A Report on Radar Observations of 5–8-day Waves in the Equatorial MLT Region

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Abstract

The MF and Meteor radar observations of horizontal winds over Koto Tabang (0.2°S, 100.3°E), Pontianak (0°, 109.3°E), and Pameungpeuk (7.5°S, 107.5°E) are utilized to study the characteristics of 5–8-day waves in the mesosphere and lower thermosphere (MLT) region over Indonesia. The wave activity is larger in zonal wind than in meridional wind and in the year 2003, it maximizes before and after northern hemispheric spring equinox. In the year 2004, the wave activity in zonal wind is larger during June–August 2004. During this period, the phase of the wave over Pontianak leads that over Koto Tabang, indicating that the wave is westward propagating with zonal wave number 1. The wave period ranges from 6.3 to 7.0 days over the equatorial sites Koto Tabang and Pontianak, whereas over the southern hemispheric site, Pameungpeuk, it is in the range 6.2–6.4 days. This shows that the dominant period of the wave changes with latitude. The amplitude and phase structures of the wave with altitude are similar among the three sites considered. The wave dominates the MLT dynamics over Pameungpeuk even during second half of CPEA (Coupling Processes in the Equatorial Atmosphere) campaign period (10 April–9 May 2004) with similar dominant wave period near 6.4-days. The wave amplitude is larger during last quarter of the campaign period.

1. Introduction

Atmospheric theory suggests that there exists a free oscillation (normal mode) having period ~5-days with symmetric meridional structure and zonal wave number 1 (Longuett-Higgins 1967). The mesosphere and lower thermosphere (MLT) observations sometimes indi-

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cate the presence of a wave having period ~6.5 days, the characteristics of which are consistent with those of 5-day wave and hence the wave has been considered as 'Doppler shifted 5-day wave' by one school of thought (Wu et al. 1994). However, the wave differs from the 5-day wave of normal mode in such a way that it shows phase variation with altitude, which has been interpreted as due to local modification of the vertical wave number by the variable background zonal wind. There is another school of thought which considers the wave as an unstable mode (Meyer and Forbes 1997; Lieberman et al. 2003), in which the wave amplitude grows in time. Talaat et al. (2001) reported a different picture of 6.5-day as internal, forced oscillation, having amplitude growth rate exceeding that of normal modes below 80 km and suggested an explanation for this as due to decrease of atmospheric density with altitude by presuming source region in the troposphere. According to their observations, the wave amplitude in zonal wind is confined to low latitudes, with the peaks concentrated near the equator and around equinox, whereas the wave amplitude in temperature, meridional wind and atomic oxygen maximizes at mid-latitudes having the same seasonal variabilities over equator. The present study aims to study the waves with periods 5–8 days as a function of altitude and time using wind observations by regional network of MLT radars over Indonesia.

2. Data

The MLT wind data acquired from the regional network of radars situated at Koto Tabang (0.2°S, 100.3°E) (Meteor radar), Pontianak (0°, 109.3°E), and Pameungpeuk (7.5°S, 107.5°E) (MF radars) for the period January 2003–May 2005 are used to study characteristics and variabilities of the 5–8-day wave. For MF radar at Pontianak, the system details, mode of operation and method of wind estimation are same as those described in Vincent and Lesicar (1991). Briefly, the radar, operating at the frequency of ~2 MHz, estimates winds using spaced-antenna method from 78 to 98 km with the highest data rate around 90 km and with the sampling rate of approximately every 2 minutes. The MF radar at Pameungpeuk is operating at the frequency of 2.008 MHz with the peak power of 30 kW. The antenna array, consisting of three antennas arranged in an equilateral triangle, is used for both transmission and reception. The Meteor radar over Koto Tabang is an all-sky meteor radar (SKiYMET system of Genesis Software Pty Ltd) operating at the frequency of 37.7 MHz with 12 kW output power, located at the EAR (Equatorial Atmosphere Radar) site. The IPP is 400 μs with a sampling pulse width and resolution of 13.3 μs (2 km in range). Typical meteor echo rate is between 3,000 and 5,000 per day, yielding horizontal wind velocity estimates with a time and altitude resolution of 1 hour × 2 km between 80 and 102 km altitude.

The observation duration of meteor and MF radars are shown in Fig. 1. The Pontianak MF radar data suffered from a lot of gaps all through the observation period, in particular, during June–July 2003 and April 2004. The data for September–November 2004 have not yet been processed. Though the Koto Tabang meteor radar data are free from many gaps in general, there are large gaps in November 2003 and April–May 2004. It may be noted that both Pontianak and Koto Tabang data are either not available or having too many gaps during the second half of CPEA campaign period (10 April–9 May, 2004) (Fukao 2006, for details about the campaign), when intensive radiosonde campaign was conducted in several sites over Indonesia (Tsuda et al. 2006). The raw data are averaged for every hour and these hourly winds are used for further analysis. The equatorial radar network is unique in the sense that Koto Tabang and Pontianak are situated almost over the equator to enable us to study the zonal characteristics of different wave motions, whereas Pameungpeuk is located in the southern hemisphere to enable us to investigate the direction of propagation of the wave and latitudinal differences in the wave characteristics.

3. Results

3.1 Correlative analysis between Koto Tabang and Pontianak

To begin with, the hourly wind data for altitudes 88–92 km over Koto Tabang and Pontianak are subjected to cross-spectral analysis in order to identify the periodicities present in both sites. Moving window cross spectrum between two sites provides not only the signifi-

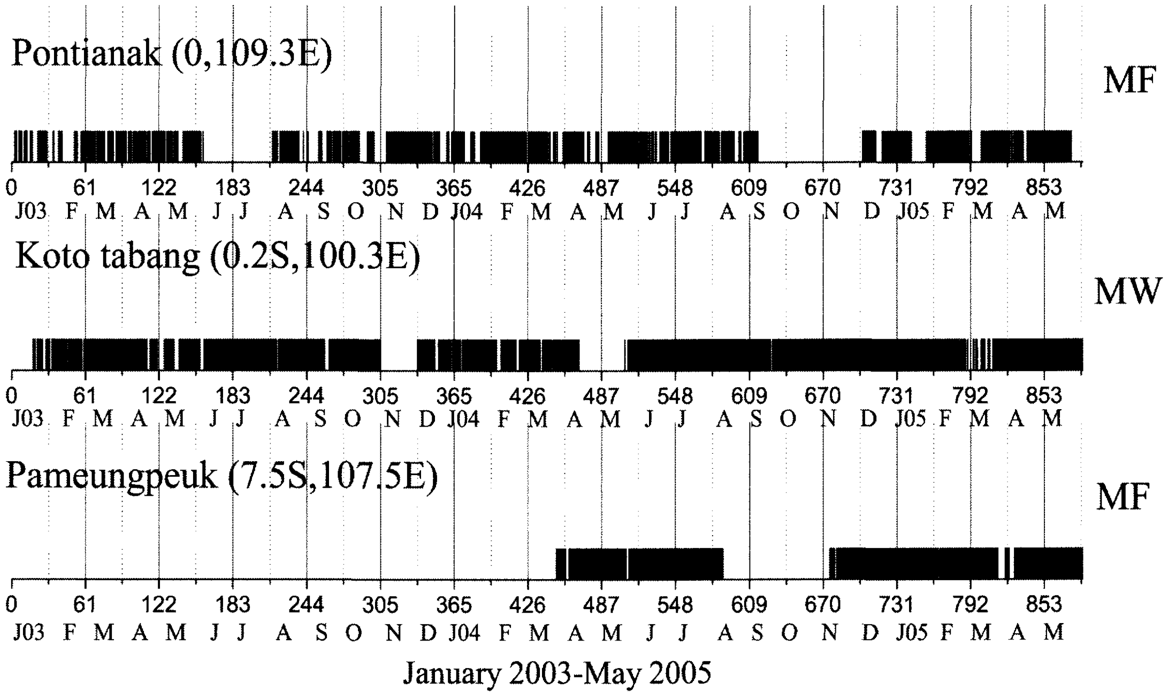


Fig. 1. Observation duration of MF and Meteor wind radars for January 2003–May 2005.

cance of oscillations present over both sites, but also its temporal behaviour. To compute mean cross spectrum, the zonal and meridional wind data are organized into 60-days. Within each 60-day data set, cross-spectral amplitudes are computed for the first 20-days window. The computation is repeated for every successive window shifted by 5-days. The amplitudes computed for all these windows in each 60-days are averaged for the altitudes 88–92 km. Hence the time variation of cross-spectral amplitudes for different frequencies (or periods) can be obtained. It is customary to express the cross spectral amplitudes in a normalized measurement with the name 'squared coherence', which is the squared value of the cross-power spectrum divided by the square root of the product of the spectra of the signals. Figure 2 shows the time-period cross section of squared coherence for zonal wind (top panel) and meridional wind (bottom panel) for January 2003–May 2005. The squared coherence values are highly significant (>0.5) at periods ~5–6 days during February–March 2003 and May 2003 and at longer periods ~5.5–8 days during June–August 2004. It can be noted that within the analyzed interval of nearly 29 months, larger coherence extended to longer periods of 5.5 to 8-days is observed only during June–August 2004. The number of cases is limited to one, as it could be due to large data gaps in the both data sets. Since the data quality of the MF radar at Pontianak is relatively poor in the beginning of the year 2003, the 5–8-day wave event during June–August 2004 is considered for further study. For meridional wind, the squared coherence values are relatively less. This shows that the wave is dominant in zonal wind, but also accompanied by smaller meridional component.

Figure 3 shows the squared coherence (top panel) and cross-spectral phase (middle panel) and zonal wave number (bottom panel) estimated from the cross spectral phase for the period ranging from 1.5 to 10 days for zonal wind at altitudes 88–92 km and for June–August 2004. The squared coherence values are highly significant at periods near ~7 days, 3.5 days, and near 2 days. The phase plot shows that on the average, Pontianak leads Koto Tabang by 4 hours. This suggests that the wave is westward propagating having zonal wave number 1. There also exists an eastward propagating 3.5-day wave with zonal wave number 1. The results are consistent with earlier observations (Riggin et al. 1997; Kovalam et al. 1999).

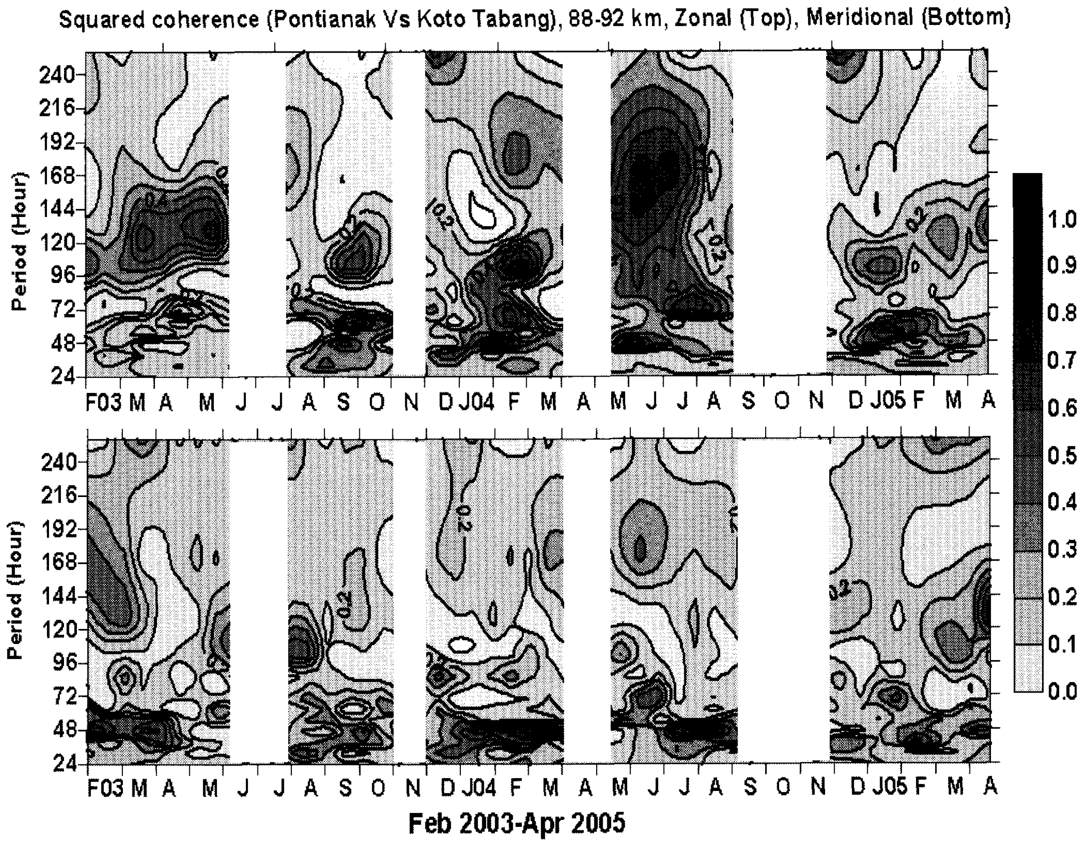


Fig. 2. Moving window of squared coherence between Pontianak and Koto Tabang at 88–92 km for zonal wind (top panel) and meridional wind (bottom panel) for the period January 2003–May 2005.

3.2 *Filtered winds*

Before studying the characteristics of 5–8-day waves in detail, the zonal wind data for the period May 24–August 7, 2004, during which nearly continuous data are available at the three sites, are subjected to a band-pass filter with cutoff periods of 120 and 192 hours (5–8-days). Figure 4 shows the filtered winds for the altitudes 84–94 km over Pameungpeuk (top panel), Pontianak (middle panel), and Koto Tabang (bottom panel). The filtered winds show that the time variations of the occurrence of 5–8-day waves are very similar, in particular, over the equatorial sites Koto Tabang and Pontianak for the entire period shown in the figure. There are two pronounced events of wave activity; one roughly between the day numbers 150–180 and the other between the day numbers 190–220. The filtered zonal winds over Pameungpeuk show larger amplitudes during the first event and the time variation of amplitude is similar to that over the equatorial sites. These two wave events are studied further to look at altitude variations of the wave characteristics.

3.3 *Altitude profiles of amplitude, phase and period of 5–8-day waves*

In order to study the altitude profile of the characteristics of 5–8-day waves in zonal wind, the period of the wave in the two wave events needs to be determined. The data for the two wave events, after removing mean, are fitted with the sinusoidal curve of period changing systematically from 120 to 192 hours in steps of every 0.5 hour, and the period of the wave is taken corresponding to the fitted curve which shows minimum residual with the data. It is found that the period of the wave, as shown in Fig. 5 (left panels), in the first wave event on an average increases from 6.3–7.0 days over Koto Tabang (solid circle) and Pontianak (open square) at altitudes 84–94 km, with the mean period of 6.7 days whereas the period over Pameungpeuk (cross) is mostly in the range 6.2–6.4 days with the mean period of 6.3 days. In the second event, the period of the wave over Pameungpeuk varies from 6.2–6.4 days, similar to the first event. Over Pontianak and Koto Tabang, it increases from 6.4–7 days with the mean period of 6.6 and 6.7 days respectively.

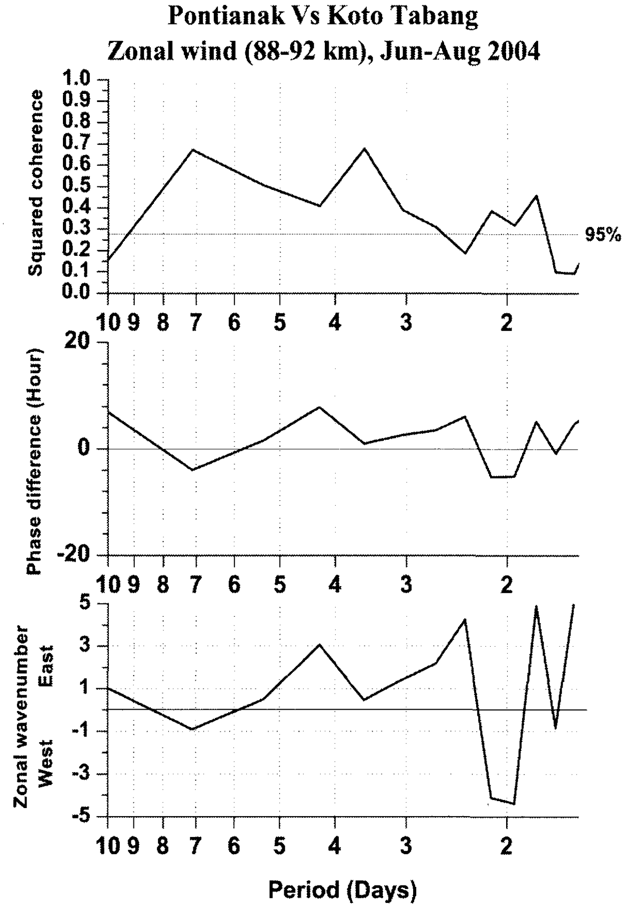


Fig. 3. Squared coherence (top panel), cross-spectral phase (middle panel), and zonal wave number (bottom panel) between zonal winds measured at Pontianak and Koto Tabang.

From these results, we can infer that the dominant period of the wave is nearly same at equatorial sites, but it changes with latitude. The less wave activity during the daynumbers 180–190 could be due to non-linear wave-wave or wave-tidal interaction. In order to investigate the differences in phase structures of the wave among the three sites considered, the period of the wave is taken as 6.5 days (156 hours) and the phase of the wave is obtained by determining the time (U.T.) of the maximum eastward winds, on a scale of 0 to 156 hours. However, to estimate the amplitude of the wave at each site, the dominant wave period corresponding to that site is taken.

The middle and right panels of the Fig. 5 show altitude profiles of the amplitude and phase of 5–8-day waves in zonal wind over the three sites for the first event (day numbers: 150–180, 2004) in top panels and the second event (day numbers: 190–220, 2004) in bottom panels. In the first event, though the wave amplitude differs considerably at altitudes less than 86 km over Koto Tabang and Pontianak, it reaches the maximum of ~14–15 m/s at 88–90 km and it decreases with altitude above 90 km in all the three sites. The amplitude of the wave over Pameungpeuk is less than that over the equatorial sites at altitudes 84–94 km and it reaches the maximum of 11 m/s at altitudes 86–88 km. Besides the identical amplitude structure, the identical phase structure of the wave with altitude over the three sites shows that waves between 86 and 98 km in the three sites seem to be due to an identical wave event. The phase (and amplitude) disturbance below 86 km over Pameungpeuk could be due to superposition (interference) of other waves. The vertical wavelength is estimated by fitting a straight line to the phase profiles of the wave. The value, on an average, is found to be ~50 km. The phase of the wave over Pontianak leads that of Koto Tabang and this suggests that the wave is propagating westward. In the second event, the most of the characteristics are same as that of the first event, except that the average amplitude of the wave during second event is less than the first event and the amplitude profile shows that the wave amplitude decreases with altitude in the altitude range 84–94 km over the equatorial sites.

The large phase difference of the wave (~35 hour) over the sites Pontianak and Pameungpeuk in both the two events could be partly due to difference in the dominant period of the wave at the two sites. It is also possible that the phase of the wave itself may vary rapidly with latitude, as it is estimated by assuming the wave period as 6.5-days, this motivates us to find the inclination of the phase front at 88–90 km for the day numbers 160–173, when the maximum amplitude of the wave is observed (Referring to Fig. 4) in the first event at both sites Pameungpeuk and Pontianak. If 'Δx' is the spatial difference in zonal direction between the two stations separated by a latitudinal difference 'Δy', it is related to phase difference (ϕ) and horizontal wavelength (λ) of the wave under consideration as $\Delta x = \phi\lambda/(2\pi)$ and the inclination of the phase front from the meridional axis, is given by $\theta = \tan^{-1}(\Delta x/\Delta y)$. Using the relation, the inclination of the phase front

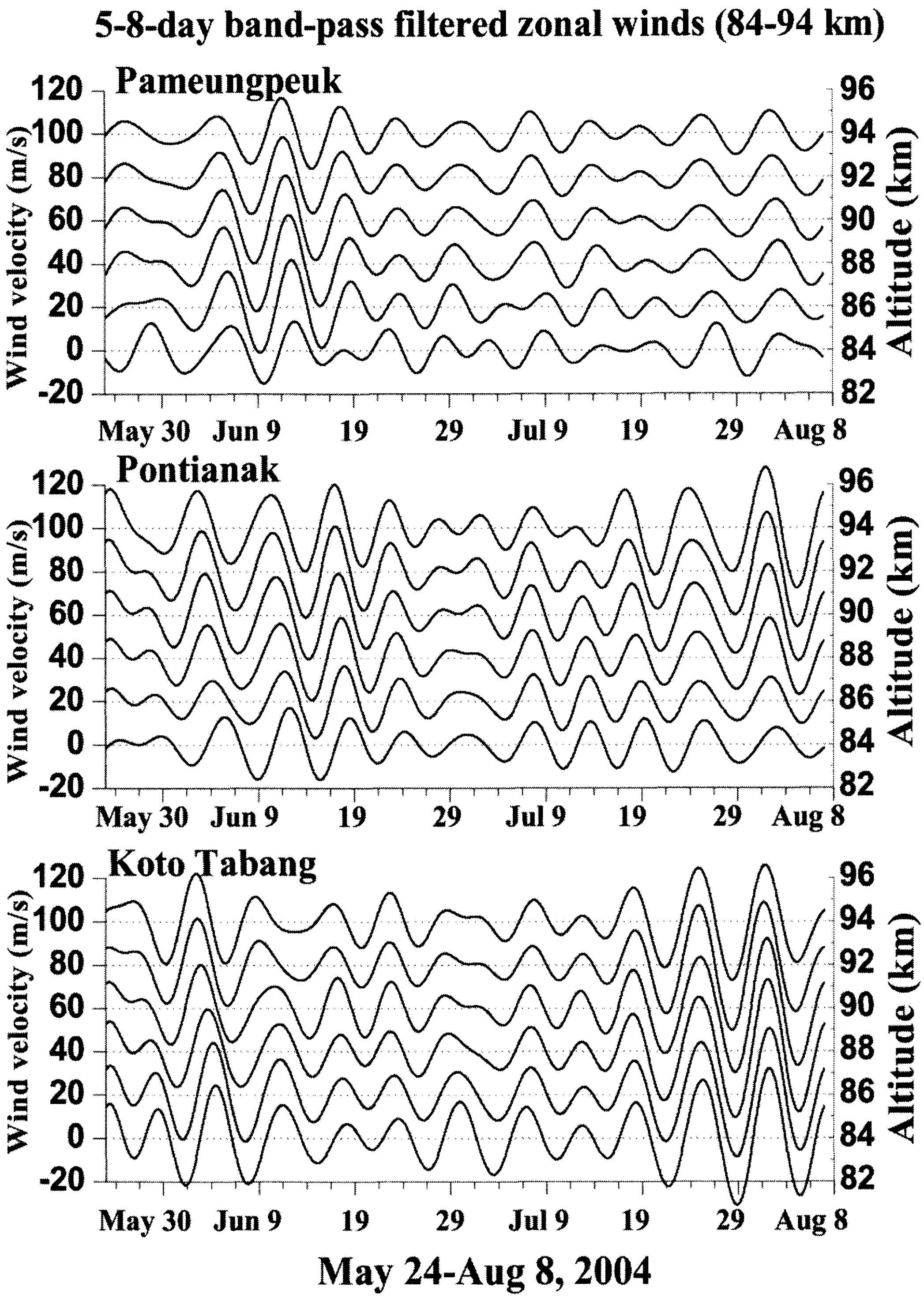


Fig. 4. 5–8-day band pass filtered zonal winds at 84–94 km over Pameungpeuk (top panel), Pontianak (middle panel) and Koto Tabang (bottom panel).

at 88–90 km, is found to be 45° eastward from Pontianak to Pameungpeuk. It may be noted that the amplitudes of the theoretical Rossby (1,1) mode corresponding to the wave under consideration show maximum simultaneously at all latitudes for a given longitude (Matsuno 1966). However, the HRDI results show that there could be steep variation of phase of the wave across latitudes (~50° phase difference in latitudes 10°S-EQ) as inferred from the top panel of Fig. 3 in Lieberman et al. (2003), which shows eastward tilt of a similar degree for wind velocities and westward tilt in temperature field. It is noteworthy that the HRDI observa-

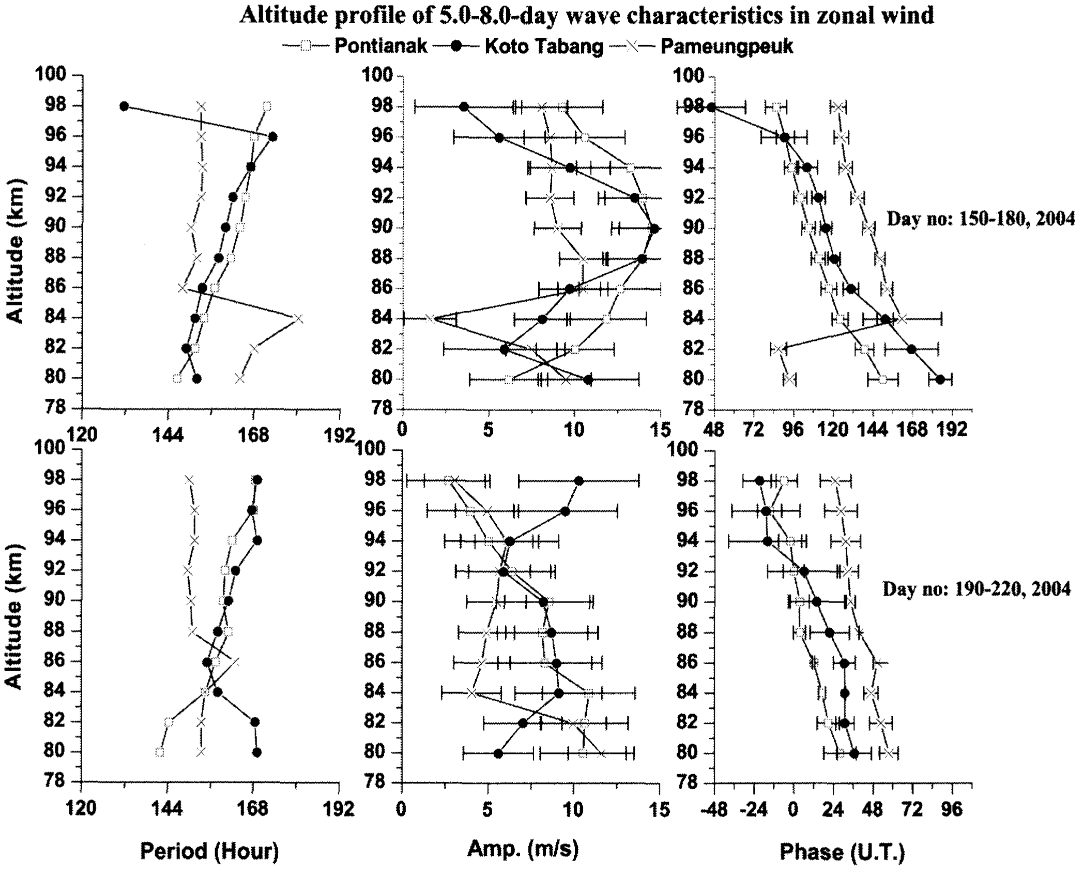


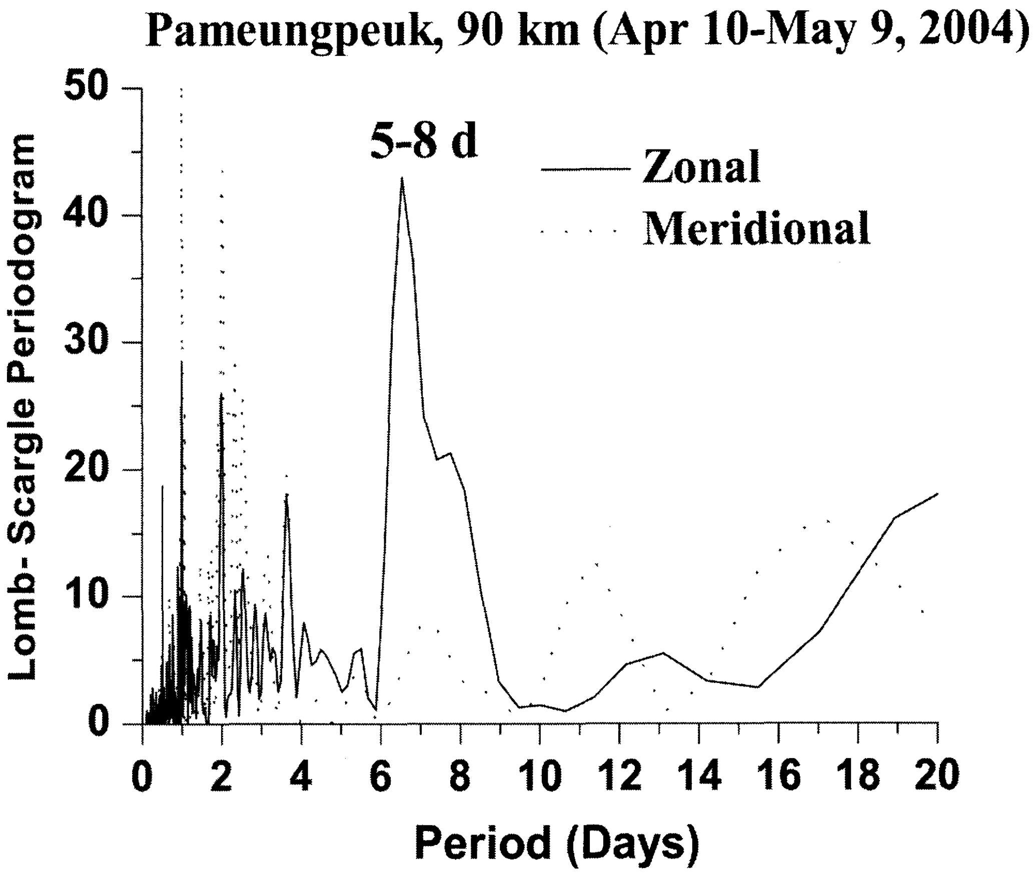
Fig. 5. Altitude profile of period of the wave in zonal wind estimated by residual sum of squares method (left panels); Amplitude of the wave corresponding to dominant period at each site (middle panels); Phase of the wave determined by fixing period of the wave equal to 156 hours (6.5-days) (right panels).

tion is a satellite board measurement with a global coverage but a longitudinal sampling is coarse (~30 deg interval), and the radar network in the present study is with a small spacing of about 8–9 degrees. As both of these global and regional observations show very similar spatial structure, this suggests that the observed horizontal map of the 6.5-day wave shown in Lieberman et al. (2003) is a pretty robust structure. Besides, the above results of coincidence of horizontal structures between the different techniques suggest that the regional network of radars around the equator have a capability of studying horizontal structure of the waves very well, despite the systems are different at three locations.

3.4 The 5–8-day wave activity during second half of CPEA campaign period (10 April–9 May, 2004)

The analysis of winds and temperature observed by the radiosondes show the presence of 7-day wave in the upper troposphere and lower stratosphere (UTLS) region. The wave is found to be an eastward propagating Kelvin wave with predominant zonal wave number 3. Since tropical convection is considered as source for Kelvin waves, OLR (Outgoing Longwave Radiation) data, which is proxy for tropical convection, are subjected to space-time Fourier analysis and the result shows that 7-day periodicity is present in OLR with zonal wave number 3. This shows that tropical convection generates 7-day wave, which can propagate vertically to lower stratosphere. These results are described in Sridharan et al. (2006).

In order to investigate the wave activity in the MLT region during the second half of CPEA campaign period (10 April–9 May 2004), due to non-availability of data over Koto Tabang and poor data quality over Pontianak during this period, a separate analysis of the MLT winds only over Pameungpeuk is carried out. The 5–8-day wave is dominantly present in



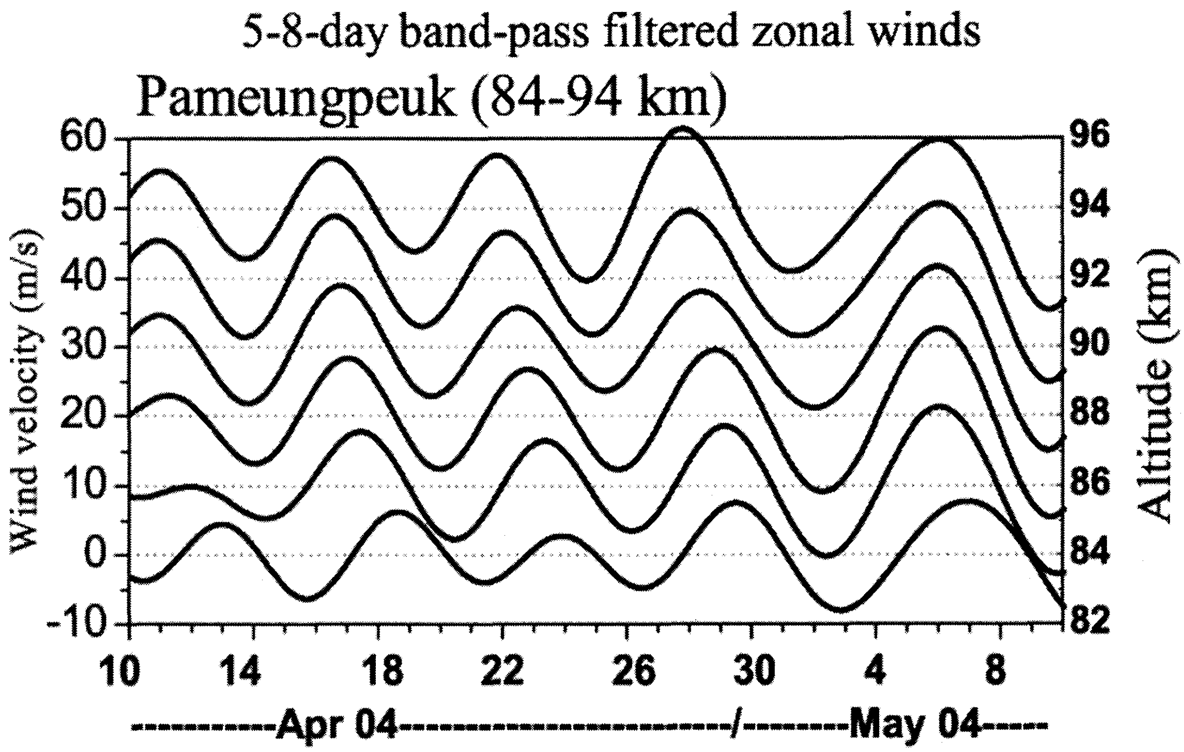


Fig. 6a. Lomb-Scargle periodogram of zonal wind (solid curve) and meridional wind (dashed curve) at 90 km for April 10–May 9, 2004.

Fig. 6b. 5–8-day band-pass filtered zonal winds over Pameungpeuk for the altitudes 84–94 km and for April 10–May 9, 2004.

zonal wind during this period, as it is clearly inferred from the Fig. 6a, which shows Lomb-Scargle periodogram of zonal and meridional winds at 90 km altitude. In meridional winds, the amplitude is much smaller. Figure 6b shows 5–8 day band-pass filtered zonal winds for the altitudes 84–94 km and for the period April 10–May 9, 2004. It can be observed from the figure that the wave is present with large amplitudes at all altitudes and in particular, during the second half of CPEA campaign period. The general character of the wave in zonal wind is summarized below. The amplitude of the wave reaches maximum value of 10 m/s at 90 km. The period of the wave is close to 6.4 days. The downward phase propagation is observed indicating upward energy propagation of the wave. The vertical wavelength estimated from the phase variation with altitude is ~45 km. From the comparison of the phase profile of the wave over Pameungpeuk with that over Tirunelveli (8.7°N, 77.8°E), an MF radar site located in the tip of Indian peninsula, we could infer that the wave is westward propagating (not shown).

4. Discussions and conclusion

The characteristics of the wave having period close to 5–8-days in Mesosphere and Lower Thermosphere over Indonesia are reported in the present work. The wave activity is larger in zonal wind than in meridional wind and it maximizes before and after the northern hemispheric spring equinox of the year 2003. The wave amplitude is larger over the equatorial sites. These results are consistent with the earlier observations (Talaat et al. 2001). The phase of the wave over Pontianak leads that of Koto Tabang, indicating that the wave is a westward propagating wave with zonal wave number 1, consistent with earlier observations (Kovalam et al. 1999). Besides, the wave is present with larger amplitudes in June–August 2004, during which the wave activity over the equatorial sites, Koto Tabang and Pontianak show similar characteristics with altitude. The vertical wavelength of the wave over the three sites, on an average is ~50 km. Kovalam et al. (1999) estimated vertical wavelength of 5–8-day wave as ~60 km for a different observation period. There is a steep variation of phase of the wave with latitude, contrary to the theoretical picture of the wave, but consistent with earlier observations (Lieberman et al. 2003), though it may be partly due to change in the dominant period of the wave across the latitudes. During second part of CPEA campaign period (April 10–May 9, 2004) also, the 5–8-day wave is observed with larger amplitudes in zonal wind over Pameungpeuk, however with slightly shorter vertical wavelength of ~45 km.

According to a few earlier observations and also in our present study, the 5–8-day wave activity in the MLT region propagates westward with zonal wave number 1 (Meyer and Forbes 1997; Kovalam et al. 1999; Talaat et al. 2001). It is interesting to note that a wave of similar periodicity is observed in the upper troposphere and lower stratosphere (UTLS) region during second half of CPEA campaign period (Sridharan et al. 2006), but it is different in the sense of its phase propagation (eastward propagating). The presence of eastward propagating wave in the UTLS region and westward propagating wave in the MLT region as observed in the present study can be explained using Gill's pattern. Earlier, Matsuno (1966) showed the existence of a series of equatorial modes as the response to the sinusoidal mass or heat input along the equator. Gill (1980) extended his study to the steady response to a equatorial heat source with finite area and obtained "Gill's pattern", i.e., the Kelvin wave-type response to the east and the Rossby wave type to the west of the heat source. The tropical convective heating in the lower atmosphere generates both eastward propagating Kelvin waves and westward propagating waves of similar periodicities. In the lower atmosphere, the Kelvin wave component could be so dominant that the westward propagating component need not appear in the power spectrum. Since the QBO in the stratosphere has been in eastward phase during the campaign period, the eastward propagating Kelvin wave component might have undergone damping or critical level absorption, while the background wind condition would have been favorable for the westward propagating component to reach MLT altitudes.

Acknowledgments

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