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Equatorial Kelvin Waves and Corresponding Tracer Oscillations in the Lower Stratosphere as seen in LIMS Data

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Abstract

We have analyzed data from the Limb Infrared Monitor of the Stratosphere (LIMS) instrument on board the Nimbus 7 to investigate equatorial Kelvin waves and dynamically wave-induced variations in the tracer fields such as ozone and water vapor in the lower stratosphere. Temperature anomalies of zonal wavenumber one, progressing eastward and having a period of 12–15 days, are clearly observed below 7 hPa for April and May 1979. Vertical phase structure with a wavelength of about 15 km progresses downward in the zonal flow being about $-16\ \mathrm{ms}^{-1}$ averaged from 50 to 10 hPa. At the same time, disturbances in the ozone field due to the Kelvin waves are observed: the amplitude is maximum at 30 hPa where vertical gradient of zonal mean ozone is largest and the longitudinal structure is in-phase with that of temperature. These features are in good agreement with linear Kelvin wave theory. In the water vapor field, at 50 hPa, we have also detected wavenumber one eastward progressing waves being in-phase with temperature though the spatial structure is not as clear as in the ozone field.

1. Introduction

It is well known that Kelvin waves are observed in the equatorial middle atmosphere and play an important role in dynamics. Wallace and Kousky (1968a) first documented the existence of the so-called "slow" Kelvin waves in the lower stratosphere based on radiosonde observations. Characteristics of observed slow Kelvin waves are as follows (see Andrews *et al.*, 1987): They are eastward progressing waves of zonal wavenumber 1–2 having a period of about 15 days with a vertical wavelength of 6–10 km; their typical temperature perturbations are 2–3 K. The importance of such equatorial waves was recognized by Holton and Lindzen (1972) advocating the fundamental mechanism of the quasi-biennial oscillation (QBO) that has accounted for the dynamical interaction between the mean flow and vertically propagating equatorial waves, one of which is the Kelvin wave. Since Kelvin waves can transfer westerly momentum upward, they are supposed to provide an important momentum source of the QBO westerly acceleration.

The QBO-synchronized variation of Kelvin wave activity in the lower stratosphere has been investigated in detail based on radiosonde observations over the equator (Wallace and Kousky, 1968b; Maruyama, 1969; Angell *et al.*, 1973; Shiotani and Horinouchi, 1993). All their results show that, in general, large Kelvin wave amplitudes are observed

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in the QBO westerly shear zone, that is, when the background zonal wind rapidly changes from easterlies to westerlies in the lower stratosphere.

In the upper stratosphere, Hirota (1978) showed the first evidence for the "fast" Kelvin waves having a period of about 7 days, based on meteorological rocket soundings over the Ascension Island (8°N, 14°W), and suggested that they might play an important role in dynamics of the semi-annual oscillation (SAO). Hirota (1979) also detected eastward moving waves with a period of 4–9 days by satellite sounding data from the Selective Chopper Radiometer (SCR) on board the Nimbus 5. The more detailed three-dimensional aspects of Kelvin waves were described by using daily global observations from the Limb Infrared Monitor of the Stratosphere (LIMS) on board the Nimbus 7. The LIMS instrument made measurements of temperature and four chemical species (ozone, nitric acid, nitrogen dioxide and water vapor) for about seven months. Though the LIMS observation period is not long enough to see even the annual cycle, LIMS provided daily global mapped fields with a high vertical resolution from the lower stratosphere to the lower mesosphere. Salby *et al.* (1984) analyzed LIMS temperature data from January to February 1979 and showed existence of the fast Kelvin waves with a period of about 7 days and the "ultra" fast Kelvin waves with a period of about 4 days in the upper stratosphere during the easterly regime of the SAO. Moreover, using the LIMS data, Hitchman and Leovy (1988) showed that the Kelvin wave is an important momentum source of westerly acceleration in the tropical stratosphere and mesosphere, though it is quantitatively not enough, suggesting a more important role in momentum transport by gravity waves.

The Kelvin waves should induce corresponding oscillations in the tracer field. If the photochemical lifetime is shorter than the advection time scale of the dynamics, tracer distributions, such as ozone in the upper stratosphere, are highly dependent on the temperature. On the other hand, if the photochemical lifetime is longer than the dynamical advection time scale, tracer distributions are determined by dynamical effect. Randel (1990) and Salby *et al.* (1990) investigated the LIMS tracer fields for the period centered around January–February 1979 when the fast Kelvin waves were clearly detected (Salby *et al.*, 1984). In particular they focused on "ozone" Kelvin waves induced by the temperature dependence of the ozone photochemical reaction in the upper stratosphere. They further discussed the amplitude and the phase relation between temperature and ozone perturbations by applying a simple linear model. The ozone Kelvin wave is out of phase with the temperature wave in the upper stratosphere and in-phase in the lower stratosphere. In addition, Hirota *et al.* (1991) and Randel and Gille (1991) found ozone Kelvin waves in the upper stratosphere from ozone profile data provided by the Solar Backscatter Ultraviolet (SBUV) instrument on board the Nimbus 7 and discussed the seasonal variation of Kelvin wave activity in relation to the zonal wind SAO. Recently, investigating the temperature and ozone data from the Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS), Canziani *et al.* (1994) discussed Kelvin wave activity associated with the QBO.

As mentioned above, Salby *et al.* (1984, 1990) and Randel (1990), using the LIMS data, mostly found the fast Kelvin waves in the upper stratosphere and corresponding tracer oscillations due to the temperature dependence of the photochemical reaction during the easterly regime of the SAO. Though they mentioned dynamically induced variations in the tracer fields, their results were not so clear as those for the photochemically induced variations. In this paper we have re-investigated the LIMS data and found that there is a robust signal of relatively slow Kelvin waves in the lower and middle stratosphere for April and May 1979. This wave event was included in Hitchman and Leovy (1988) as one of samples for momentum flux estimation by the Kelvin wave. They indicated that this Kelvin wave event is characterized by an eastward progressing zonal wavenumber one component with a period of 12 days and with a vertical wavelength of 16 km around the middle stratosphere in early May. For the present analysis we choose a 60-day segment from March 30 to May 28 at the end of the LIMS period. In the lower stratosphere, the photochemical lifetime of nitrogen dioxide is very short and that of nitric acid is not sufficiently long, while ozone and water vapor are long-lived and can be regarded as dynamical tracers (Brasseur and Solomon, 1986). The purpose of this study is to investigate the behavior of Kelvin waves in the lower and middle stratosphere and corresponding dynamically induced oscillations in the long-lived chemical tracer fields, such as ozone and water vapor.

Figure 1 shows two vertical profiles of the zonal wind observed at Singapore; one is averaged over April and May 1979 (solid line) and the other is averaged over January and February 1979 (dashed line). The latter corresponds to the period when Salby *et al.* (1984) investigated the Kelvin waves. The difference between the two profiles seems to be small, though a zero wind line moves down at 40 hPa in April and May and the easterly wind regime spreads widely above that level. Generally speaking, the LIMS period corresponds to the QBO easterly shear regime when Kelvin waves in the lower stratosphere are not supposed to be clearly observed (*e.g.* Maruyama, 1991).

The quality of the LIMS data and analysis method

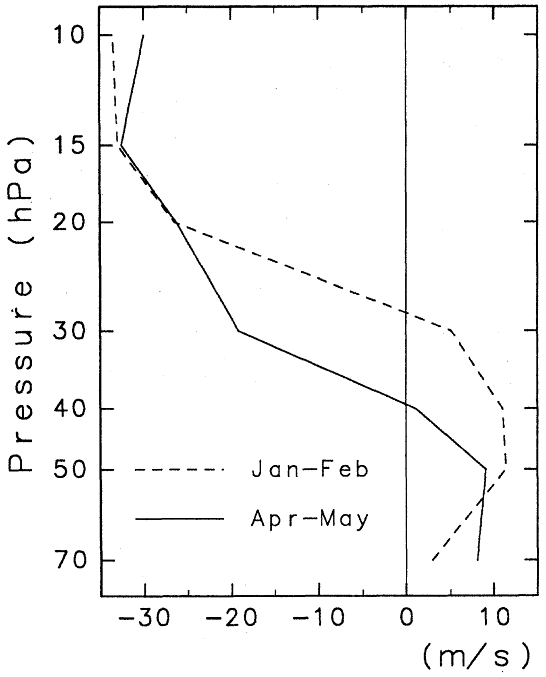

Fig. 1. Zonal wind profiles averaged over April–May 1979 (solid line) and January–February 1979 (dashed line) observed at Singapore (1°N, 104°E).

are mentioned in Section 2. In Section 3, we will show clear evidence of Kelvin waves in the lower and middle stratosphere. Analyses on tracer oscillations induced by dynamical advection will be given in Section 4 and results will be compared according to linear Kelvin wave theory.

2. Data and analyses

The Limb Infrared Monitor of the Stratosphere (LIMS) instrument on board the Nimbus 7 sounded the atmospheric constituents and thermal structure of the stratosphere from October 25, 1978 to May 28, 1979 for 216 days using a technique of thermal infrared limb scanning. Gille and Russell (1984) discussed performance and results of the LIMS experiment. In addition to temperature, LIMS provides daily global mapped fields of four atmospheric species: ozone (O_3), nitric acid (HNO_3), nitrogen dioxide (NO_2) and water vapor (H_2O). In this paper we limit our analyses to temperature, ozone and water vapor fields, because photochemical lifetimes of nitrogen dioxide and nitric acid are not sufficiently long in the lower stratosphere (Brasseur and Solomon, 1986). Moreover, we will mainly discuss the ozone field because the data quality of the water vapor field seems to be somewhat poorer than that of the ozone field.

We make use of the LIMS Version 5 (V5) data. Data are arranged in the form of a zonal mean value and zonal Fourier coefficients (up to wavenumber 6) for every 4° latitude (84°N∼64°S) through a Kalman filter technique (Rodgers, 1976). Temperature and ozone data are available at the following 17 standard pressure levels: 100, 70, 50, 30, 16, 10, 7, 5, 3, 2, 1.5, 1, 0.7, 0.5, 0.4, 0.2, and 0.1 hPa (with an interval of about 3.5 km), except 100–1.0 hPa for water vapor. Because zonal wavenumber one variations due to Kelvin waves are dominant (as will be shown in Fig. 3), we will focus on the zonal wavenumber one component for 60-day period from March 30 to May 28, 1978. Data are smoothed latitudinally by applying a 1–2–1 weighted mean. Further, a 3-day running mean is applied to time-height and time-longitude cross sections. Since the wave structure associated with the Kelvin wave can scarcely be seen in the upper stratosphere, we will show results for the height range up to 2 hPa. For chemical species, data at the 100 hPa pressure level are not used in this paper, because they seem to have large variations irrelevant to the Kelvin wave.

As a reference of the background flow, we use monthly mean zonal wind data observed at Singapore (1°N, 104°E).

Spectral analysis is suitable to this study because Kelvin wave property is easily described as space-time composition. In Sections 3 and 4, we perform a space-time spectral analysis to qualitatively confirm the existence of the Kelvin waves. Space-time spectra are estimated by a direct Fourier transform method and smoothed in frequency using a Gaussian spectral window for stability.

3. Temperature field

Figure 2 shows a time-height section of temperature cosine coefficients of the zonal wavenumber one component over the equator. A similar figure, but for the whole LIMS period, was drawn by Hitchman and Leovy (1988). Downward phase propagation is clear, especially during mid-April to May, with a period of about two weeks and a vertical wavelength of about 15 km. The variations are large in the middle stratosphere. Figure 3 shows a time-longitude section of zonal anomalies constructed from components of the zonal wavenumbers one to three at the equator and 50 hPa. Temperature anomalies of zonal wavenumber one are dominant and propagate eastward with a period of about two weeks having a maximum amplitude of about 2 K. All these features suggest the existence of equatorial Kelvin waves in the lower stratosphere.

Figure 4 shows a frequency (cycles/60 day^{-1}) or period (days)-height section of power spectral density for the zonal wavenumber one component at the equator. Distinctive maxima are seen corresponding to eastward moving waves with periods of 12–15 days below 7 hPa. The amplitudes are small in the lower stratosphere and largest around 10 hPa. The Kelvin wave amplitude is proportional

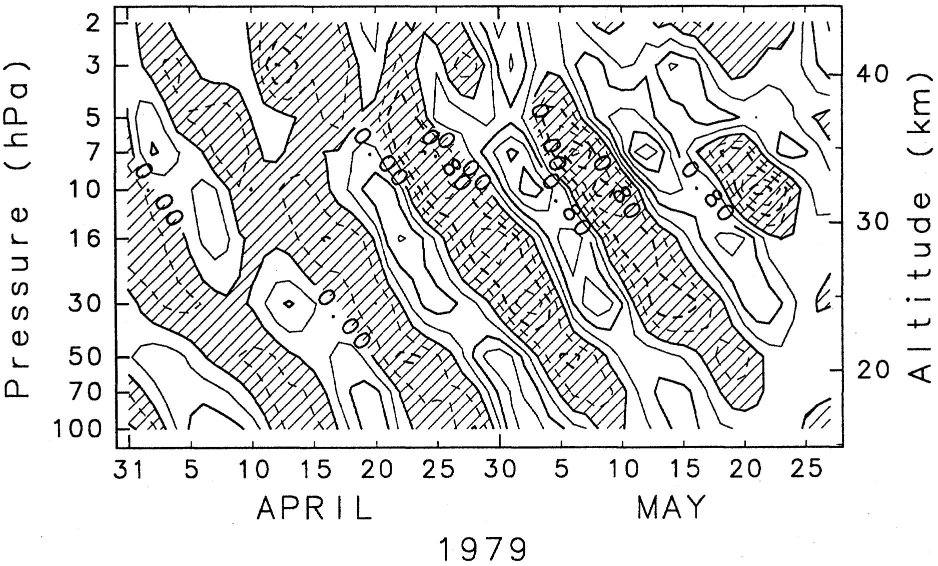

Fig. 2. Time-height section of temperature cosine coefficients of the zonal wavenumber one component at the equator (contour interval 0.4 K; negative values are hatched).

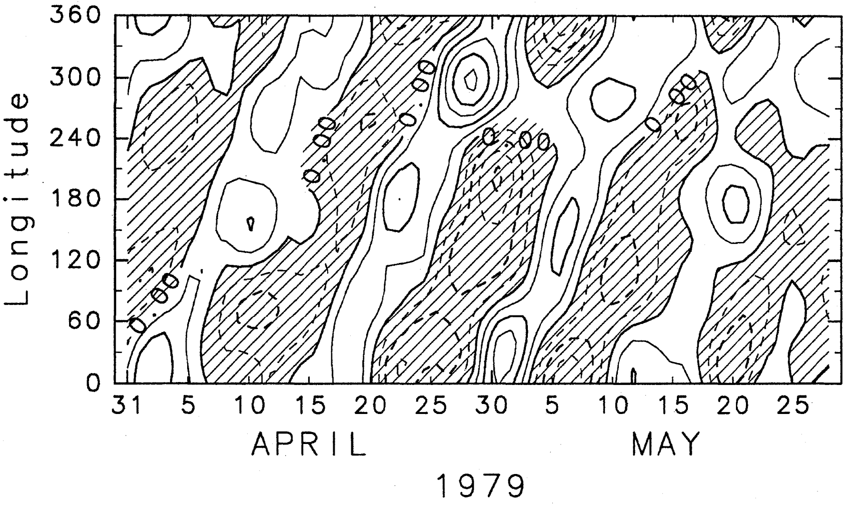

Fig. 3. Time-longitude section of zonal anomalies constructed from components of the zonal wavenumbers one to three at the equator and 50 hPa (contour interval 0.4 K; negative values are hatched).

to $(c-\overline{u})^{-\frac{3}{2}}$ (c: phase velocity of the Kelvin wave (>0), $\overline{u}$: zonal wind speed), if momentum flux is uniform (Holton, 1975). Thus, in general, the amplitude is expected to get larger where the zonal wind changes from easterlies to westerlies with increasing height (Shiotani and Horinouchi, 1993). In a westerly regime, on the contrary, the vertical group velocity becomes smaller and the Kelvin waves are effected by the radiative damping efficiently, resulting in decreasing the amplitude. These situations are realized and seen in Fig. 4 in April and May when the regime in the upper stratosphere is westerly due to the SAO (*e.g.* Hirota, 1978). However, this idea is not applicable to the lower stratosphere, because the amplitudes become larger with increasing height in the easterly shear of the QBO (Fig. 1). The enhancement of the Kelvin wave amplitude in the middle stratosphere can be simply explained by the exponential decrease of atmospheric density with increasing height while wave momentum is conserved.

Figure 5 shows a meridional cross section of amplitudes calculated from the square root of twice the power spectra and phases for the eastward moving wave with a period of 12 days. The amplitude is a maximum over the equator and symmetrically decreases away toward higher latitudes. The phase tilts eastward with increasing height, having a vertical wavelength of about 13–18 km, the horizontal structure being almost in phase. From the results

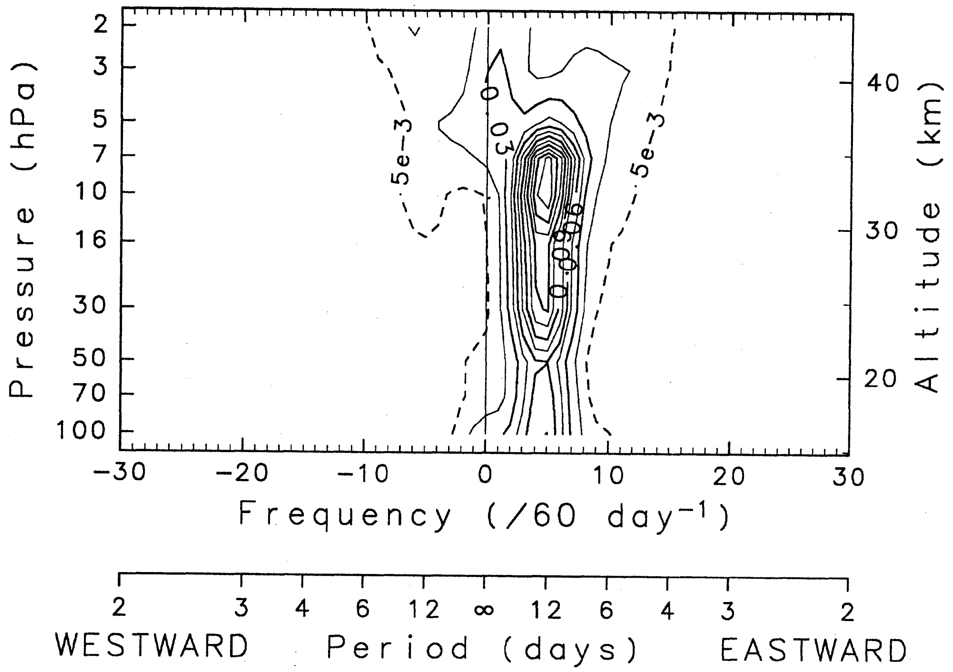

Fig. 4. Frequency (cycles/60 day^{-1}) or period (days)-height section of power spectral density for the zonal wavenumber one component at the equator (contour interval 0.015 K^2).

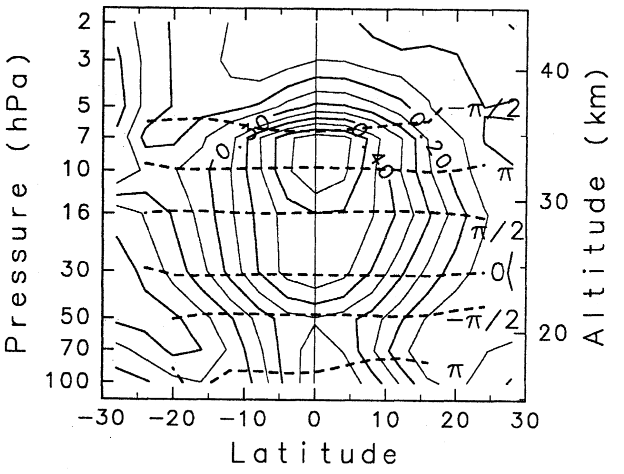

Fig. 5. Meridional cross section of the amplitude and the phase for the eastward moving wavenumber one component with a period of 12 days (contour interval 0.05 K). The phase is calculated with a reference point at the equator and 30 hPa.

of the spectral analyses, we can check the dispersion relation for Kelvin waves (Andrews *et al.*, 1987):

$$\omega = -N\frac{k}{m}, \tag{1}$$

where notations are standard. For the height range from 50 hPa (≈21 km) to 10 hPa (≈32 km), the intrinsic phase velocity (relative to averaged zonal flow -16 ms^{-1}) is about 55 ms^{-1} and the vertical wavelength is about 15 km. These parameters satisfy this dispersion relation. As for the meridional extent, the e-folding decay width $[2(c-\overline{u})/\beta]^{1/2}$ (*e.g.* Andrews *et al.*, 1987) is about 1600 km at 50 hPa for an intrinsic zonal phase velocity about 30 ms^{-1}. This also agrees with that of a typical Kelvin wave.

Judging from these characteristics, we conclude that the temperature variations seen in the lower and middle stratosphere are due to the equatorial Kelvin waves. Moreover, we infer that these waves are the so-called "slow" Kelvin waves, though the vertical wavelength (~15 km) is longer than that for the typical slow Kelvin waves (*cf.* Andrews *et al.*, 1987).

4. Tracer fields

4.1 Ozone

Since the photochemical lifetime of ozone in the upper stratosphere is shorter than the Kelvin wave advection time scale, the space-time variation of ozone is sensitive to that of temperature. On the other hand, in the lower stratosphere (below 10 hPa) the photochemical lifetime of ozone becomes longer and ozone behaves like a conservative tracer (Brasseur and Solomon, 1986). In this Section, we focus on the ozone oscillation induced by dynamical advection associated with Kelvin waves in the lower stratosphere.

Figure 6 shows a time-height section of cosine coefficients of the zonal wavenumber one component in the ozone field. Downward phase propagation is

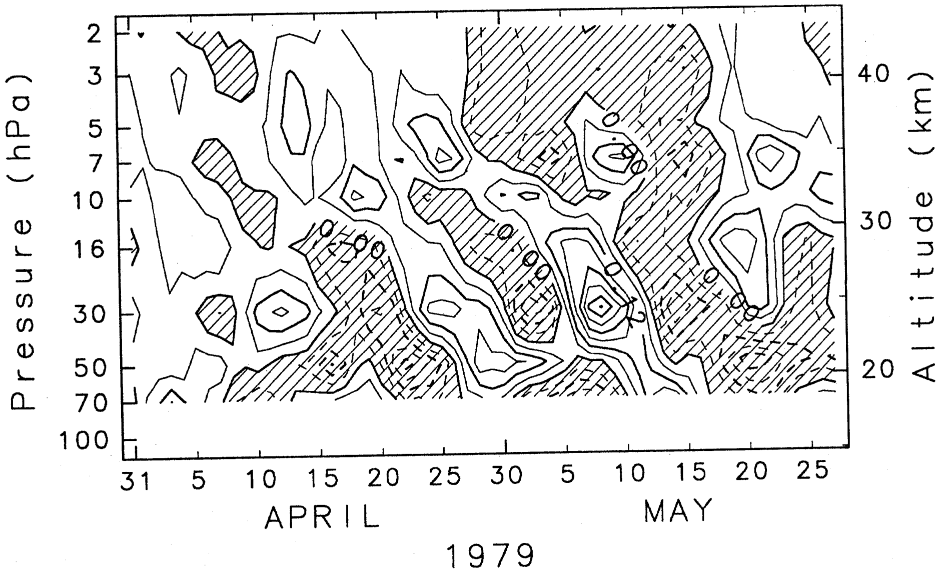

Fig. 6. Time-height section of ozone cosine coefficients of the zonal wavenumber one component at the equator (contour interval 0.06 ppmv; negative values are hatched).

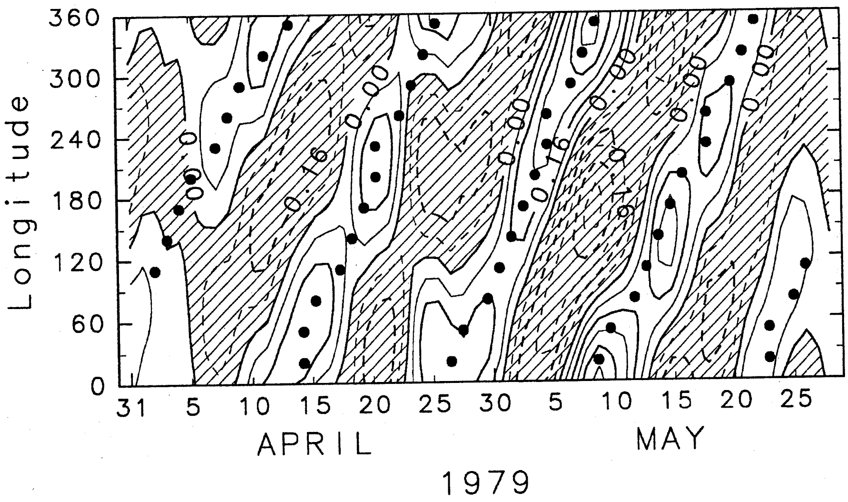

Fig. 7. Time-longitude section of zonal wavenumber one variations in the ozone field at the equator and 30 hPa (contour interval 0.08 ppmv; negative values are hatched). Dots indicate where maximum positive deviations are located for the wavenumber one temperature field at 30 hPa.

clear, especially during late April to May, but the phase relation below and above 10 hPa looks almost out of phase. The amplitude seems to be a maximum around 30 hPa. Figure 7 shows a time-longitude section of wavenumber one ozone variations at the equator and 30 hPa. Dots indicate where maximum positive deviations are located for the wavenumber one temperature field. It is clear that ozone anomalies propagate eastward with a period of about two weeks and are in-phase with those in the temperature field. These characteristics, the ozone perturbation amplitude being a maximum around 30 hPa and the in-phase relation between temperature and ozone, will be discussed in the next subsection in terms of linear Kelvin wave theory.

The result of spectral analysis for the ozone field is basically similar to that of the temperature: Power spectral density has a maximum for eastward moving component with periods of 12–15 days. Figure 8 is as Fig. 5, but for ozone. The amplitude is a maximum over the equator and decreases with increasing latitude. At the equator, there are two peaks with height, one around 30 hPa and the other around 7 hPa, as suggested also in Fig. 6. The horizontal structure is almost in phase, but this is not clear around 10 hPa where the amplitudes are small. The vertical wavelength estimated below 10 hPa is al-

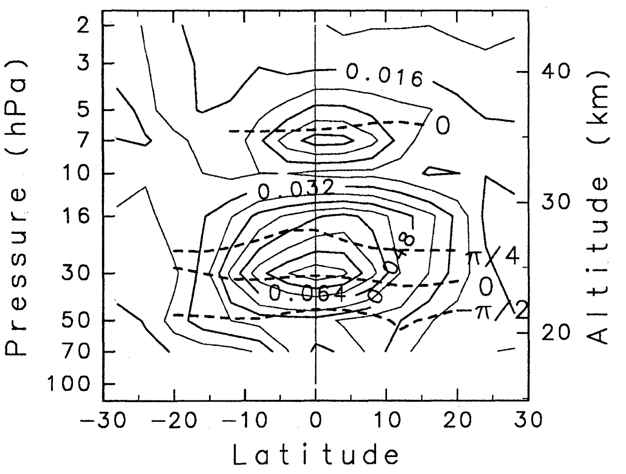

Fig. 8. Meridional cross section of the amplitude and the phase for eastward moving zonal wavenumber one component of ozone with a period of 12 days (contour interval 8.0×10^{-3} ppmv). The phase is calculated with a reference point at the equator and 30 hPa. Here, this reference point is chosen to match that for the temperature field.

most the same as that for temperature (~15 km).

4.2 Comparison with linear Kelvin wave theory

Next we discuss the amplitude of ozone perturbation induced by dynamical advection due to the Kelvin wave and the phase relation between the temperature and ozone fields on the basis of a simple linear theory as followed by Randel (1990). In this theory, perturbation temperature and ozone equations linearized about the zonal mean flow are solved under the condition in which the effects of radiative damping of the temperature perturbations and radiative heating due to ozone perturbations are neglected. These are appropriate assumptions, because the radiative relaxation time scale in the stratosphere is much longer than the Kelvin wave advection time scale, and because the radiative heating due to ozone perturbations is smaller than advection effects (Hartmann, 1978).

In the upper stratosphere, where the photochemical equilibrium dominates, the ozone perturbations can be described by photochemical parameters. On the other hand, in the lower stratosphere, dynamical advection excels. Because the Kelvin wave has a vanishing meridional wind perturbation ($v^{'} = 0$), a relation between the ozone and temperature perturbations in terms of ozone mixing ratio $\mu^{'}$ satisfies

$$\mu^{'} = \frac{\overline{\mu}_z}{S} T^{'}, \tag{2}$$

where

$$\overline{\mu}_z = \frac{\partial \overline{\mu}}{\partial z}, \tag{3}$$

$$S = \frac{1}{H}\left(\frac{2}{7}\overline{T} + H\frac{\partial \overline{T}}{\partial z}\right), \tag{4}$$

and other notations are standard. Overbar and prime indicate zonal mean and perturbation from zonal mean, respectively (See Randel, 1990; for detailed derivation).

First, we discuss the amplitude. A change in background static stability parameter S with increasing height is very small in the stratosphere over the equator, but vertical gradient of zonal mean ozone $\overline{\mu}_z$ has a characteristic profile suggesting a considerable influence on the ozone amplitude. In other words, the ozone perturbation amplitude should be maximum at the level where vertical gradient of the zonal mean ozone field is largest. Figure 9 shows (a) the vertical gradient of ozone mixing ratio at the equator and (b) amplitudes of observed ozone variations for the eastward progressing component with a period of 12 days at the equator (solid line). The maximum amplitude at 30 hPa corresponds to the maximum vertical gradient of zonal mean ozone mixing ratio. Our analysis shows qualitatively good agreement with the theory. A dashed line in Fig. 9 represents calculated amplitudes from Eq. (2) due to the Kelvin wave. The profile shows the same peak as observation, but the maximum value is about one half of the observed ozone amplitude. The larger amplitude of observation than estimation (seen in the LIMS V5 data) in the lower stratosphere has already pointed out by Randel (1990). He analyzed both the LIMS V4 and V5 data and showed that the V4 amplitude is smaller than the estimated amplitude.

For conservative transport, the phase relation between temperature and ozone is expected to be in-phase if the vertical gradient of ozone is positive ($\overline{\mu}_z > 0$, *i.e.*, below 10 hPa. See Fig. 9a). This in-phase structure is clearly seen at 30 hPa (Fig. 7). We confirmed that it is still in-phase up to 16 hPa. During the retrieval process, if the temperature were erroneously high, it could make the ozone low. Our results show, however, that the ozone variation is in-phase with that of temperature, suggesting the phase relation we observed is really due to the dynamical effect. (This is also the case for water vapor. See the next subsection). Fig. 6 also shows photochemically induced ozone Kelvin waves above about 10 hPa; the phase difference with temperature is about 90° at 7 hPa based on the cross-spectral analysis. This difference can be also inferred from Figs. 5 and 8. Around 7 hPa is a transition region where the dominant effect on the ozone field changes from dynamics to photochemistry. According to Randel (1990), the phase difference with the temperature wave becomes 180° above about 1 hPa.

Finally, we try to extend present discussion about the latitudinal profile of amplitudes. It is known

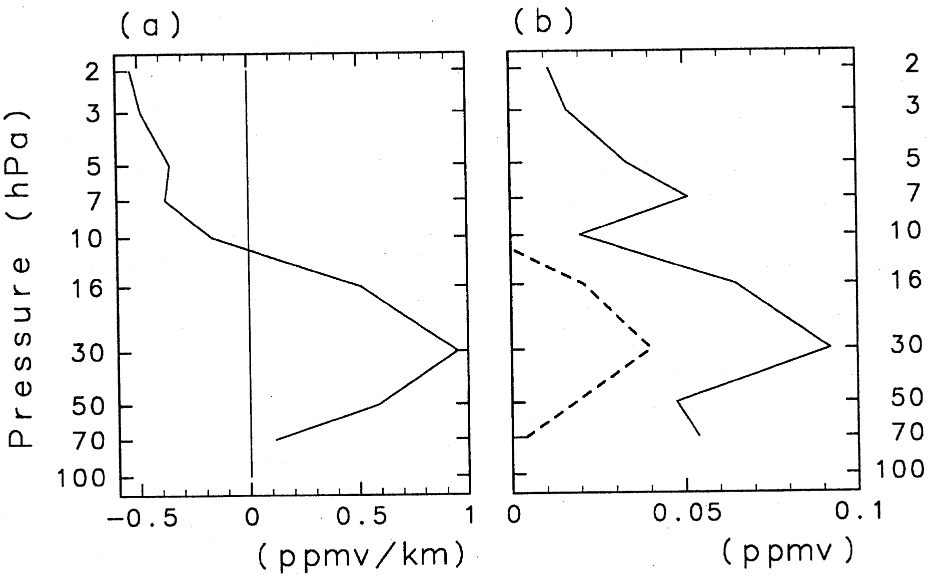

Fig. 9. (a) Vertical gradient of zonal mean ozone for March 30 to May 28. (b) Amplitudes of observed ozone variations (solid line) and those calculated from Eq. (2) (dash line) for eastward progressing components with a period of 12 days at the equator.

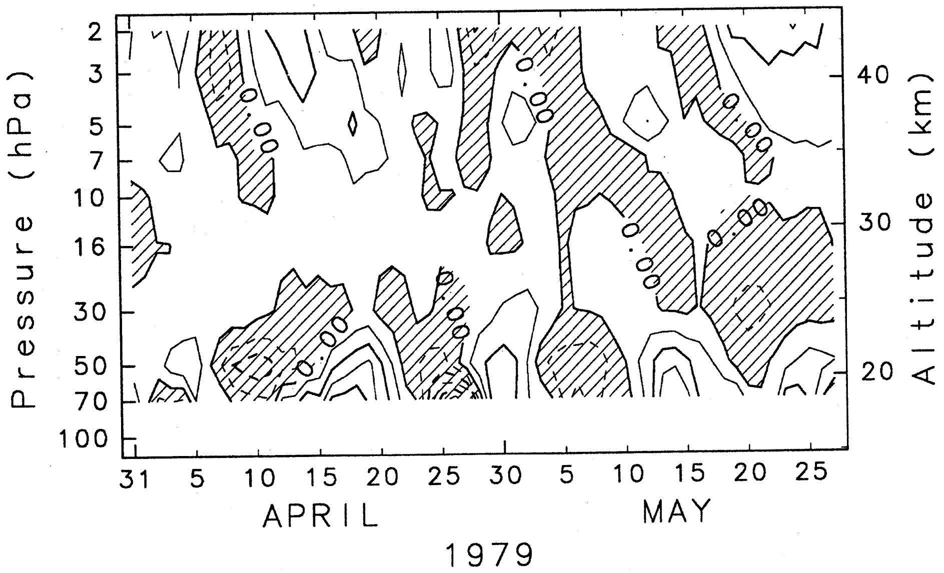

Fig. 10. As in Fig. 6, but for water vapor (contour interval 0.1 ppmv; negative values are hatched).

that the meridional structure of the Kelvin wave amplitudes has the form of a Gaussian function with a maximum at the equator. Ozone amplitudes seem to have a smaller latitudinal extent than temperature if we compare Figs. 5 and 8. The e-folding decay width of the temperature for the eastward progressing component with a period of 12 days at 30 hPa is estimated to be about 18.4° by fitting a Gaussian function. For both the observed ozone and the estimated $T' \cdot (\overline{\mu}_z/S)$ amplitude, the decay widths are 16.5° and 16.8°, respectively; these are about 10 % smaller than that of the temperature field. The narrower latitudinal decay of ozone than of temperature amplitudes may be promoted because the vertical gradient of the zonal mean ozone ($\overline{\mu}_z$) is largest over the equator and becomes smaller away from the equator.

4.3 Water vapor

We briefly mention results of water vapor, whose photochemical lifetime is very long in the whole stratosphere. The vertical gradient of zonal mean water vapor is positive, and it is rather large in the lower stratosphere.

Figure 10 shows a time-height section of cosine coefficients of the zonal wavenumber one component

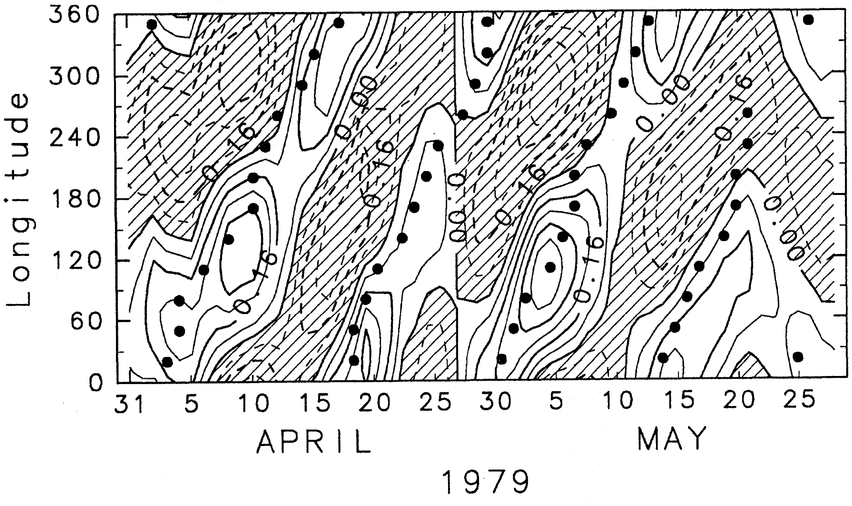

Fig. 11. As in Fig. 7, but for water vapor at 50 hPa (contour interval 0.08 ppmv; negative values are hatched). Dots indicate where maximum positive deviations are located for the wavenumber one temperature field at 50 hPa.

in the water vapor field at the equator. We can see variations with a period of about two weeks around the bottom of the stratosphere. Figure 11, as Fig. 7 but for water vapor at 50 hPa, shows that there exist eastward propagating anomalies with a period of about two weeks and that they are roughly in-phase with temperature. Our cross-spectral analysis shows that the phase difference between the two is estimated to be about 20°.

Spatial structures of "water vapor" Kelvin waves found in the lower stratosphere are summarized as follows: The amplitude is a maximum over the equator and the phase tilts eastward with height, the horizontal structure being almost in phase but only for the latitude band 10°N∼10°S at 50 hPa. Consequently the meridional extent of water vapor Kelvin waves is clearly smaller than that of temperature and ozone Kelvin waves.

5. Summary

Using daily global data of temperature and trace species monitored by LIMS on board the Nimbus 7, we have investigated the equatorial Kelvin waves and corresponding oscillations in the tracer fields induced by dynamical advection in the lower stratosphere.

We examined temperature data throughout the LIMS period and found a robust signal of eastward progressing anomalies of zonal wavenumber one in the lower and middle stratosphere during April to May 1979. We have focused on this 60-day period and showed that there clearly exists an equatorial Kelvin wave in the lower and middle stratosphere. The period of this wave is 12–15 days and the vertical wavelength is about 15 km. Many reports about Kelvin waves in the lower stratosphere based on radiosonde observations show that they are generally observed in the regime where the zonal wind changes from easterlies to westerlies of the QBO (Wallace and Kousky, 1968b; Maruyama, 1969; Angell *et al.*, 1973; Shiotani and Horinouchi, 1993). Though the regime of the zonal wind during the LIMS period corresponds to the westerly to easterly transition of the QBO, it is interesting to see that a robust signal of Kelvin waves is observed up to 7 hPa. Even in the westerly regime of the QBO (below 50 hPa), eastward progressing waves are clearly confirmed. In addition to the QBO-synchronized variation, Maruyama (1991) also suggested that Kelvin wave activity shows a gentle annual variation with a maximum in March in the lower stratosphere based on radiosonde observations for period of 1961–1989.

Next, we have analyzed tracer fields. Randel (1990) and Salby *et al.* (1990) investigated the LIMS atmospheric chemical species and showed that Kelvin waves can induce tracer oscillations such as in the ozone and nitrogen dioxide fields owing to the temperature dependence of photochemistry in the upper stratosphere. Their discussion referred to not only photochemically induced oscillation, but also wave-induced oscillation in the conservative region. However, they have not shown the clear existence of wave-induced oscillations related to the Kelvin wave, because the Kelvin wave itself was not clearly observed in the lower stratosphere during the period they analyzed. In this paper, we tried to find clear evidence of wave-induced oscillation in the tracer field in the lower stratosphere.

We found Kelvin wave-induced variations in the ozone field. Ozone anomalies clearly progress eastward having the same period and the same longitudinal phase relation as temperature. We discussed the ozone Kelvin waves in terms of linear Kelvin wave theory: For conservative transport, the ozone perturbation amplitude is expected to be a maximum at the largest vertical gradient of zonal mean ozone. We confirmed that the observed ozone amplitude is a maximum at 30 hPa, corresponding to the maximum vertical gradient of zonal mean ozone, and that this observed profile is qualitatively in good agreement with the theoretical estimate which is calculated from the temperature perturbation and tracer vertical gradient. However, the two profiles are quantitatively different; the theoretical estimate is about half of the observed ozone. This difference may be understood as an effect of ozone radiative-photochemical feedback. Echols and Nathan (1995) performed analytical and numerical model studies considering effects of ozone heating on Kelvin waves, and examined the LIMS experiment reported by Salby *et al.* (1990). They showed that the feedback effect enhances the Kelvin wave amplitude in the lower stratosphere, while it reduces the wave amplitude in the upper stratosphere. That is, in the lower stratosphere, the linear theory applying to our discussion causes an over estimate of the theoretical ozone perturbation amplitude calculated from the temperature amplitude. Their argument agrees with the V4 results in which the theoretical estimate is larger than that of the observed ozone (see Fig. 8 in Randel, 1990), but it is in disagreement with the V5 results in which the theoretical estimate is smaller than the observed ozone. Randel (1990) mentioned that the difference between V4 and in V5 data is due to the two temperature retrieval schemes which could affect short vertical scale features, resulting in stronger variations in V4 than V5 profiles.

"Water vapor" Kelvin waves were also observed in the lower stratosphere. Water vapor anomalies progressing eastward have a period of about two weeks and are roughly in-phase with temperature anomalies. The spatial structure is not so clear as that of ozone, because the vertical gradient of water vapor is weak in almost the whole stratosphere except at the bottom of the stratosphere.

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References

Andrews, D.G., J.R. Holton and C.B. Leovy, 1987: *Middle Atmosphere Dynamics*, Academic Press, 498pp.

Angell, J.K., C.F. Cotton and J. Korshover 1973: A climatological analysis of oscillations of Kelvin waves period at 50 mb, *J. Atmos. Sci.*, **30**, 13–24.

Brasseur, G. and S. Solomon, 1986: *Aeronomy of the Middle Atmosphere: Chemistry and Physics in the Stratosphere and Mesosphere*, Second edition, D, Reidel, Dordrecht, 452pp.

Canziani, P.O., J.R. Holton, E. Fishbein, L. Froidevaux and J.W. Waters 1994: Equatorial Kelvin waves: a UARS MLS view, *J. Atmos. Sci.*, **51**, 3053–3076.

Echols, R.S. and T.R. Nathan, 1995: Effects of ozone heating on forced equatorial Kelvin waves, *J. Atmos. Sci.*, **53**, 263–275.

Gille, J.C. and J.M. Russell, 1984: The limb infrared monitor of the stratosphere: experiment description, performance, and results, *J. Geophys. Res.*, **89**, 5125–5140.

Hartmann, D.L., 1978: A note concerning the effect of varying extinction on radiative-photochemical relaxation, *J. Atmos. Sci.*, **35**, 1125–1130.

Hitchman, M.H. and C.B. Leovy, 1988: Estimation of the Kelvin wave contribution to the semiannual oscillation, *J. Atmos. Sci.*, **45**, 1462–1475.

Hirota, I., 1978: Equatorial waves in the upper stratosphere and mesosphere in relation to the semiannual oscillation of the zonal wind, *J. Atmos. Sci.*, **35**, 714–722.

Hirota, I., 1979: Kelvin waves in the equatorial middle atmosphere observed by the Nimbus 5 SCR, *J. Atmos. Sci.*, **36**, 217–222.

Hirota, I., M. Shiotani, T. Sakurai and J.C. Gille, 1991: Kelvin waves near the equatorial stratopause as seen in SBUV ozone data, *J. Meteor. Soc. Japan*, **69**, 179–186.

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

Holton, J.R., 1975: *The Dynamic Meteorology of the Stratosphere and Mesosphere*, Meteor. Monogr., No. 37, Am. Meteor. Soc., Boston, Massachusetts.

Maruyama, T., 1969: Long-term behavior of Kelvin waves and mixed Rossby-gravity waves, *J. Meteor. 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. Meteor. Soc. Japan*, **69**, 219–232.

Randel, W.J., 1990: Kelvin wave-induced trace constituent oscillations in the equatorial stratosphere, *J. Geophys. Res.*, **95**, 18641–18652.

Randel, W.J., and J.C. Gille, 1991: Kelvin wave variability in the upper stratosphere observed in SBUV ozone data, *J. Atmos. Sci.*, **48**, 2336–2349.

Roders, C.D., 1976: Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation, *Rev. Geophys.*, **14**, 609–624.

Salby, M.L., D.L. Hartmann, P.L. Bailey and J.C. Gille, 1984: Evidence for equatorial Kelvin modes in Nimbus-7 LIMS, *J. Atmos. Sci.*, **41**, 220–235.

Salby, M.L., P. Callaghan, S. Solomon and R.R. Garcia, 1990: Chemical fluctuations associated with vertically propagating equatorial Kelvin waves, *J. Geophys. Res.*, **95**, 20491–20505.

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

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 waves and the quasi-biennial oscillation, *J. Meteor. Soc. Japan*, **46**, 496–502.

LIMSデータに見られる下部成層圏の赤道ケルビン波とそれにともなうトレーサー場の擾乱について

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人工衛星Nimbus 7号に搭載された測器Limb Infrared Monitor of the Stratosphere (LIMS)が観測したデータを用いて、下部成層圏の赤道ケルビン波とその力学的な移流効果によってトレーサー(オゾン、水蒸気)の場に誘起された擾乱の解析をおこなった。まず温度データから、1979年の4–5月を中心とする7 hPa以下の領域において、ケルビン波活動にともなう東西波数1、周期12–15日の東進波成分が確認できた。背景風が約 -16 ms^{-1} (50–10 hPaの平均)の中を鉛直波長約15 kmの波が下方に伝播している。

次に、オゾンの場からケルビン波の移流効果によって誘起された擾乱を検出した。その擾乱の振幅は東西平均したオゾン混合比の鉛直勾配が最大になる30 hPa付近で大きく、またそれは温度と同じ位相構造を持っている。これらの特徴は線型理論にもとづく予想と一致する。いっぽう水蒸気の場では、下部成層圏の50 hPaを中心に温度と同位相の東西波数1の東進波成分が見いだされた。ただし水蒸気においては、その空間構造はオゾンの場ほどはっきりしていない。