NOTES AND CORRESPONDENCE

Kelvin Wave Activity and the Quasi-Biennial Oscillation in the Equatorial Lower Stratosphere

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Abstract

This note presents observational results and their mechanistic understanding of the long-term variation of Kelvin wave activity in the equatorial lower stratosphere. Analyses are made for 15 years (1974–1988), using the rawinsonde station data at Singapore (1°N, 104°E). Occasionally, clear fluctuations with periods near two weeks can be observed in the zonal wind and temperature fields, suggesting the prominent existence of Kelvin waves. The variability of Kelvin wave activity (measured by the power spectral density integrated over periods in the range around two weeks) is clearly related to the quasi-biennial oscillation (QBO) of the zonal wind in the lower stratosphere. Around the 30 mb level, the Kelvin wave activity is vigorous when the wind régime of the QBO rapidly changes from easterlies to westerlies. In order to understand the observational results, we perform a simplified mechanistic calculation following an idea that the momentum flux due to the Kelvin wave is locally constant and suffers damping which is inversely proportional to the vertical group velocity. In this calculation the observed monthly-mean zonal wind data are used for estimating Kelvin wave amplitudes on a monthly basis. Results of the calculation represent well the long-term variation of Kelvin wave activity associated with the QBO.

1. Introduction

The quasi-biennial oscillation (QBO) in the equatorial lower stratosphere is one of the most dominant long-term variations of the zonal wind in the atmosphere. (Observational studies of the QBO are reviewed by Wallace, 1973; an updated record of the QBO is given by Naujokat, 1986.) It is now accepted that the QBO is a representative atmospheric phenomenon resulting from the wave-mean flow interaction (*e.g.*, Holton, 1975; Andrews *et al.*, 1987). It is also believed that the Kelvin wave and the Rossby-gravity wave trapped in the equatorial latitude play an important role in transporting momentum upward, since Holton and Lindzen (1972) succeeded in simulating the QBO by taking into account the two equatorial waves. According to linear theory, the Kelvin waves (first reported by Wallace and Kousky, 1968a) propagate eastward and transport westerly momentum upward; the Rossby-gravity waves (first reported by Yanai and Maruyama, 1966) propagate westward and transport easterly momentum upward.

Among these two equatorial wave modes, the existence of Kelvin waves has been documented fairly well compared with Rossby-gravity waves, because the Kelvin wave mode has much longer horizontal and vertical scales than the Rossby-gravity wave mode. In the lower stratosphere, Kelvin waves with periods around 15 days have been observed in the rawinsonde station data by several authors (*e.g.*, Wallace and Kousky, 1968a, b; Maruyama, 1969, 1979, 1991). In addition to the lower stratospheric Kelvin wave, Hirota (1978) found the upper stratospheric Kelvin wave with a period about 7 days using the meteorological rocket sonde data at Ascension Island (8°S, 14°W). Recently, the upper stratospheric Kelvin wave has been also detected in the satellite data. Salby *et al.* (1984) and Hitchman and Leovy (1988) found its existence in the temperature field observed by the limb infrared monitor of the stratosphere (LIMS). Using the ozone mixing ratio data from the solar backscatter ultraviolet (SBUV), Hirota *et al.* (1991) and Randel and Gille (1991) found "ozone Kelvin waves" as a reflection of

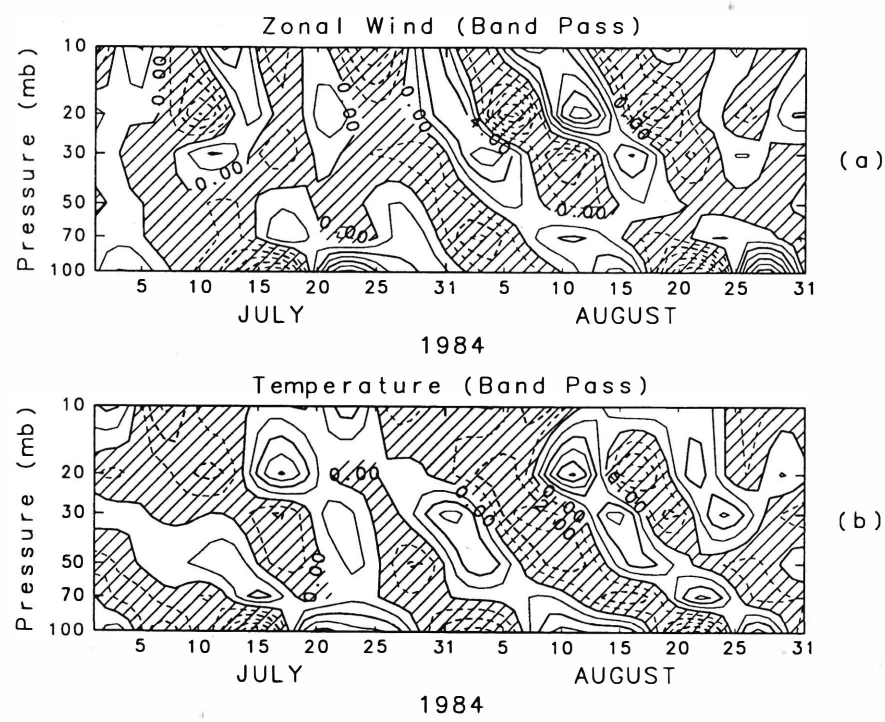

Fig. 1. Time-height sections of the band-pass filtered fields for (a) the zonal wind (contour interval 2 ms^{-1}) and (b) the temperature (contour interval 1 K) during the period of July to August 1984. Negative values are hatched.

their temperature fluctuations. The upper and lower stratospheric Kelvin waves have been also identified in general circulation model (GCM) simulations by Hayashi *et al.* (1984), Boville and Cheng (1988) and Boville and Randel (1992).

Some of the above observational studies further investigated the relation of Kelvin wave activity to the background (zonal mean) flow. As to the lower stratospheric Kelvin wave, there are several studies showing that Kelvin wave activity is observed mostly during the transition from easterlies to westerlies of the QBO, suggesting a dominant role of the Kelvin wave in accelerating the westerlies of the QBO. (Wallace and Kousky, 1968b; Maruyama, 1969, 1979, 1991, Angell *et al.*, 1973; Miller *et al.*, 1976). On the other hand, Randel and Gille (1991) showed that Kelvin wave activity in the upper stratosphere is vigorous when the semi-annual oscillation (SAO) is in the extremes of easterlies, indicating that the Kelvin wave may not play a major role in accelerating the westerlies of the SAO.

Although a large number of observational analyses of the lower stratospheric Kelvin wave have been performed in the last few decades, the nature of generation and propagation is still not fully understood. This is because the lower stratospheric Kelvin wave can be captured so far only by ground-based radiosonde observations which usually have limitations of spatial coverage. Very recently, Maruyama (1991) has extensively investigated annual and QBO-synchronized variations of both Kelvin and Rossby-gravity waves in the lower stratosphere for the period 1961 to 1990. Although a part of his observational results is equivalent to ours, he made analyses only for 70, 50 and 30 mb.

In this note, using the recent rawinsonde data of the stratospheric wind and temperature at Singapore for 15 years, we re-examine the long-term variation of Kelvin wave activity associated with the QBO up to 10 mb (almost complete analyses are made up to 20 mb) and perform a simplified mechanistic calculation to interpret the observational results.

2. Data

The wind and temperature data used in this study are based on daily (00Z) rawinsonde observations at Singapore (1°N, 104°E). Data are available at the following 6 pressure levels: 100, 70, 50, 30, 20 and 10 mb. The period of the present analysis was chosen for 15 years, 1974 to 1988; during this period, the observational density is fairly good for the upper levels compared with the period before 1974. Missing data were linearly interpolated.

3. Existence of Kelvin waves

Figure 1 shows time-height sections of the band-pass (10–30 days) filtered zonal wind and temperature fields from July to August 1984. During this period, easterlies prevail in this height range except

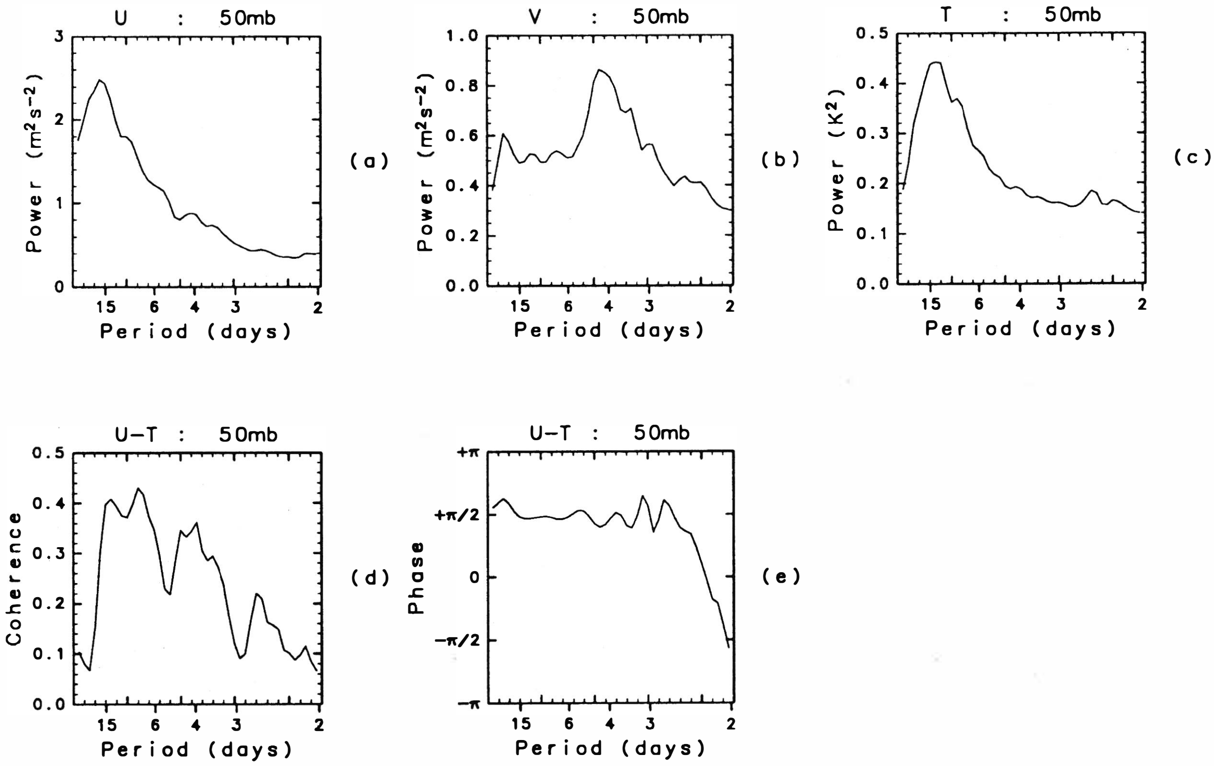

Fig. 2. Power spectral density of (a) the zonal wind, (b) the meridional wind and (c) the temperature; (d) coherence and (e) phase between the zonal wind and temperature at 50mb. Calculation was done for 91 days of data centered on the middle of each month, then averaged over the 15 years of months.

at 10 mb, with weak westerlies (see Fig. 3). From the end of July to the middle of August, there are clear fluctuations in both the zonal wind and temperature fields, having periods of about two weeks and showing evidence of downward phase propagation. Such contour plots with only 6 pressure levels may be inappropriate to illustrate the vertical structure of Kelvin waves, because vertical wavelengths decrease rapidly as the waves approach critical levels (Lindzen, 1971). It is stressed here, however, that there is a clear phase relationship of the fluctuations between any successive two levels when amplitudes are large. During the analysis period of 15 years, such systematic variations with characteristic time scales of about two weeks are observed, when the background zonal wind changes from easterlies to westerlies; this will be shown clearly in Section 4. A typical vertical wavelength is about 10 km and the phase of fluctuations propagates downward with time. When fluctuations are large, amplitudes of the zonal wind exceed 10 ms^{-1} and those of the temperature exceed 3 K. A phase relationship between the zonal wind and temperature fluctuations is clear; the phase of temperature maxima precedes the westerly maxima with a phase angle of about quarter of a cycle, which will be statistically confirmed from the cross-spectral analysis performed below. All these features suggest that the fluctuations are due to the Kelvin waves.

Before investigating the long-term variation of Kelvin wave activity, we survey briefly the spectral properties for the time series of the zonal and meridional wind components and temperature. Spectral analyses using a simple Fourier transform method were made for 91 days of data centered on the middle of each month, and then the resulting spectral profiles were averaged for the 15 years of months. Before spectral analyses were performed, low-frequency fluctuations with periods longer than about 60 days were removed from the original time series. Figure 2a–2c shows power spectral density for the zonal wind, meridional wind and temperature at 50 mb, respectively. The basic features described below are generally observed between the 70 to 20 mb levels. In both zonal wind and temperature spectra (Fig. 2a and 2c), there is a clear spectral peak with a period of about two weeks. In the meridional wind component (Fig. 2b), however, there is no peak around two weeks but around 4–5 days, which may be due to the Rossby-gravity waves. Spectral peaks in the power of the zonal wind and temperature are rather small in comparison with the fluctuations seen in Fig. 1a and 1b, because Fig. 2 is calculated by averaging over the whole months including active and inactive periods of the Kelvin waves. Around the period of about two weeks, coherence between the zonal wind and temperature is fairly high (Fig. 2d) and the phase of the temperature precedes that

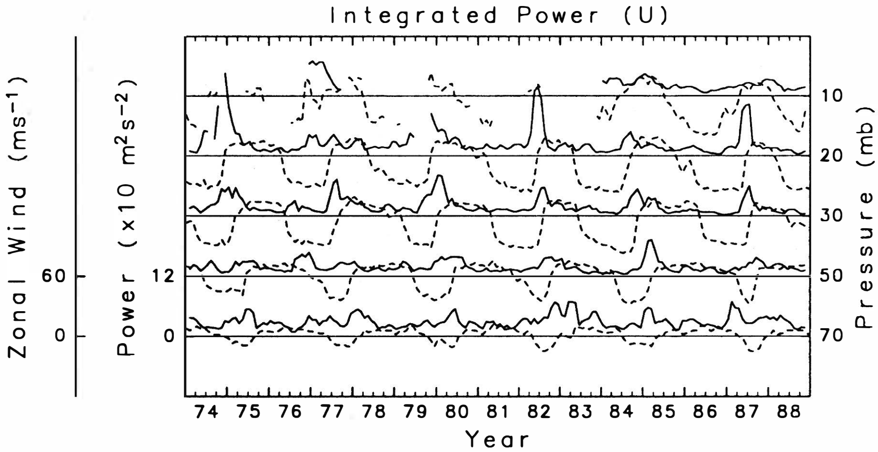

Fig. 3. Time series of the integrated spectral density (solid line; see text for the calculation) and the monthly-mean zonal wind (dashed line) for the five levels, 70, 50, 30, 20 and 10 mb.

of the zonal wind with a phase angle of $+\pi/2$. According to these wave structures (Figs. 1 and 2), although the propagating direction cannot be determined from the single station analysis, it may be concluded that the fluctuations with periods near two weeks seen in the zonal wind and temperature are due to the Kelvin waves. Assuming the dispersion relationship for the Kelvin wave, $\omega = -Nk/m$ (where standard notation is used), the wave has a wavelength of about 40000 km (zonal wavenumber 1). These are consistent with results in the early stage of observations on the Kelvin waves (*e.g.*, Wallace and Kousky, 1968a).

4. Variation of Kelvin wave activity

We next investigate the long-term variation of Kelvin wave activity and its relation to the background flow. As a measure of Kelvin wave activity, the power spectral density calculated from 91 days of data centered on the middle of each month was integrated (here, simply summed up) over the frequency range for 0.033–0.12 (cycle day^{-1}) (in period, 30.3–8.3 days), which might be due mainly to the Kelvin waves. Figure 3 shows temporal variations of the integrated power spectra of the zonal wind component in solid lines and those of the monthly mean zonal wind in dashed lines for 70 to 10 mb. Time series at 100 mb were not shown, because we can not see any clear QBO signal in the zonal wind nor in the Kelvin wave activity. The integrated spectral density is not plotted if there are missing data over 60 days; the monthly-mean zonal wind is not plotted if entire days of the month are missing. As was suggested in several papers (*e.g.*, Maruyama, 1991), it may be better to examine variations of Kelvin wave activity using quadrature spectra between the zonal wind and temperature, because the phase difference between the two should be $\pi/2$ for the ideal Kelvin wave. In this note, however, we separately treat the two components in order to compare observational results with those from a simplified mechanistic calculation which will be performed in the next section. Indeed, it is found that the results for the temperature spectra and the quadrature spectra are essentially similar to those for the zonal wind spectra.

The temporal variation of the integrated power spectra for the zonal wind component (Fig. 3) shows clear relations to the zonal wind QBO. At 20 and 30 mb, large peaks of the integrated spectra can be seen during the period of the rapid westerly acceleration of the QBO; peak-to-peak variation is relatively smaller at 30 mb than at 20 mb. At 30 mb (and also at 50 mb) there is a slight exception of Kelvin wave activity around the end of 1976 when the westerlies are decelerated. The QBO-related variation seems to be smeared out at 10 mb, though the observational set is not complete there. At 50 and 70 mb, the active period of Kelvin waves spreads out, but the variation of the integrated spectra seems to be still connected with the QBO. As was reported by Maruyama (1991), an appearance of the spectral peaks comes earlier with respect to the maximum westerly acceleration of the QBO, as the pressure level goes down from 30 to 70 mb. Then, at 70 mb, variations of the two time series look almost out of phase. It should be noted that times of vigorous Kelvin wave activity do not appear simultaneously at several pressure levels, but they show a time-lag of a few months with the next pressure level. As was also pointed out by Maruyama (1991), the variation at 70 mb may include a contribution from the annual modulation of Kelvin wave activity.

5. Simplified mechanistic calculation

In order to understand features seen in Fig. 3 easily, we estimate Kelvin wave amplitudes by performing a simplified mechanistic calculation assuming that the momentum flux due to the Kelvin wave

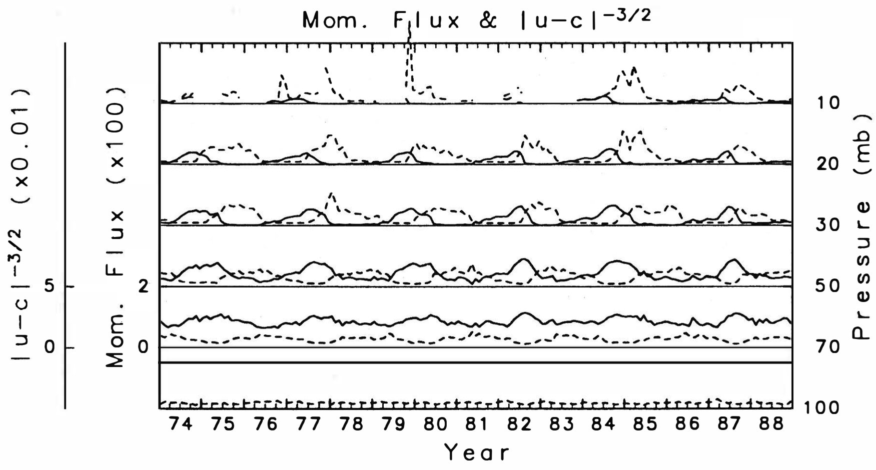

Fig. 4. Time series of the two terms, momentum flux (solid line) and $|u-c|^{-\frac{3}{2}}$ (dashed line) calculated from the observed monthly-mean zonal wind for the six levels, 100, 70, 50, 30, 20, and 10 mb.

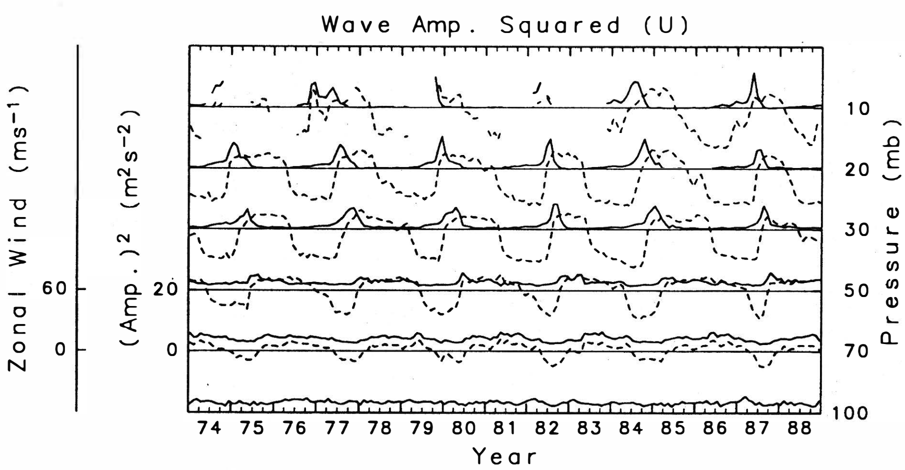

Fig. 5. Time series of the calculated wave amplitude squared (solid line) and the monthly-mean zonal wind (dashed line).

is locally constant and suffers damping which is inversely proportional to the vertical group velocity. Vertical structure of the Kelvin and Rossby-gravity waves in shear flow was investigated in detail by Lindzen (1971) using a method of two-scale perturbation analysis. Though his framework is much more accurate than ours described below, he only investigated the vertical wave structure for a typical wind profile. In the following, Kelvin wave amplitudes are estimated for each month by using the observed monthly-mean zonal winds for the 15 years, 1974–1988.

According to Holton (1975), the Kelvin wave amplitude of the zonal wind component (U) can be written as

$$U^2 = 2N\beta^{\frac{1}{2}}\pi^{-\frac{1}{2}}\rho^{-1}k^{-1}\,|u-c|^{-\frac{3}{2}}\,M, \tag{1}$$

where the notation is based on Holton (1975). This equation is derived as a zeroth-order solution on the assumption that the latitudinally-integrated momentum flux (M) is constant in the sense of a WKB analysis (Lindzen, 1971). Thus, the zonal wind amplitude squared is determined by multiplying some constants, $|\text{the intrinsic phase speed}|^{-\frac{3}{2}}$ and the latitudinally-integrated momentum flux (M). The vertical group velocity of the Kelvin wave can be written as

$$C_{gz} = kN^{-1}\,|u-c|^2\,. \tag{2}$$

Then we assume the momentum flux is damped with a time scale inversely proportional to the vertical group velocity:

$$M = M_0 \exp\left(-T(z,t)/\tau\right), \tag{3}$$

$$T(z,t) \equiv \Delta z / C_{gz}. \tag{4}$$

This assumption is basically similar to a parameterization used in Holton and Lindzen (1972) in which the presence of only Newtonian cooling is considered. The meaning of Eqs. (3) and (4) is that taking much time to propagate the wave suffers much damping. For a simplified calculation, we assume a zonal wavenumber 1 and an eastward phase velocity of 30 ms^{-1}. Moreover, the momentum flux is assumed to be constant at the lower boundary at 100 mb. This assumption seems to be adequate according to an observational study by Randel (1992) showing no distinctive spectral peaks corresponding to Kelvin waves at the upper troposphere. Then calculation of the momentum flux for each month is advanced from 100 mb to 10 mb and Kelvin wave amplitudes are estimated, by substituting the observed monthly-mean zonal winds for u in Eqs. (1) and (2). A coefficient for the damping time scale (τ) is set constant at 6 days, though this should be much longer at the bottom of the lower stratosphere. The sensitivity of the QBO simulations using Holton-Lindzen (1972) model to the profiles of damping coefficients is discussed by Hamilton (1981).

Temporal variations of the two terms, momentum flux (solid line) and $|u-c|^{-\frac{3}{2}}$ (dashed line), are shown in Fig. 4. By multiplying the two terms and some constants, we can estimate Kelvin wave amplitudes (Fig. 5). First the relation of the two terms to the zonal wind is examined: Because the phase velocity c is chosen as a positive value (30 ms^{-1}), the term $|u-c|^{-\frac{3}{2}}$, shown by the dashed line, tends to be larger during the westerlies than during the easterlies. On the other hand, the momentum flux term, shown by the solid line, should be larger while the Kelvin wave suffers less damping with a larger vertical group velocity in the easterlies. Now, by multiplying the two terms, the time series for Kelvin wave amplitudes of the zonal wind component are obtained (Fig. 5). It is clear that the Kelvin wave amplitudes are large only when there are contributions from the two terms, *i.e.*, when the zonal winds rapidly accelerate eastward. The results of our calculation agree well with the observations at 20 and 30 mb, although peak-to-peak variation is not reproduced. The QBO-related variation at 10 mb in the model result could be diminished, as in the observational result, if much faster damping time scale is chosen. At 50 mb the calculated variation associated with the QBO is relatively smaller; at 70 mb the variation looks almost in phase with the zonal wind variation, which is a contrary result to the observation. If we take a longer damping time scale around this level as is usually chosen, the momentum flux suffers less damping and the variation seen in Fig. 5 would be exaggerated without any phase reversal. Therefore, we should take into account another factor to explain the negative correlation between the Kelvin wave activity and zonal wind at the bottom of the lower stratosphere, but at present we have no satisfactory answer to this.

6. Conclusions

Using the rawinsonde station data at Singapore for 15 years (1974–1988), we have found the prominent existence of Kelvin waves. The long-term variation of Kelvin wave activity shows a clear relation to the zonal wind QBO. At 20 and 30 mb, the Kelvin wave activity is vigorous when the zonal winds rapidly accelerate eastward, while at 70 mb it looks almost out of phase with the zonal wind variation. By performing a simplified calculation using the observed monthly-mean zonal winds, we tried to understand the QBO-related variation of Kelvin wave activity mechanistically. The results of our calculation represent well the long-term variation of Kelvin wave activity associated with the QBO around the 30 mb level. At 70 mb, however, our calculation shows a contrary result to the observation.

Around the stratopause level, Randel and Gille (1991) reported the semi-annual variation of the upper stratospheric Kelvin wave activity in the ozone field, showing that vigorous activity is observed when the SAO is in the extremes of easterlies. This feature is somewhat similar to the relation between the lower stratospheric Kelvin wave activity and the QBO at 70 mb. However, the phase velocity of the upper stratospheric Kelvin wave is much faster than that of the lower stratospheric Kelvin wave, and thus the term $|u-c|^{-\frac{3}{2}}$ in Eq. (1) for the upper stratospheric Kelvin wave may not be affected so much by the variation of the background flow. Hence, the variation of the fast Kelvin wave activity associated with the SAO can be understood mainly as the variation in damping of the momentum flux, resulting in the negative correlation between the Kelvin wave activity and the SAO. On the other hand, for the lower stratospheric Kelvin wave the variation of the term $|u-c|^{-\frac{3}{2}}$ cannot be negligible, because the phase velocity is of a compatible order to the background flow. Thus, our model result shows an opposite phase relation to the observation. This discrepancy may be solved by taking account of contributions from several modes of the Kelvin waves.

Recently, it has been suggested that the westerly momentum deposition by Kelvin waves is smaller than required to drive the QBO and that gravity waves may significantly contribute to the zonal momentum budget (Hitchman and Leovy, 1988; Takahashi an Boville, 1992). Although it is difficult in the present observational framework to estimate the zonal momentum budget quantitatively, it seems that there are still interesting subjects to investigate in the equatorial stratosphere concerning the dynamical interaction between the equatorial waves and the mean flow. According to our results that the Kelvin wave activity is confined to a fairly narrow height range, it would be desirable to make observations with a high vertical resolution which would enable us to discuss the more minute features of equatorial waves, including gravity waves.

Acknowledgments

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赤道域下部成層圏におけるケルビン波の活動性と準2年周期振動

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ここでは赤道域下部成層圏におけるケルビン波の活動性の長周期変動に関する観測結果を示すとともに、簡単なモデルを用いてそのメカニズムの理解を試みる。シンガポール (1N, 104E) におけるゾンデ観測データを用い、1974 年から 1988 年の 15 年間にわたって解析をおこなったところ、ときおりケルビン波にと

もなうと考えられる約2週間の周期性を持った変動を東西風および温度場に見ることができる。ケルビン波の活動性（ここでは約2週間の周期帯で積分したパワースペクトル密度で定義した）は、明らかに下部成層圏の東西風に見られる準2年周期振動 (QBO) と関連して変動している。30 mb 付近では、東西風の QBO が急速に東風から西風に変わるときケルビン波の活動性が活発になる。この観測結果を理解するために次のような考え方にもとづいて簡単な計算をおこなった：すなわち、ケルビン波にともなう運動量フラックスは局所的に一定で鉛直群速度に反比例するような減衰を受ける。この計算では、月毎にケルビン波の振幅を見積もるため、観測された月平均東西風データを用いた。計算結果は QBO と関連したケルビン波の活動性の長周期変動をよく再現している。