Journal of the Meteorological Society of Japan, Vol. 72, No. 6, pp. 859–872, 1994

Short-Period Disturbances in the Equatorial Lower Stratosphere

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(Manuscript received 25 April 1994, in revised form 21 September 1994)

Abstract

Temperature and horizontal wind fluctuations with periods shorter than 3 days in the equatorial lower stratosphere are examined by using data from routine rawinsonde observations at Singapore (1N, 104E) during 1978–1993. Internal wave-like structures having a period of about 2 days and a short vertical wavelength of 5 km are occasionally observed both in temperature and wind fluctuations. The result of power spectral analysis indicates that short-period fluctuations have significant energy, separated from Kelvin waves and mixed Rossby-gravity waves.

Long-term variations of the spectral characteristics are investigated in relation to the quasi-biennial oscillation (QBO). Zonal wind and temperature variances due to the short-period fluctuations are generally large and particularly enhanced in the QBO phase when the direction of mean wind changes from easterly to westerly. Co-spectra of temperature and zonal wind fluctuations at short periods are significantly larger than the quadrature spectra, and the sign of co-spectra changes according to the phases of the QBO. These results indicate strong connection of the short-period disturbances with the QBO.

1. Introduction

It is well known that there are dominant planetary-scale waves trapped in the equatorial regions. Mixed Rossby-gravity waves, which were firstly documented by Yanai and Maruyama (1966), propagate westward with a period of about 4–5 days and a zonal wavelength of about 10,000 km. Another well-known planetary-scale wave, named the Kelvin wave, which was reported first by Wallace and Kousky (1968a), migrates in the opposite direction, eastward. A typical period and zonal wavelength are about 15 days and 20,000–40,000 km, respectively. Kelvin waves and mixed Rossby-gravity waves are identified on an equatorial beta plane derived by Matsuno (1966) as an $n = -1$ mode and an $n = 0$ mode of oscillation, respectively. Since upward transport of zonal momentum of these waves is considered to be essential to the mechanism of the QBO, a lot of effort was devoted to studies of the wave characteristics and generation mechanism. Statistical studies showed that amplitude variations of Kelvin waves and mixed Rossby-gravity waves in the lower stratosphere are synchronized with the QBO (Wallace and Kousky, 1986b; Maruyama, 1969; Maruyama, 1991; Shiotani and Horinouchi, 1993; Dunkerton, 1993). Such studies should be extended to other wave modes having shorter periods in the equatorial region, since the importance of gravity waves for the mechanism of the QBO is suggested by the numerical models of Takahashi and Holton (1991).

Gravity waves in the extra-tropical latitudes have been vigorously examined for the last decade in terms of structure, propagation direction, sources, and seasonal variation, with the aid of recently-developed observation tools such as VHF/UHF Doppler radars, lidars, radiosondes, and rockets (*e.g.*, Hirota, 1984; Kitamura and Hirota, 1989;

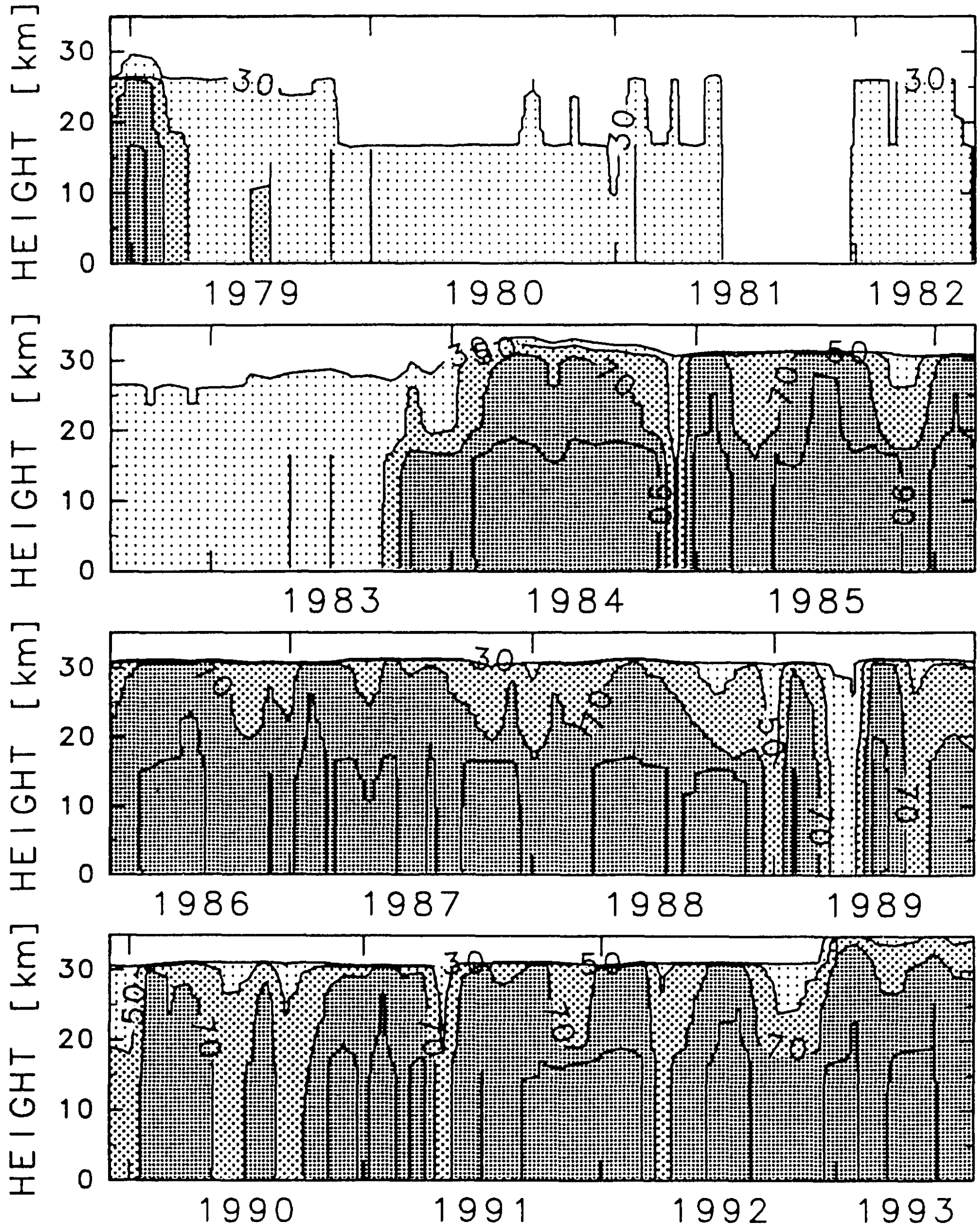

Fig. 1. A contour map of percentage of available data with respect to twice-daily sampling in a time-height section. The percentage is obtained for each height and month. Contour intervals are 20 %.

Sato, 1994) providing data with fine resolution and excellent accuracy. Through these observational studies, it is strongly confirmed that the gravity waves play an important role in global-scale atmospheric circulations (Tsuda *et al.*, 1990; Sato, 1994). In the equatorial region we can also expect intensive short-period disturbances which are mainly generated by vigorous convections over the ocean.

Cadet and Teitelbaum (1979) made a pioneering study of inertia-gravity waves in the tropical stratosphere using radiosondes launched at an interval of 3 h on a stationary-positioned satellite tracking ship for four days of the GARP Atlantic Tropical Experiment (GATE). They reported wavelike disturbances having a period of 35 h and a vertical wavelength of about 5 km. Their argument that the propagation of waves is westward, judged from the rotation of wind vector with time is wrong, however. It is shown theoretically that the wind vector rotates clockwise (anti-clockwise) in the northern (southern) hemisphere, regardless of the propagation direction (Gill, 1982). In order to estimate the horizontal propagation direction from data at one location, we need other information on the vertical wind or temperature component of the waves (Kitamura and Hirota, 1989; Sato, 1994). Another campaign observation

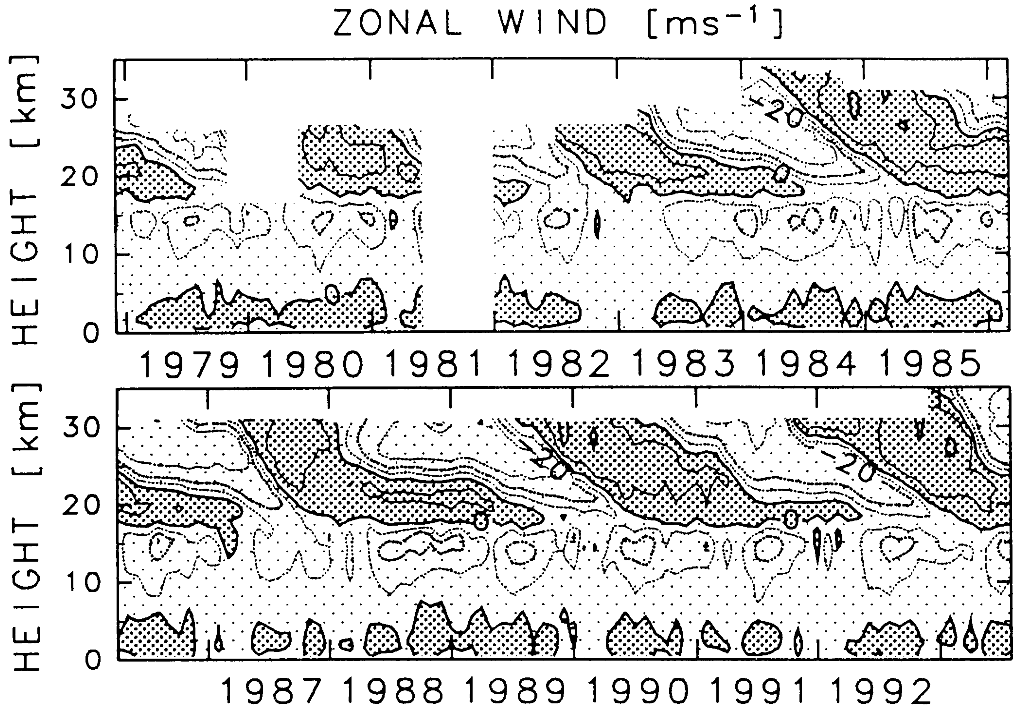

Fig. 2. A time-height section of monthly-averaged zonal wind. The contour intervals are 10 m s^{-1}. Westerly wind regions are darkly hatched. Contours of negative values are dotted.

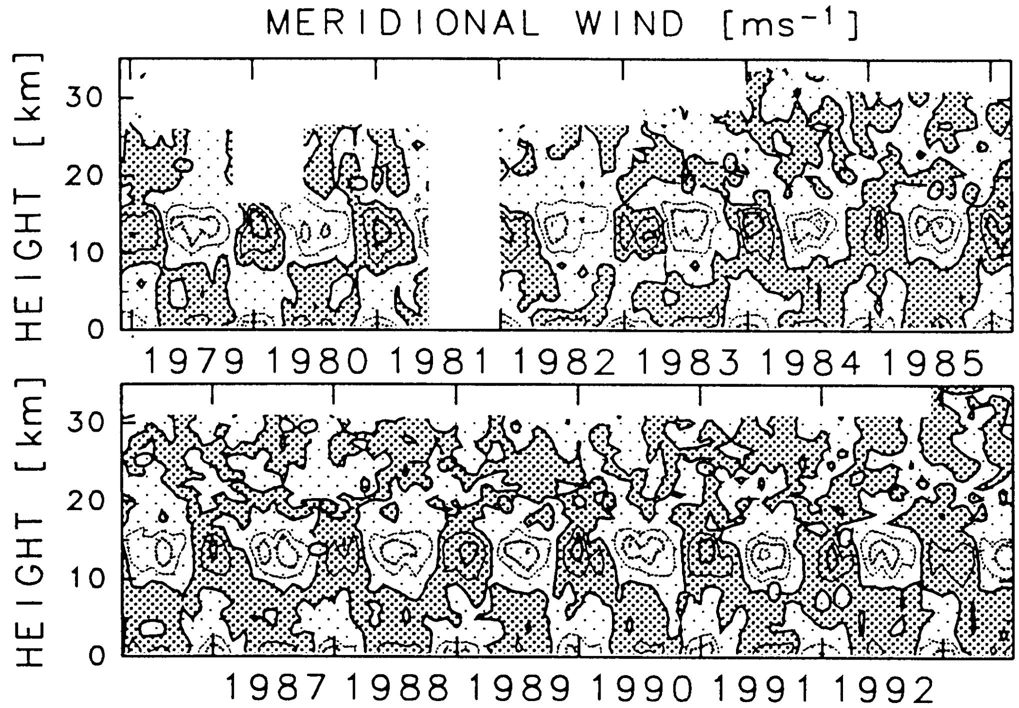

Fig. 3. A time-height section of monthly-averaged meridional wind. The contour intervals are 3 m s^{-1}. Northward wind regions are darkly hatched. Contours of negative values are dotted.

using radiosondes was made in East Java Indonesia by Tsuda *et al.* (1994) for 24 days during a QBO phase when the mean zonal wind changed from easterly to westerly. Dominant vertical wavelengths were 2–2.5 km in the lower stratosphere. It was inferred from the phase relations among horizontal wind and temperature components that most of the inertia-gravity waves propagate eastward. Very recently, Maruyama (1994) made a statistical study on short-period waves using Singapore rawinsonde data obtained over ten years. It was shown that vertical flux of zonal momentum associated with the waves was enhanced in the lower stratosphere when the mean zonal wind changes from easterly to westerly.

In the present study, we use Singapore data obtained over a ten-year period to make an analysis from a viewpoint different from Maruyama (1994). First we show an internal wave-like structure observed in short-period fluctuations in the lower stratosphere. Through a power spectral analysis, the dominance of short-period disturbances is examined over a wide spectral range including Kelvin waves and mixed Rossby-gravity wave components. Long-term variation of power and cross spectra of wind and temperature fluctuations related to the QBO is also described, to enable discussion of the characteristics of short-period disturbances.

2. Data description

We used horizontal wind and temperature data from rawinsondes launched at Singapore (1N, 104E) from December 1978 to August 1993. The observations were routinely made twice daily after November 1983 (00Z and 11Z before 1984, and 00Z and 10Z after 1985), while the frequency of observation was once a day before. Since short-period fluctuations may have short vertical wavelengths, data at significant levels as well as at standard pressure levels are examined. A geopotential height (hereafter simply referred to as height) h_s at a significant level p_s is estimated using heights h_1 and h_2 at two standard pressure levels of p_1 and p_2 nearest p_s ($p_1 > p_s > p_2$):

$$h_s = \frac{\ln p_1 - \ln p_s}{\ln p_1 - \ln p_2}(h_2 - h_1) + h_1. \tag{1}$$

After doubtful data are removed, we obtained data with the same height intervals of 500 m, roughly corresponding to the original vertical resolution, after a linear interpolation. Further, the time series with a fixed interval of 12 h are made, ignoring the difference of 1–2 h of observation time from 12Z.

The percentage of available data with respect to twice-daily sampling for each month and height is shown in Fig. 1 as a contour map. More than 50 % data are available for the height region up to 30 km for most periods after 1984. Thus the spectral analysis is made only for 1984–1993.

3. Background wind fields

Figure 2 presents the monthly average of zonal winds in a time-height section. The QBO is clearly observed above the tropopause height ($\approx$17 km). The vertical transition near the tropopause from an easterly wind region in the troposphere to the QBO region in the stratosphere is very sharp. It is noted that there are four cycles of the QBO in the period from 1984 to 1993 for which the spectral analysis is made. A time-height section for the monthly-mean meridional wind is shown in Fig. 3. An annual cycle in the meridional wind is clear in the troposphere, reflecting the north-south shift of the Hadley cell with season, while no significant variation is observed in the stratosphere. The upper and lower meridional flows are centered at a height of 14 km and near the ground, respectively, having peak values of about 10 m s^{-1}.

4. The presence of short-period disturbances

First we made a time-height section of temperature (T) and horizontal wind (u, v) fluctuations having periods shorter than 3 days using a high-pass filter. We removed tidal components by processing the time filter separately for two time series of data at 00Z and 12Z.

Internal wave-like structures are occasionally observed in a time-height section of the short-period fluctuations. Figure 4 shows a typical example of the wave-like fluctuations observed in February 1985. Clear downward propagation of phases is observed in all of the zonal (u) and meridional (v) wind, and temperature (T) components in the stratosphere. The wave period is about 2–3 days and the vertical wavelength is about 5 km. Note that the wave structure in the T component is contaminated by fluctuations having shorter wavelengths, which may due to different vertical resolution between temperature and wind measurements by radiosondes. The downward phase propagation implies that the waves propagate energy upward. This is true, of course, only when the Doppler effect of the background wind is not strong enough to make the direction of intrinsic phase speed opposite to the ground-based phase speed.

Next we examine frequency power spectra as a function of height so as to compare the intensity of the short-period fluctuations with those of Kelvin waves and mixed Rossby-gravity waves. Power spectra are calculated with a Blackman-Tukey method for data series of three months around each month at each height in 1984–1993, only when more than 50 % data are available. Note that available data are more than 70 % for almost half of the period of 1984–1993 and that 50 % does not imply once-daily coverage. Missing data are distributed at random in time, so that we can obtain meaningful spectra at periods below 2 days. Figure 5 shows the ten-year average of the spectra for each component in an energy content form.

In the troposphere, spectral amplitudes of u components are dominant at periods longer than 10 days, which may be due to Kelvin waves, because the period is about the same as that of stratospheric Kelvin waves and there is no corresponding peak in the v spectra. A peak is observed in v spectra

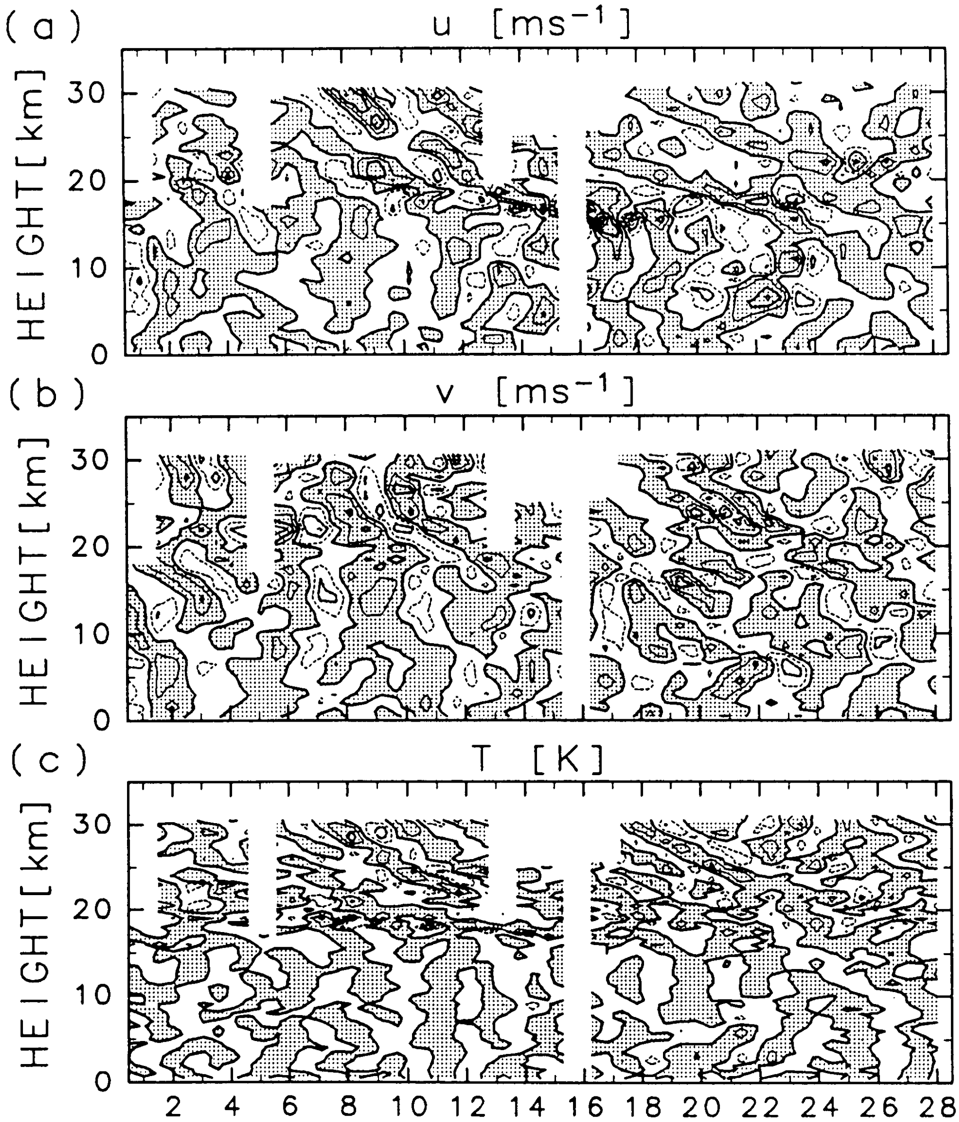

Fig. 4. Time-height sections of short-period fluctuations for (a) u, (b) v, and (c) T components for February 1985. The contour interval is 2 m s^{-1} for (a) and (b) and 1 K for (c). Positive regions are hatched.

around a period of 5 days, which may be due to mixed-Rossby gravity waves, since the period correspons to that of stratospheric mixed-Rossby gravity waves and there is no corresponding peak in the u spectra. The spectral amplitudes at the peaks of the u and v components are large around the tropopause ($\approx$17 km). Dominance of about 10-day period components is also observed in the T spectra around or just above the tropopause, though there are no significant peaks at long periods in the troposphere.

In the stratosphere, peaks of u and T spectra are shifted to shorter periods. The peaks for u and T components are located at 9 days at 20 km and 6 days at 30 km, corresponding to Kelvin waves. Peaks around 5 days in the v spectra observed in the troposphere disappear in the stratosphere and components of 3–4 days are dominant, corresponding to mixed Rossby-gravity waves. The period of the mixed Rossby-gravity waves seems to decrease with height. This feature is consistent with the result by Dunkerton (1993) based on rawinsonde data at several locations over the tropical pacific. Noteworthy is that spectral amplitudes at periods shorter than 2–3 days are as large as those of the long-period components due to Kelvin waves and mixed Rossby-gravity waves. Therefore, the short-period disturbances may play an important role in momentum transport in the stratosphere.

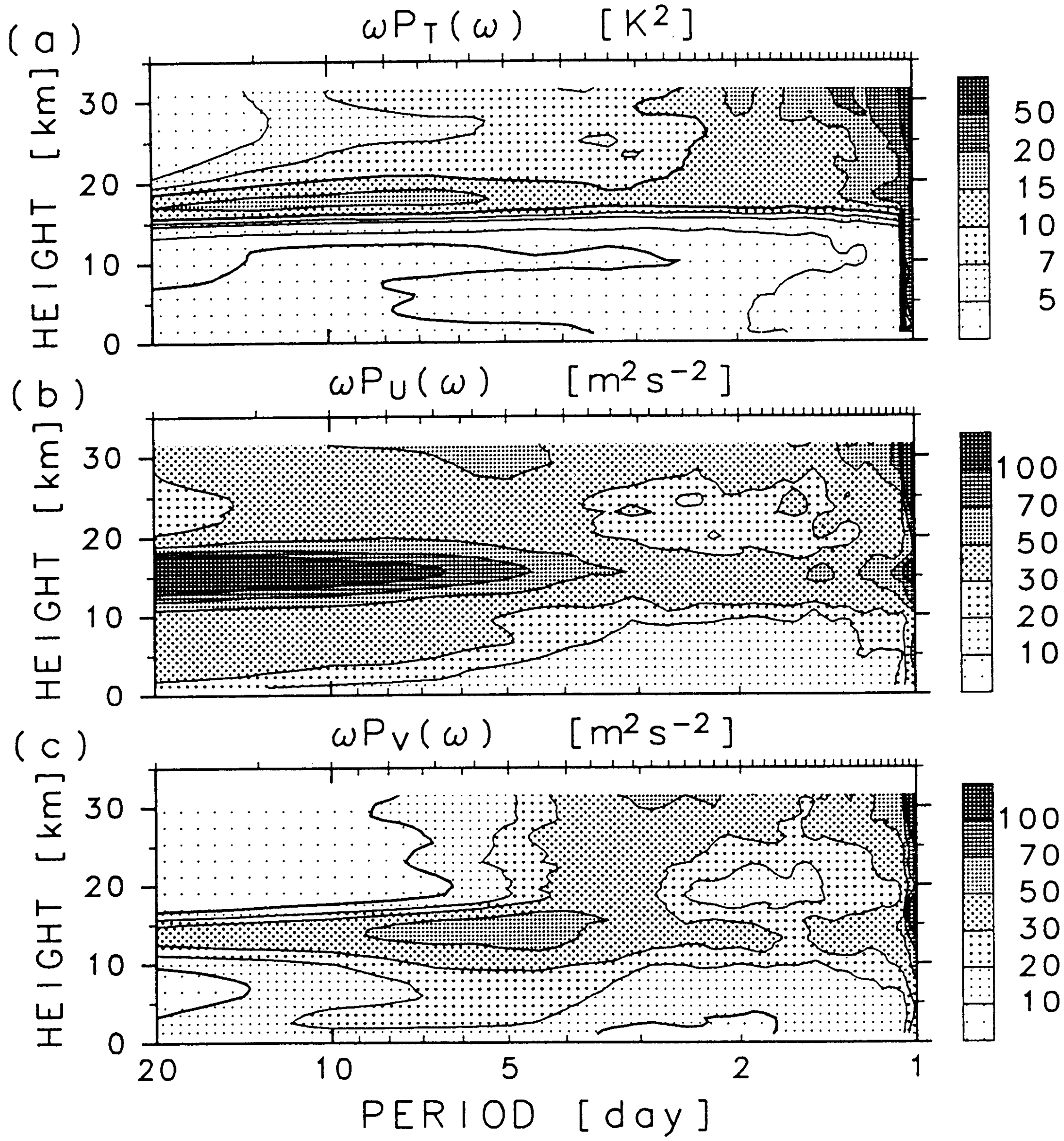

Fig. 5. Power spectra of (a) T, (b) u, and (c) v fluctuations as a function of height in an energy content form averaged for the whole period of 1984–1993. Units of the contours are K^2 for (a) and m^2s^{-2} for (b) and (c).

5. Spectral characteristics synchronized with the QBO

5.1 Power spectra

Power spectra in an energy content form averaged for a height region of 20–24.5 km in the lower stratosphere for T, u, and v fluctuations are shown as a function of time in Fig. 6. To make it easy to look at the relation with the QBO, we smoothed the dynamic power spectra using a low-pass filter with a cutoff length of 15 months. A thick curve indicates the mean zonal wind for the same height region whose scale is denoted by the right axis. Peaks in the T and u spectra appear regularly around a period of 10 days, corresponding to Kelvin waves, when the direction of zonal wind changes from easterly to westerly (hereafter we refer to this time period as the EW time period). Enhancement of T and u spectral amplitudes in EW time periods is also observed at periods shorter than 2.5 days. There are dips in the spectra between the long- and short-period ranges, indicating that large variances at short periods are not due to contamination of the peaks of long-period Kelvin waves. On the other hand, v spectra have peaks at periods of 4 days at the beginning of the time period when the direction of zonal wind changes from westerly to easterly (WE time period). Spectral enhancement is observed for a shorter-period region of around 3 days, although

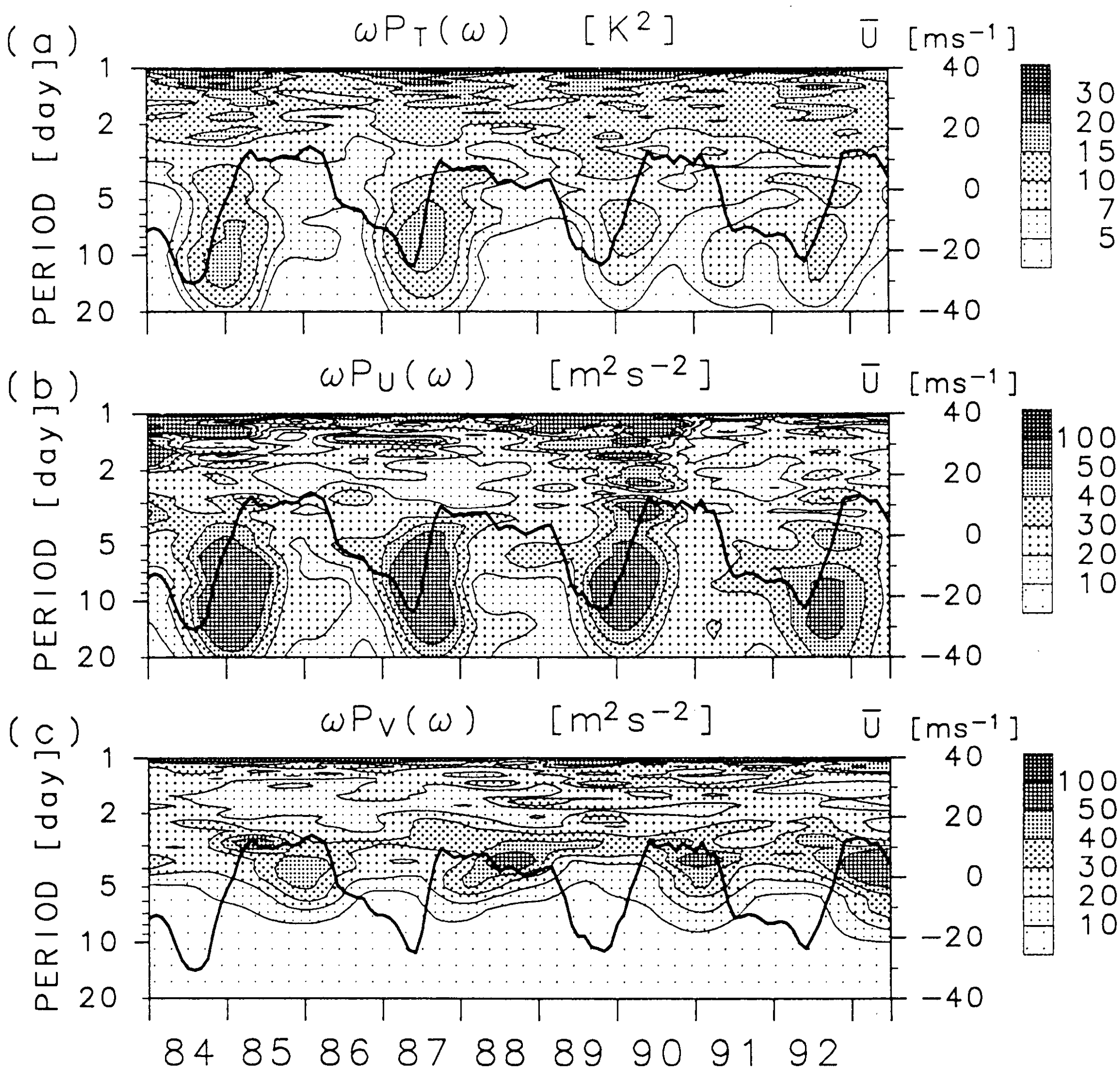

Fig. 6. Power spectra of (a) T, (b) u, and (c) v fluctuations averaged for a height region of 20–24.5 km as a function of time. Units of the contours are K^2 for (a) and m^2s^{-2} for (b) and (c). Thick curves show monthly-mean zonal winds averaged for the same height region.

the occurrence precedes slightly that of the 4-day period component. The QBO modulation is not observed at periods shorter than 2 days in the v spectra. Those features in power spectra for a height region of 20–24.5 km are also observed for an upper height region of 25–30 km (now shown).

As found from Fig. 2, phases of the QBO propagate downward. Variances of T and u components having periods of 8–20 days (Kelvin waves), are plotted in the time-height sections of Figs. 7a and 7b, respectively. Enhancement of variances in EW time periods is clearly observed at each height, which is examined by Shiotani and Horinouchi (1993) in terms of the damping of Kelvin waves modulated by the mean wind. This feature is consistent with the acceleration of the westerly mean wind of the QBO due to the convergence of Eliassen-Palm (E-P) flux associated with Kelvin waves (Holton and Lindzen, 1972). Time-height sections for the short-period disturbances are shown in Figs. 7c and 7d. Enhancement in EW time periods is also clear, suggesting connection between the QBO and short-period disturbances. It is worth noting that the variances of short-period T and u fluctuations are of the same order of those for Kelvin waves. The T variance for the short-period range is maximized around 30 km, while the Kelvin wave variance is large at lower stratospheric levels, suggesting different characteristics of vertical propagation.

Figure 8a is a time-height section of variances of a v component with periods of 3.3–5 days, which are considered to be due to mixed Rossby-gravity waves. Enhancement synchronized with the QBO is observed in WE time periods, in contrast to the case of Kelvin waves. This is again consistent with Holton and Lindzen's QBO theory in the sense that

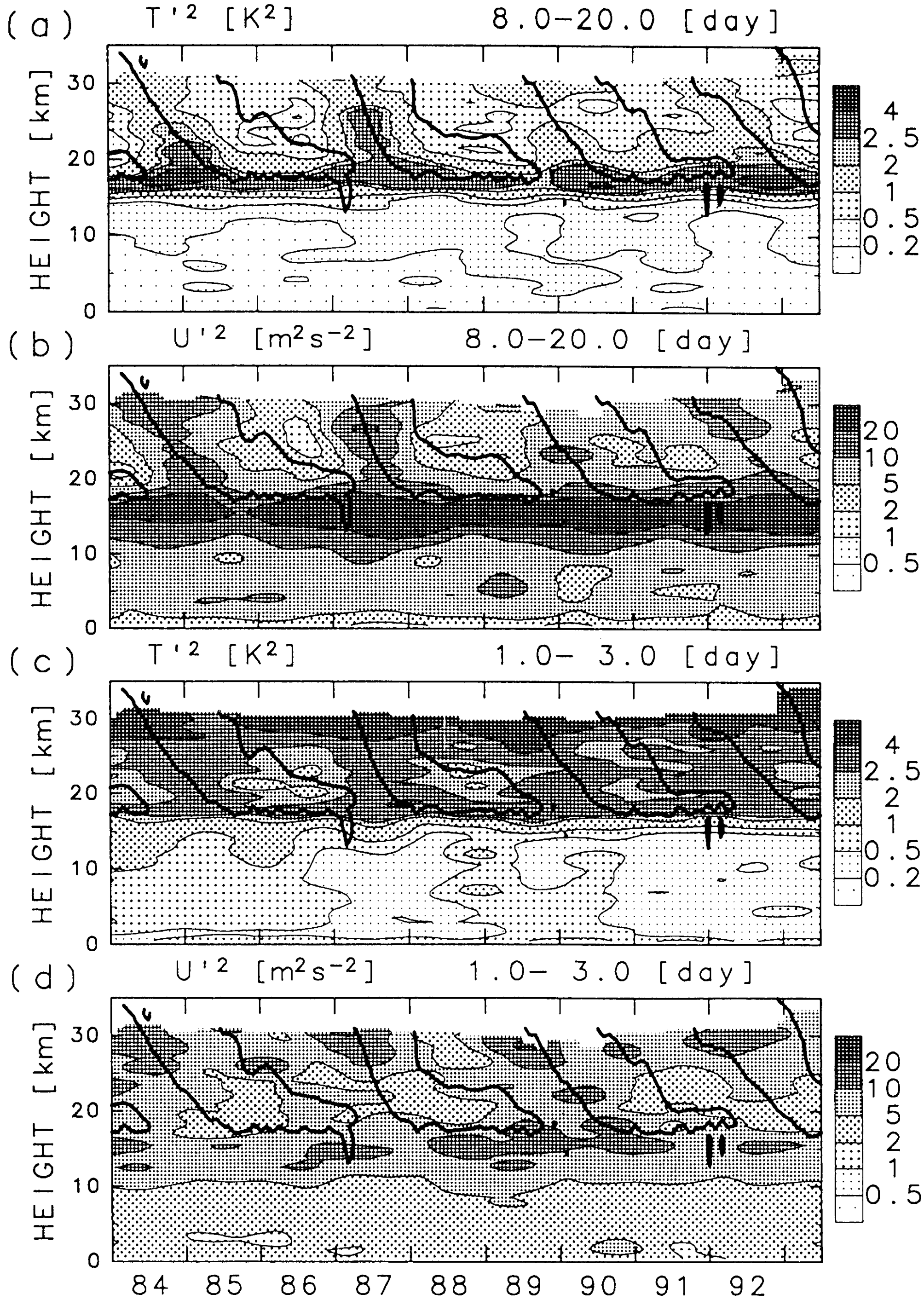

Fig. 7. Time-height sections of variance due to (a) T and (b) u fluctuations with periods of 8–20 days, and (c) T and (d) u fluctuations with periods of 1–3 days. Units of contours are K^2 for (a) and (c) and m^2s^{-2} for (b) and (d). Note that scales are taken to be the same for the same quantities. Thick curves trace zero values of monthly mean zonal wind.

easterly wind acceleration is due to the convergence of EP flux associated with mixed Rossby-gravity waves. It is clear that the region of large variance lowers following downward QBO phase motion. Since v disturbances have shorter periods at upper levels (Fig. 5), the precedence of shorter-period components observed in the dynamic power spectra of Fig. 6 corresponds to the precedence of the upper-level disturbances. On the other hand, v components with periods of 1–3 days have no significant variation associated with the QBO (Fig. 8b).

Next we examine the difference in disturbance in-

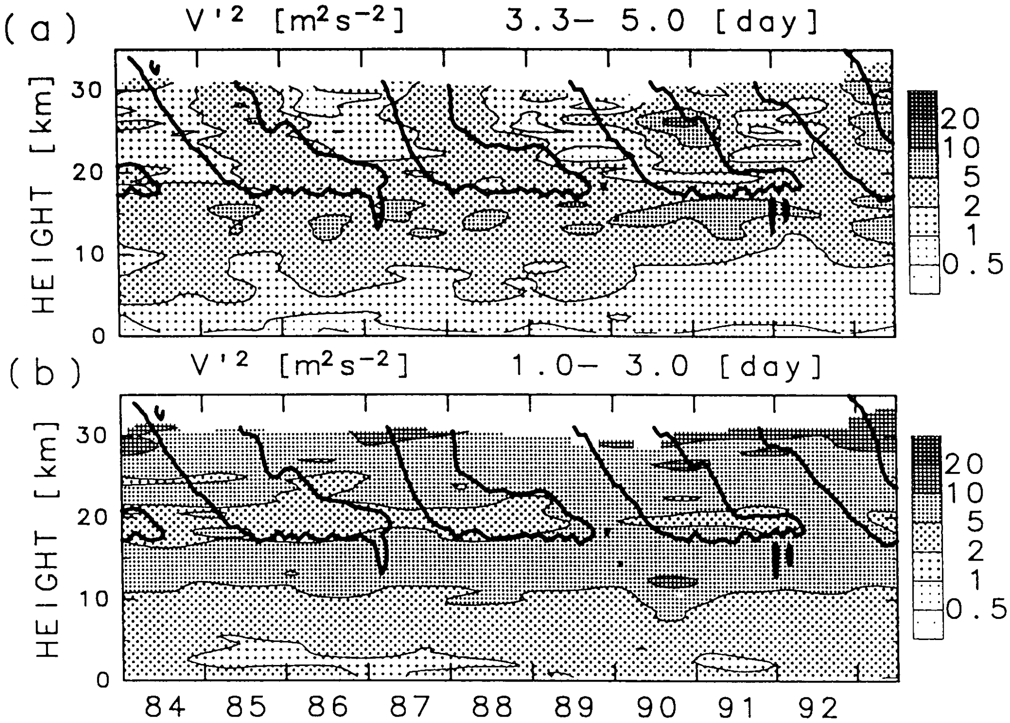

Fig. 8. Time-height sections of variance due to v fluctuations with periods of (a) 3.3–5 days and (b) 1–3 days. Units of contours are m^2s^{-2}. Thick curves trace zero values of monthly mean zonal wind.

tensity over a wide range of frequencies between EW and WE time periods. We obtained power spectra for EW (WE) time periods as a function of height by averaging spectra for periods between negative (positive) and positive (negative) peaks of the QBO of the mean zonal wind at each height. Figure 9 is a plot of the mean spectra for T fluctuations in an energy content form as a function of height. For EW time periods spectral densities are maximized in two regions of periods around 4–10 days and shorter than 3 days. For WE time periods the variance of longer-period components is very small, and large spectral densities are observed only at shorter periods. Although the variance of short-period components is smaller in WE time periods than in EW time periods, the variance in WE time periods is still large and the difference from the variance in EW time period is only about 30 %. Therefore, the short-period disturbances cannot be ignored even in WE time periods.

5.2 Cross spectra

Next we make an analysis of cross spectra to see the structure of the disturbances. Maruyama (1994) estimated the vertical flux of zonal momentum ($\overline{u'w'}$) associated with 2-day-period disturbances from the covariance of u and dT/dt in the sense that dT/dt is proportional to $-w$, where t is time and w is the vertical component of winds. Assuming that the 2-day-period disturbances are due to short-period Kelvin waves, and ignoring the Doppler effect of the mean wind, almost the same magnitude of momentum flux was obtained as that of long-period Kelvin waves in EW time periods. We examined quadrature spectra $Q_{Tu}(\omega)$ of T and u, which can be regarded as the covariance of u and dT/dt for fluctuations having an observed frequency of ω. The $Q_{Tu}(\omega)$ values are related to $\overline{u'w'}$ according to

$$\overline{u'w'} = -(R\hat{\omega}/HN^2)Q_{Tu}(\omega), \tag{2}$$

where primes indicate the fluctuation components, R the gas constant for dry air, H the scale height, N the Brunt-Väisälä frequency, and $\hat{\omega}$ the intrinsic frequency (Maruyama, 1968). We also examined co-spectra $C_{Tu}(\omega)$ of T and u components, which have not been examined in the previous studies even for the long-period range of Kelvin waves.

The cross spectra averaged for a height region of 20–24.5 km are presented as a function of time in Fig. 10. The same smoothing as for the dynamic power spectra was made for the dynamic cross spectra. The values of $Q_{Tu}(\omega)$ are generally negative at periods longer than 2 days (Fig. 10a). In particular, clear negative peaks in EW time periods are dominant around a period of 10 days, which corresponds to positive $\overline{u'w'}$ associated with Kelvin waves propagating energy upward. Large magnitude of $Q_{Tu}(\omega)$ values is confined in a period region longer than 3 days. The negative weak peaks in EW time peri-

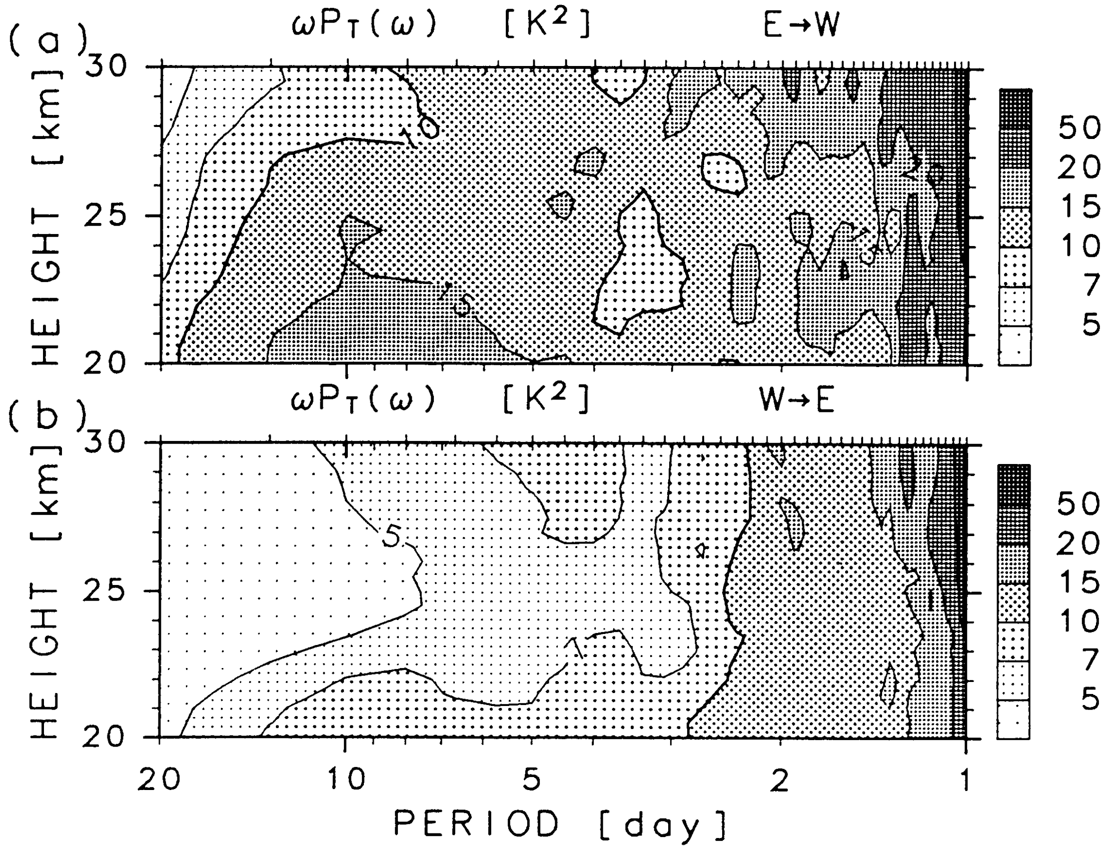

Fig. 9. Power spectra of T fluctuations in an energy content form averaged for (a) EW and (b) WE time periods. Units of contours are K^2.

ods are also observed around a period of 2 days, in agreement with the analysis of Maruyama (1994). The synchronization with the QBO is hardly recognizable in $Q_{Tu}(\omega)$ values for periods shorter than 2 days.

On the other hand, $C_{Tu}(\omega)$ values are significantly synchronized with the QBO in the whole period region (Fig. 10b). In the Kelvin wave region, positive peaks are observed in EW time periods, while the values in WE time periods are negative and weak. At periods shorter than 3 days, positive and negative peaks having almost the same magnitudes alternately appear in EW and WE time periods, respectively. This suggests that the short-period disturbances have different characteristics between EW and WE time periods, while the variances are large both in EW and WE time periods (Fig. 9).

Integrations of $C_{Tu}(\omega)$ and $Q_{Tu}(\omega)$ for a short-period region of 1–3 days, which are hereafter respectively referred to as $C(Tu)$ and $Q(Tu)$, are plotted in time-height sections in Fig. 11. It is clear that positive and negative $C(Tu)$ peaks propagate downward synchronized with the QBO, while no distinct QBO signal is observed in the $Q(Tu)$ profile. The magnitude of $C(Tu)$ is significantly larger than that of $Q(Tu)$.

Cross spectral analysis was also made for pairs of T and v components and of u and v components. However, there are not such notable features as observed in cross spectra of T and u components.

6. Discussion

6.1 Non-zero correlation between u and T fluctuations

It is difficult to explain the results of cross spectral analysis, even for the frequency region of well-known Kelvin waves, by only the simple theory of neutral equatorial waves in a constant background wind field as described in several standard textbooks (*e.g.*, Andrews *et al.*, 1987). Kelvin waves in a constant background wind have T and u components which are connected through a polarization relation:

$$T' = \frac{H\hat{\omega}}{Rk}\left(\frac{1}{2H} + im\right)u', \tag{3}$$

where k and m is the zonal and vertical wavenumbers, respectively, and primes indicate fluctuation components. Equation (3) implies the relation between $C_{Tu}(\omega)$ and $Q_{Tu}(\omega)$:

$$C_{Tu}(\omega) = \frac{Q_{Tu}(\omega)}{2Hm}. \tag{4}$$

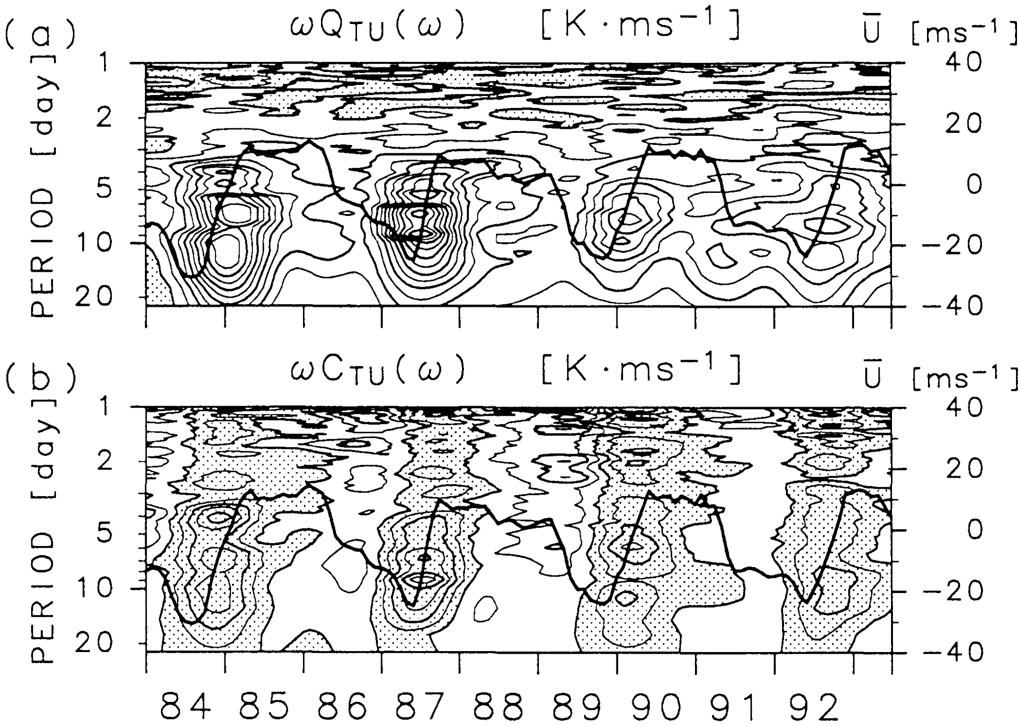

Fig. 10. (a) Quadrature spectra $Q_{Tu}(\omega)$ and (b) co-spectra $C_{Tu}(\omega)$ in a flux content form averaged for a height region of 20–24.5 km of T and u fluctuations. Contour intervals are 2.5 K m s^{-1}. Thick curves show monthly-mean zonal wind averaged for the same height region. Areas with positive values are shaded.

Since Kelvin waves propagate eastward, $Q_{Tu}(\omega)$ should be negative so that $C_{Tu}(\omega)$ must be positive, which is consistent with the sign observed in EW time periods (Fig. 10). Here we assumed upward energy propagation ($m < 0$). Using (4) we can estimate the vertical wavelength λ_z ($= 2\pi/|m|$). Since the ratio of $|Q_{Tu}(\omega)|$ to $|C_{Tu}(\omega)|$ around a 10-day period is always about 2.5 for EW time periods (Fig. 10), (4) indicates that the vertical wavelength should be 40 km for a scale height H of 8 km. This estimate is much larger than a typical observed vertical wavelength of 10 km. Therefore the magnitude of the observed $C_{Tu}(\omega)$ is too large to be explained by the simple equatorial Kelvin wave theory.

The zonal wind QBO in the equatorial stratosphere has been considered to be caused by acceleration due to EP flux convergence associated with equatorial wave damping. The damping of wave amplitude can produce a correlation between T and u fluctuations, which is equivalent to the effect of making H larger in (4) and gives a more unrealistic estimation of vertical wavelength. If the damping is large enough to make the imaginary part of m greater than $1/2H$, the sign of $C_{Tu}(\omega)$ is changed to be negative (see Eq. (3)), which is inconsistent with observation. Thus, the damping effect cannot explain the observed $C_{Tu}(\omega)$.

As for the disturbance having periods shorter than 3 days, synchronization with the QBO is observed only in $C(Tu)$ and is not clear in $Q(Tu)$ (Fig. 11). The values of $Q(Tu)$ are negligibly small compared with $C(Tu)$ values. If the short-period disturbances are due to short-period Kelvin waves, (4) implies that the vertical wavelength must be infinitely large, which is in contradict with the assumption of internal waves. Thus the cross spectra for short-period disturbances cannot be explained, at least by the simple Kelvin wave theory, either. A similar argument can be made for other possibilities of zonally propagating planetary-scale internal waves such as inertia-gravity waves.

Next we consider the possibility of small-scale internal inertia-gravity waves propagating meridionally, which obey polarization relations:

$$T' = i\frac{(\hat{\omega}^2 - f^2)Hm}{R\hat{\omega}l}v', \tag{5}$$

$$T' = \frac{(\hat{\omega}^2 - f^2)Hm}{Rfl}u', \tag{6}$$

where l is the meridional wavenumber and f is the inertial frequency (Andrews *et al.*, 1987). Since gravity waves propagating upward have negative m, positive (negative) $C(Tu)$ values mean southward (northward) propagation. If the QBO feature in the $C(Tu)$ variation is due to such meridionally propagating inertia-gravity waves, long-term variations

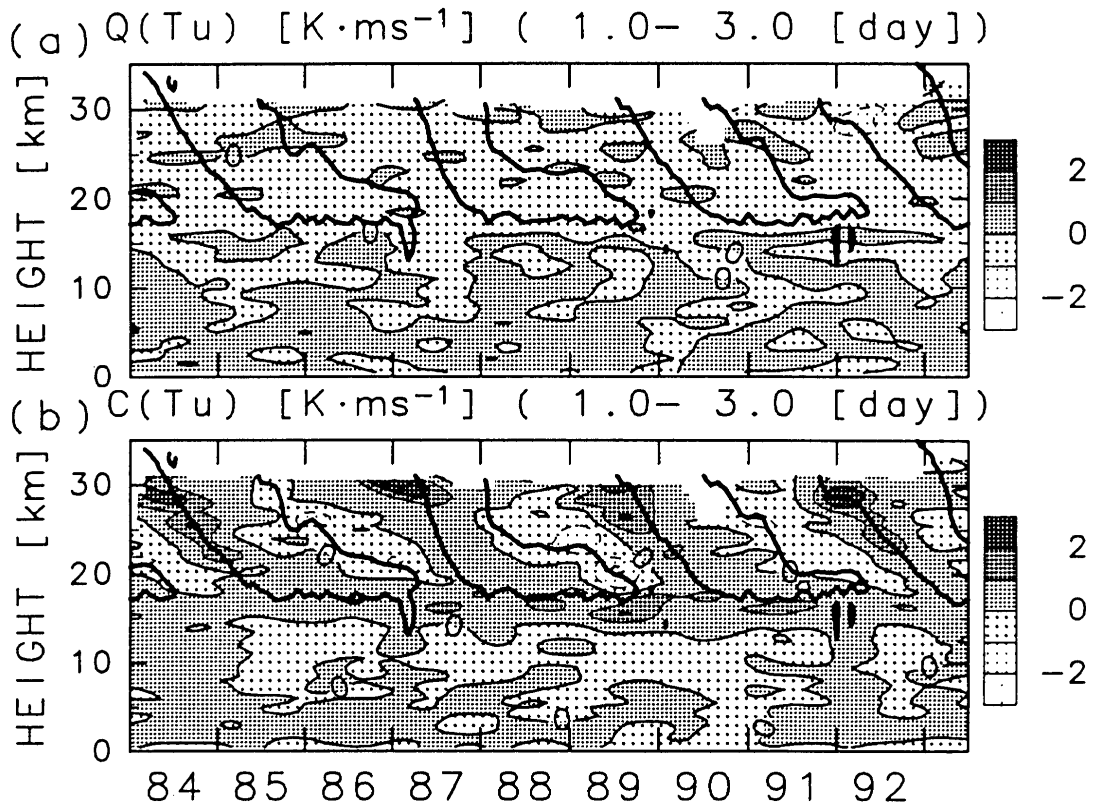

Fig. 11. Time-height sections of (a) integration of quadrature spectra $Q(Tu)$ and (b) co-spectra $C(Tu)$ for a period range shorter than 3 days. Units of contours are K m s^{-1}. Thick curves trace zero values of monthly mean zonal wind.

of $Q_{Tv}(\omega)$ at short periods synchronized with the QBO must be observed simultaneously, corresponding to the momentum flux of $\overline{v'w'}$ that the waves should have. However, as mentioned in the previous section, such variation is not observed in the $Q_{Tv}(\omega)$ profile. Therefore the characteristic variation of $C(Tu)$ cannot be attributed to meridionally-propagating inertia-gravity waves.

To explain the synchronization of $C_{Tu}(\omega)$ with the QBO over the whole frequency range shown in Fig. 10, we need rather to consider other effects which are not included in the simple equatorial wave theory and/or unstable motions. One possible explanation is the effect of large vertical shear of the mean zonal wind associated with the QBO (Dunkerton, 1994). Variation of the sign of $C_{Tu}(\omega)$ produced by the effect is consistent with observations: *i.e.*, positive (negative) $C_{Tu}(\omega)$ values in a positive (negative) shear of mean zonal wind. Another possibility is convective and/or turbulent motions associated with the breaking of large-scale waves, such as Kelvin waves and mixed-Rossby gravity waves. Positive (negative) values of $C(Tu)$ in EW (WE) time periods indicate that the vortex tilted eastward (westward) with height. The QBO observed in $C(Tu)$ may be a reflection of unstable motions associated with the breaking of large-scale waves whose propagation direction is selected by the QBO of mean zonal winds. The phase tilt with height of breaking waves which depends on the propagation direction would affect the shape of associated convective unstable motions. It is necessary to examine the detailed structure of short-period disturbances related to the large positive and negative $C(Tu)$ values.

6.2 Short-period internal waves

As shown in Fig. 4, a clear internal wave-like structure having a typical vertical wavelength of about 5 km and a period of a few days is occasionally observed in the time-height section of short-period fluctuations of all T, u, and v components. Similar disturbances have been reported also by Maruyama (1994), although the structure was not so clear in v profiles. Since the wave-like structure is observed, at least in T and u components, this disturbance cannot be due to mixed Rossby-gravity waves. Although Maruyama analyzed the disturbances only in terms of short-period Kelvin waves, a planetary-scale internal inertia-gravity wave is also a possible candidate. It is found from the dispersion relation curves of equatorially trapped waves (*e.g.*, Fig. 11.1 in Gill, 1982) that the waves can be an $n = 1$ mode, though both eastward and westward propagation directions are possible. The existence of the wave structure observed in v fluctuations in Fig. 4, which should not associated with the $n = 1$ mode, may be explained by the effective β (*e.g.*, Andrews, *et al.*, 1982) coming from meridional shear of the mean wind.

Another likely candidate for the internal waves having the period of 2 days is small-scale inertia-gravity plane waves crossing the equator. These waves have large v components which may explain almost the same magnitude of v variances as that of u variances for the shorter periods observed in Fig. 5. It is important to examine the horizontal structure of the short-period internal waves using data distributed over a wide horizontal area.

7. Summary

Using rawinsonde observation data at Singapore for the ten years of 1984–1993, characteristics of short-period disturbances in the equatorial lower stratosphere were examined. The results are summarized as follows:

1. An internal wave structure whose phases propagate downward is occasionally observed in all of the T, u and v components in the lower stratosphere. The wave period is about 2 days and the vertical wavelength is about 5 km.

2. A power spectral analysis shows that short-period fluctuations have large energy comparable to long-period Kelvin waves.

3. The variances of u and T components due to the short-period fluctuations are maximized in EW time periods. Even in WE time periods, the variances of short-period fluctuations are still significantly large.

4. A QBO signal is clearly observed in the co-spectra of T and u components at short periods, while the QBO synchronization is not found in the quadrature spectra. The sign of co-spectra changes according to the QBO phase, namely, it is positive (negative) in EW (WE) time periods.

Quite recently Takayabu (1994) detected westward-propagating internal inertia-gravity waves with a period of about 2 days in a large-scale cloud structure observed by the GMS (Geostationary Meteorological Satellite). A recent study by Bergman and Salby (1994) using Synoptic Global Cloud Imagery based on six satellite observation suggests that the spectrum of the vertical component of EP (Eliassen-Palm) flux is dominated by gravity waves of period shorter than 2 days. It is important to examine the short-period disturbances in the equatorial lower stratosphere observed in radiosonde data in terms of connection with convective motions and waves in the troposphere.

Acknowledgments

The present authors are grateful to staff members of the Numerical Prediction Division of the Japan Meteorological Agency and T. Maruyama of the Meteorological Research Institute for their courtesy in supplying us with the rawinsonde data. Thanks are extended to M. Takahashi and T.J. Dunkerton for their valuable comments.

References

Andrews, D.G., J.R. Holton and C.B. Leovy, 1987: Middle Atmosphere Dynamics. *Academic Press*, 489 pp.

Bergman, J.W. and M.L. Salby, 1994: Equatorial wave activity calculated from fluctuations in observed convection. *J. Atmos. Sci.*, (in press).

Cadet, D. and H. Teitelbaum, 1979: Observational evidence of internal inertia-gravity waves in the tropical stratosphere. *J. Atmos. Sci.*, **36**, 892–907

Dunkerton, T.J., 1993: Observation of 3–6-day meridional wind oscillations over the tropical pacific, 1973–1992: Vertical structure and interannual variability. *J. Atmos. Sci.*, **50**, 3292–3307.

Dunkerton, T.J., 1994: Horizontral buoyancy flux of internal gravity waves in vertical shear. Submitted to *J. Met. Soc. Japan.*

Gill, A.E., 1982: Atmosphere-Ocean Dynamics. *Academic Press*, 662 pp.

Hirota, I., 1984: Climatology of gravity waves in the middle atmosphere. *J. Atmos. Terr. Phys.*, **46**, 767–773.

Holton, J.R. and R.S. Lindzen, 1972: An updated theory of the quasi-biennial cycle of the tropical stratosphere. *J. Atmos. Sci.*, **29**, 1076–1080.

Kitamura, Y. and I. Hirota, 1989: Small-scale disturbances in the lower stratosphere revealed by daily rawin sonde observations. *J. Met. Soc. Japan*, **67**, 817–831.

Maruyama, T., 1968: Upward transport of westerly momentum due to large-scale disturbances in the equatorial lower stratosphere. *J. Met. Soc. Japan*, **46**, 404–417.

Maruyama, T., 1969: Long term behavior of Kelvin waves and mixed Rossby-gravity waves. *J. Met. Soc. Japan*, **47**, 245–254.

Maruyama, T., 1991: Annual and QBO-synchronized variations of lower-stratospheric equatorial wave activity over Singapore during 1961–1989. *J. Met. Soc. Japan*, **69**, 219–232.

Maruyama, T., 1994: Upward transport of westerly momentum due to disturbances of the equatorial lower stratosphere in the period range about 2 days —A Singapore data analysis for 1983–1993. *J. Met. Soc. Japan*, **72**, 423–432.

Matsuno, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Met. Soc. Japan*, **44**, 25–43.

Sato, K., 1994: A statistical study of the structure, saturation and sources of inertio-gravity waves in the lower stratosphere observed with the MU radar. *J. Atmos. Terr. Phys.*, **56**, 755–774.

Shiotani, M. and T. Horinouchi, 1993: Kelvin wave activity and the quasi-biennial oscillation in the equatorial lower stratosphere. *J. Met. Soc. Japan*, **71**, 175–182.

Takahashi, M. and J. R. Holton, 1991: The mean zonal flow response to Rossby wave and gravity wave forcing in the equatorial lower stratosphere: Relationship to the QBO. *J. Atmos. Sci.*, **48**, 2078–2087.

Takayabu, Y.N., 1994: Large-scale cloud disturbances associated with equatorial waves. Part II: Westward-propagating inertio-gravity waves. *J. Met. Soc. Japan*, **72**, 451–465.

Tsuda, T., T. Murayama, M. Yamamoto, S. Kato and S. Fukao, 1990: Seasonal variation of momentum flux in the mesosphere observed with the MU radar. *Geophys. Res. Let.*, **17**, 725–728.

Tsuda, T., Y. Murayama, H. Wiryosumarto, S.W.B. Harijono and S. Kato, 1994: Radiosonde observations of equatorial atmosphere dynamics over Indonesia PartII: Characteristics of gravity waves. *J. Geophys. Res.*, **99**, 10507–10516.

Wallace, J.M. and V.E. Kousky, 1968a: Observational evidence of Kelvin waves in the tropical stratosphere. *J. Atmos. Sci.*, **25**, 900–907.

Wallace, J.M. and V.E. Kousky, 1968b: On the relation between Kelvin waves and the Quasi-Biennial Oscillation. *J. Met. Soc. Japan*, **46**, 496–502.

Yanai, M. and T. Maruyama, 1966: Stratospheric wave disturbances propagating over the equatorial pacific. *J. Met. Soc. Japan*, **44**, 291–194.

赤道下部成層圏の短周期擾乱

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シンガポール (1N, 104E) の 1978～1993 年に亘るレーウィンゾンデデータを用いて、赤道域下部成層圏における周期 3 日以下の温度・水平風擾乱の解析を行なった。短周期擾乱は温度・風成分共に、時折り鉛直波長 5 km 程度の時間と共に位相の下がる内部波的な構造を持つ。その位相構造から、これは内部慣性重力波によるものと考えられる。また、パワースペクトル解析の結果、短周期帯には、これまで良く調べられている周期 15 日前後のケルビン波や 4~5 日周期の混合ロスビー重力波とは独立なピークが存在し、そのエネルギーも大きいことがわかった。

次にスペクトル特性の時間変化と平均東西風準 2 年周期振動 (QBO) との関係を調べた。東西風と温度の短周期擾乱は、ケルビン波と同様、平均風が東風から西風にかわるフェーズ (EW フェーズ) でバリアンスが極大となるが、ケルビン波と異なり、平均風が西風から東風にかわるフェーズ (WE フェーズ) でもエネルギーが大きい。さらにクロススペクトルについては、これまでケルビン波についてさえほとんど調べられていない、温度と東西風成分のコスペクトルも解析した。その結果、短周期帯において温度と東西風成分のコスペクトルの絶対値がクオドラチャースペクトルの絶対値よりかなり大きいことがわかった。興味深いのは、コスペクトルの符号が QBO の位相に合わせて変化していることである。すなわち、温度と東向き風成分は EW フェーズではプラス、WE フェーズではマイナスの相関を持つ。これらの結果は短周期擾乱が QBO と深い関わりを持つことを示している。