorded. For the present study, we use the level-3 version-005 data produced by the GeoForschungsZentrum (GFZ), Potsdam, using their
Fig. 2.
standard method for RO processing. See Wickert et al. (2001; 2004) for more details regarding the data analysis, initial results and validation. In comparison with the radiosonde data, the accuracy of the temperature measurements in the CHAMP/GPS RO data is less than 0.5–1 K, and the height resolution varies from 0.4 to 1.5 km. The latitude and longitude distribution of the RO data can be seen in Schmidt et al. (2004). Data are interpolated to 200 m for a height range between 10 and 30 km. Note that SAC-C measurements were not available during the CPEA campaign.

### 3. Background conditions during the CPEA campaign

We next describe the background conditions over the campaign sites. First, Fig. 3(a) shows the long-term monthly mean eastward wind velocity between January, 2001 and December, 2004. To provide a detailed view, the mean wind velocity is shown for each month. The data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) and were interpolated to 2 km resolution. The data are represented as mean wind velocity at 300 km altitude, which is the approximate altitude of the tropical tropopause. The mean wind velocity is shown as a color-filled bar for each month. The color scale is shown below the figure. The blue line indicates the 300 km altitude level. The horizontal line in each slot is drawn at 17.5 km (tropopause) and 30 km.

### Table 1. Statistics of balloon burst height (H) during CPEA campaign at seven sites.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>H &lt; 16 km</th>
<th>H &gt; 20 km</th>
<th>H &gt; 25 km</th>
<th>H &gt; 30 km</th>
<th>Total</th>
<th>H &gt; 25 km</th>
<th>H &gt; 30 km</th>
</tr>
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<td><strong>851</strong></td>
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**Day time released:**

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<th>H &gt; 25 km</th>
<th>H &gt; 30 km</th>
<th>Total</th>
<th>H &gt; 25 km</th>
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<td><strong>385</strong></td>
<td><strong>298</strong></td>
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**Night time released:**

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<th>H &gt; 25 km</th>
<th>H &gt; 30 km</th>
<th>Total</th>
<th>H &gt; 25 km</th>
<th>H &gt; 30 km</th>
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<tbody>
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<td>53</td>
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<td>90.0</td>
<td>83.3</td>
</tr>
<tr>
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<tr>
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<td>70</td>
<td>55</td>
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<td>95.9</td>
<td>75.3</td>
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<tr>
<td>Bandung</td>
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<td>57</td>
<td>45</td>
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<td>95.0</td>
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<tr>
<td><strong>Total</strong></td>
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<td><strong>382</strong></td>
<td><strong>354</strong></td>
<td><strong>254</strong></td>
<td><strong>407</strong></td>
<td><strong>86.8</strong></td>
<td><strong>62.7</strong></td>
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</table>
2004 observed at Singapore, indicating that the CPEA campaign period coincided with the eastward phase of QBO.

The mean profiles of radiosondes during the CPEA campaign in April–May, 2004 are plotted for temperature, relative humidity, eastward and northward wind velocity and Brunt-Väisälä frequency squared ($N^2$) in Fig. 3(b). For this figure, all of the available profiles are averaged at the seven sites, after which small perturbations were removed by applying a low-pass filter with a cutoff at 2 km and 1 km for the wind velocity and temperature profiles, respectively. The overall structure of the background conditions is not modified by applying these filters, even near the tropopause.

During the CPEA campaign, the temperature profiles were nearly the same among all seven sites, except for the first few kilometers near the ground. The cold point tropopause was located at approximately 17.5 km, and the corresponding temperature was 187.4 K. There existed significant differences in humidity at different stations, showing latitude variations. The zonal winds were westward throughout the troposphere with a peak amplitude of 15 m/s at approximately 17 km and changed to eastward at an altitude of 20 km and became approximately 15 m/s, which is consistent with the eastward phase of QBO in Fig. 3(a). The mean meridional wind velocity was generally weak throughout the altitude region, even though some structures are recognized in the troposphere. Northward winds with amplitudes of less than 3 m/s were seen near ~10 km and changed to southward with equivalent amplitudes near the 12 km altitude. The mean $N^2$ value was ~1.0–1.5 x 10^{-4} (rad/s)^2 below approximately 14 km, which gradually increased through 15–19 km, and became fairly constant at approximately 5.0 x 10^{-4} (rad/s)^2 in the stratosphere.

The daily gridded outgoing long-wave radiation (OLR) provided by the NOAA Climate Diagnostics Center website (http://www.cdc.noaa.gov) is used as a proxy for tropical deep convection. Figure 3(c) shows the longitude-time distribution of OLR averaged between 2.5°N and S from March 10 to June 10, 2004, including the CPEA campaign. Two large-scale convective systems propagating eastward from the Indian Ocean reached the observation sites on April 22–23 and May 4–5, 2004. Another cloud system was observed over the observation sites near the end of April, 2004, though its propagation direction was unclear. The readers are referred to Shibagaki et al. (2006) for more details on super cloud clusters and Madden-Julian oscillation-related topics.

The average cloud top height (not shown here) estimated by converting OLR temperatures to the corresponding height from radiosonde measurements during the CPEA campaign was 8.4 km, with a maximum cloud top height of 16.5 km. The cloud top height exceeded 13 km for approximately 15% of the measurements.

4. Long-period oscillations (Kelvin waves)

4.1 Local and global variations during the CPEA campaign

We applied a periodogram analysis to find the dominant period of Kelvin waves during the CPEA campaign, which was found to be longer than 15 days in the lower troposphere which changed to 10–12 days near the tropopause. In the lower stratosphere (around 20 km), the dominant periods varied between 5.5 and 8 days, with the mean at 7 days. In order to extract these long period oscillations, we subtracted the mean values at each altitude and then applied a low-pass filter with a cutoff at three days, so that the effects of gravity waves were mostly removed. Although the filtered long-period fluctuations consist of both 7-day and 10- to 12-day oscillations, we concentrate herein on the behavior of the latter, and
Fig. 3. Height-time cross section of (a) monthly mean eastward wind velocity observed from January 2001 to December 2004 in Singapore. The vertical lines show the CPEA campaign period of April–May, 2004. (b) Mean profiles of temperature, relative humidity, eastward and northward wind velocity, and Brunt Väisälä frequency squared averaged over the CPEA campaign period at seven sites. (c) Time-longitude section of outgoing long-wave radiation (OLR) over 2.5°N to 2.5°S from 10 March to 10 June, 2004. The horizontal line around 100°E shows the approximate location of Koto Tabang, and vertical lines indicate the CPEA campaign period.
the characteristics of 7-day oscillations are discussed by Sridharan et al. (2006).

Figure 4 shows a typical example of a time-height section of low-pass filtered profiles of temperature (T), zonal (U) and meridional (V) wind velocities observed at JB during the CPEA campaign. Note that this station is selected because more balloons (146) were released and the balloon burst height was higher on average (see Table 1).

Perturbations were observed to be very different between the troposphere and the stratosphere. In the troposphere, oscillations with periods greater than the campaign duration, which are thought to be mainly due to Madden-Julian oscillation, can be seen. Vertically propagating waves with downward phase propagation appeared in the temperature and zonal wind velocity just above the tropopause but not in the meridional winds. The relative phase of the temperature perturbations, shown in Figs. 4(d) and 4(e), in the lower stratosphere and near the tropopause, respectively, preceded that of zonal winds by approximately a quarter of the wave cycle. These characteristics are consistent with the Kelvin wave. Near the tropopause, 10- to 12-day oscillations were clearly seen dominant throughout the campaign, whereas in the lower stratosphere 7-day oscillation was dominant during the first half of the CPEA campaign. However, during the second half of the campaign the 10- to 12-day oscillation was dominant. Similar features were also observed by Tsuda et al. (1994), Shimizu and Tsuda (1997) using a radiosonde campaign conducted over Indonesia.

The 10- to 12-day oscillations are noticed at all of the other six stations during the CPEA campaign, indicating the predominance of a global-scale wave. In order to see the horizontal structure of the waves, simultaneous CHAMP/GPS RO observations are utilized. For extraction of Kelvin waves with zonal wave numbers of 1 and 2 from GPS RO data, the procedure implemented by Tsai et al. (2004) is closely followed. We selected the latitude within $\pm 10^\circ$ from equator in order to avoid mixing of waves other than the Kelvin waves, with the height coverage of 10–30 km. Extraction of Kelvin waves using CHAMP/GPS RO involves three processes. First, 30-day median profiles (15 days before and after) were removed to obtain temperature fluctuations ($T'$). In the second step, profiles are further smoothed along the altitude, with a cut-off at 4 km using two Chebyshev low-pass filters. Finally, to isolate dominant wave numbers, a fitting function,

$$f(x) = \sum_{s=1}^{2} A_s \sin s(x – \varphi_s)$$

consisting of wave numbers 1 and 2 is then applied to best fit the $T'$ (hereafter referred to as fitted $T'$) with amplitude $A_s$ and phase $\varphi_s$ by means of a non-linear least-squares method. Since CHAMP is a polar orbiting satellite with an inclination angle of $87^\circ$, there are only 10–13 ROs per day near the equator. Therefore, the fitted $T'$ are generated every three days and are shifted by one day (three-day running fitting). This method can be effectively used to study Kelvin waves with periods greater than approximately 10 days and with reduced amplitudes for less than seven-day oscillations (Tsai et al. 2004; Randel and Wu 2005).

As an example, the smoothed profiles of temperature fluctuations observed on May 3–5, 2004 (treated as May 4, 2004) are shown in Fig. 5(a). Each profile is drawn at its corresponding longitude as indicated by a dotted vertical line. Note that most of the $T'$ profiles were enhanced around the cold-point tropopause. The locations of individual RO events are shown in Fig. 5(c). The temperature profiles in Fig. 5(a) that occur at proximate locations, for example between $60^\circ$–$120^\circ$W, are very similar, indicating that the GPS RO measurements are highly accurate. The temperature profiles also satisfy the definition of the background mean, which we assume for estimating the Kelvin wave fluctuations. Figure 5(b) shows the sinusoidal fit along longitude at an altitude of 20 km, showing the amplitude of temperature oscillations of approximately 3 K and a wave number 2 structure. Performing this data processing over the long-term we can reveal the time evolution of the zonal wave propagation. Note that the wave amplitude appears to decrease to some extent due to the curve fitting, which will be discussed again later. Nevertheless, because of the availability of measurements across the globe, GPS RO data gives important information on the horizontal structure of the Kelvin waves.
Fig. 4. Low-pass filtered profiles (cutoff at three days) of (a) temperature, (b) eastward wind velocity, and (c) northward wind velocity observed at Jambi during the CPEA campaign period. Time series of the zonal wind velocity and temperature observed at (d) 20–21 km and (e) 17–18 km.
Figure 6 shows a time-longitude section of the fitted $T_s'$, the amplitude, and the phase for wave numbers 1 and 2 at an altitude of 19–20 km during the CPEA campaign. Here, $T_s'$ clearly showed eastward phase propagation. During the first half of the CPEA campaign, wave number 1 is dominant, whereas in latter half, wave number 2 also appeared dominant with amplitudes occasionally exceeding 2 K. However, both wave components appeared to coexist. When the amplitudes were large, the phase clearly shows eastward progression for both wave numbers 1 and 2. The dominant wave periods are similar to the radiosonde results shown in Fig. 4.

4.2 Height-time comparison between radiosonde and CHAMP/GPS observations

This section is devoted to a detailed comparison of the wave characteristics between the radiosonde and GPS RO techniques. Figures 7(a) and 7(b) show the height-time section of the temperature perturbations for both GPS RO and radiosonde results at JB, where the GPS RO data are taken at 105°E, corresponding to JB. The variations clearly show enhancement above the tropopause (17.5 km) with downward phase propagation. Note that 7-day oscillations are also seen at higher altitudes (Sridharan et al. 2006). From the radiosonde plots, this downward phase propagation can be

![Figure 6](image-url)
recognized to extend well below the tropopause during the second half of the CPEA campaign, but was restricted to the tropopause during the first half of the campaign. However, with respect to the GPS RO measurements, the phase progression seemed to stop even well above the tropopause. A similar difference in the wave behavior across the tropopause was also noticed for the two different techniques during another intensive radiosonde campaign in November, 2002, which is reported in detail in a companion paper (Ratnam et al. 2006a).

Figure 7 indicates that the fluctuations observed with GPS RO generally agree well with the radiosonde results above approximately 18 km, which demonstrates that the perturbations caused by Kelvin waves were effectively captured by GPS RO measurements by taking advantage of the high vertical resolution (Wicket et al. 2004; Randel et al. 2003). However, near and below the tropopause the agreement is significantly worse. Temperature perturbations in the troposphere could be induced by oscillations with smaller horizontal scales, i.e., with higher (>2) wave numbers, likely due to the effects of a localized wave generation source (Ratnam et al. 2006a). Then, GPS RO analysis may not be able to describe the variations, as only wave number 1 and 2 components are assumed.

In order to investigate the differences in the amplitudes between the two independent methods, we compared the temperature fluctuations at 20–21 km and 17 km in Figs. 7(c) and 7(d), respectively. Note that the longitude selected for GPS RO is 105°E, while radiosonde results are taken from the seven sites mentioned in Fig. 1. At 20–21 km, the 7-day wave was dominant during the first half, and at 17 km the 10- to 12-day wave was dominant throughout the campaign. The radiosonde results showed amplitudes that were approximately 25–30% larger than those indicated by the GPS RO measurements. The smaller amplitudes for GPS RO measurements are attributed to smoothing and fitting in the analysis procedure. Although the distribution of the radiosonde sites for the CPEA campaign is much smaller than the zonal wavelength, a slight phase shift, consistent with eastward propagation, can be recognized.

4.3 Altitude-longitude variations during the CPEA campaign

Figure 8 shows two examples of the altitude-longitude section of the fitted Ts’ observed by
Fig. 7. Height-time cross sections of fitted $T_s'$ during the CPEA campaign obtained using (a) GPS RO data at 105°E longitude and (b) radiosonde data at Jambi (103.64°E). Time series of low-pass filtered temperature variations observed at different stations at (c) 20–21 km and (d) 17 km, in comparison with the corresponding GPS RO observations.
GPS RO measurements on different days (generated using three consecutive days) selected during the first and second halves of the CPEA campaign when the wave numbers 1 and 2, respectively, became dominant. The corresponding OLR distribution is also plotted in the bottom panels of Fig. 8. On April 30, 2004, the positive perturbations are generated to the east of the deep convective centers (low OLR values) between 10 and 15 km along with negative perturbations near the tropopause directly over the deep convective centers, consistent with earlier study by Randel et al. (2003). However, this agreement could merely be in a broad sense, and one-to-one correspondence was not seen continuously (Ratnam et al. 2006b), probably because the advection speed of OLR is small (<5 m/s) compared to the propagating waves (20–30 m/s, depending on the period and background conditions). Note that enhanced negative perturbations are still seen near the tropopause over the maritime continent although the deep convective areas are not situated there in the case of April 15, 2004.

In both cases in Fig. 8, the phase progression tilted eastward and upward and was approximately regular, showing another periodical characteristic of Kelvin waves in the vertical direction. Since the large perturbations are located in and around the tropopause, the thermal structure of the tropopause can be significantly modified by the Kelvin waves.

4.4 Effects of Kelvin waves on the tropopause structure

Using the Koto Tabang radiosonde data, the amplitudes and phases of the Kelvin wave are plotted in Fig. 9, assuming the wave period to be 10 days. Both the zonal wind velocity and temperature were enhanced around the tropopause and showed a local minimum at around 19 km. They were enhanced again in the lower stratosphere up to approximately 25 km, accompanied by clear upward phase propagation. Note that the enhanced amplitudes extending up to 25 km can also be seen in the altitude-longitude section with GPS RO analysis in Fig. 8.

It is well reported that Kelvin waves significantly affect the thermal structure near the tropopause (Tsuda et al. 1994), which could influence the dehydration and cirrus formation (Fujiwara et al. 1998). Furthermore, the enhanced turbulence can be associated with the Kelvin wave breaking near the tropopause, which plays an important role in Stratospheric-Tropospheric (S-T) exchange, for example, causing downward transport of the stratospheric ozone into the troposphere (Fujiwara et al. 2003).

This CPEA campaign can be effectively used to study the effects of the large-amplitude Kelvin waves on the tropopause structure, as both local (radiosondes) and global observations (GPS RO) were available simultaneously. Figure 10(a) shows the time variations of the cold-point tropopause height along with superimposed zonal wind fluctuations observed by.
The low-pass filtered zonal velocities with a cut-off at three days reveals that the amplitude of Kelvin waves reached 15 m/s, extending up to 25 km. The CHAMP/GPS RO observations within $\pm 10^\circ$ and $\pm 20^\circ$ from KT in latitude and longitude, respectively, are also plotted for comparison in Fig. 10(c). Comparison of the cold-point tropopause temperature between GPS RO and radiosondes in Fig. 10(d) reveals that the tropopause temperature can be modulated peak-to-peak up to 5–10 K at an altitude of up to 3 km due to these Kelvin waves, which is consistent with earlier results reported by Shimizu and Tsuda, (1997; 2000). The altitude of minimum temperature showed downward phase propagation between 19 and 16 km. Clear jumps in the tropopause height are observed during the periods of April 10–12, 24–26 and May 8–9, 2004, when the zonal winds due to Kelvin waves exceeded 15 m/s.

In general, the GPS RO results in Figs. 10(c) and 10(d) reasonably agree with radiosondes, even though a large selection criteria for GPS ($\pm 10^\circ$ latitude and $\pm 20^\circ$ longitude from KT) is applied, suggesting that the impact of Kelvin waves upon the tropopause was extended to a large area. However, we are unable to determine the area of its impact based on the present CHAMP/GPS measurements because the ROs were not sufficient.

In order to investigate the vertical distribution in more detail, potential temperature deviation from the monthly mean during the CPEA campaign was examined and is shown in Fig. 10(b). Note that the potential temperature deviation is proportional to the downward displacement for adiabatic motions when Brunt-Väisälä frequency squared ($N^2$) is constant (Fujiwara et al. 1998). A large downward displacement near the tropopause appeared during the second half of the CPEA campaign. However, such downward displacement was not seen during the first half of the CPEA campaign.

5. Summary and concluding remarks

Height and time variations of equatorial Kelvin waves were analyzed using radiosonde results collected over seven tropical sites at Indonesian sector from April–May, 2004 (CPEA campaign). In the lower stratosphere, vertically propagating waves with downward phase progression with periods of 10–12 days and vertical wavelengths of approximately 6–7 km were observed. (Seven-day oscillation

![Fig. 9. Profiles of (a) monthly mean eastward wind velocity, (b) amplitudes and (c) phases fitted for a 10-day period for the data obtained at Koto Tabang.](image)
Fig. 10. Height-time variations of (a) low-pass filtered (with cut off at three days) contours of zonal wind velocity along with superimposed cold-point tropopause height observed during the CPEA campaign at Koto Tabang. The tropopause height inferred from GPS RO data is also plotted (open circles) for comparison. (b) Height-time distribution of potential temperature deviation from the monthly mean observed at Koto Tabang along with cold-point tropopause height. Inter-comparison of tropopause (c) height and (d) temperature between radiosonde (open circle) and CHAMP/GPS RO data (cross).
was also dominant during the first half of the CPEA campaign.)

In order to see the global structure of the Kelvin wave, simultaneous CHAMP/GPS RO observations are utilized. First, a great deal of attention was given to the comparison of the observed features of Kelvin waves between GPS RO and radiosonde observations. In general, the overall features revealed by these two independent techniques agreed well, although differences in the amplitudes, which arose mainly due to smoothing by harmonic fitting for GPS RO analysis, were observed. In the troposphere, a larger discrepancy between these two exists, perhaps due to the predominance of larger wave numbers, which cannot be defined precisely through GPS RO analysis, which assumes wave numbers 1 and 2 only.

During the CPEA campaign, temperature fluctuations clearly showed eastward phase propagation in time-longitude section. Zonal wave number 1 was dominant during the first half of the CPEA campaign, whereas wave number 2 was dominant during the latter half of the campaign. Modification of the tropopause structure, observed by radiosondes, was also shown by GPS RO measurements.

Since the main features of Kelvin waves were clearly captured by GPS RO measurements, except for a slight decrease in the wave amplitudes, they can be used to study the long-term characteristics of the Kelvin waves, especially under different background wind conditions with high vertical resolution and global coverage.

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