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MERIDIONAL DISTRIBUTION OF SHORT-VERTICAL-SCALE FLUCTUATIONS IN THE LOWER STRATOSPHERE REVEALED BY CROSS-EQUATORIAL OZONESONDE OBSERVATIONS ON "SHIRASE"

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Abstract: Meridional distribution of magnitude for short-vertical-scale fluctuations in the lower stratosphere over the wide latitudinal region between 62°S-43°N roughly along 120°E is investigated on the basis of vertical wavenumber spectra analyzed from temperature and ozone mixing ratio data observed by ozonesondes on "SHIRASE" cruises from 1987 to 1990. The power spectral densities of the 4.0 km, 2.7 km and 2.0 km wavelength components for normalized temperature and normalized ozone mixing ratio in the altitude range of 19-27 km are plotted as functions of latitude. It is found that there are symmetrical distributions with maxima near the equator as the first component and asymmetrical ones with larger value in the Northern Hemisphere as the second component for power spectral densities of normalized temperature. However, similar features are not found in distributions of ozone mixing ratio. To investigate this inconsistency, detailed short-vertical-scale structures of potential temperature and ozone mixing ratio have been compared. It is found that they do not show good agreement in the mid-latitude region.

1. Introduction

The meridional distribution of gravity wave activity in the middle atmosphere is important to understand the momentum and energy budget in the atmosphere. However, this subject has been examined by a relatively small number of observational studies, mainly because of limitation of observations.

Gravity wave activity in the lower stratosphere was investigated by KITAMURA and HIROTA (1989) using operational rawinsonde observations over Japan (27-45°N) for 1986. They showed large amplitudes of both temperature and zonal wind disturbances at the north edge of the jet stream, suggesting the existence of large amplitude gravity waves. They also showed those of only temperature disturbances around 16 km level in lower latitude and of only zonal wind disturbances near the jet stream, although they considered that these results might be contaminated by the vertical structures of the tropopause and the jet stream. Similar results have been confirmed by YAMANAKA *et al.* (1996) and OGINO *et al.* (1997) in the Baiu season in 1991 with detailed discussions on detectability of rawinsondes for wind disturbances associated with dominant gravity waves. Temperature amplitude increase with decreasing latitude in the Southern Hemisphere has been obtained by ALLEN and VINCENT (1995) using the temperature data of radiosonde observations over Australia (12–43°S and 69°S) during 1990–1993. OGINO *et al.* (1995) showed symmetrical distributions with maxima near the equator for both temperature and wind amplitudes based on cross-equatorial rawinsonde observations on the research vessel "HAKUHO-MARU" which cruised from 13.78°S to 24.50°N roughly along 150°E from November 1 to December 4, 1992. However, this result was based on only one observational cruise and requires confirmation.

In this paper we examine meridional distributions of short-vertical-scale fluctuations in the lower stratosphere over a large latitudinal region (60°S–43°N) based on ozonesonde observations for 4 years on the research vessel "SHIRASE". We first describe the data used in this study in Section 2. In Section 3, we show vertical wavenumber spectra of temperature and ozone mixing ratio. Meridional variations of the power spectral densities are presented in Section 4. In Section 5, a comparison of detailed structure between temperature and ozone mixing ratio is presented. Discussions and conclusions are given in Section 6.

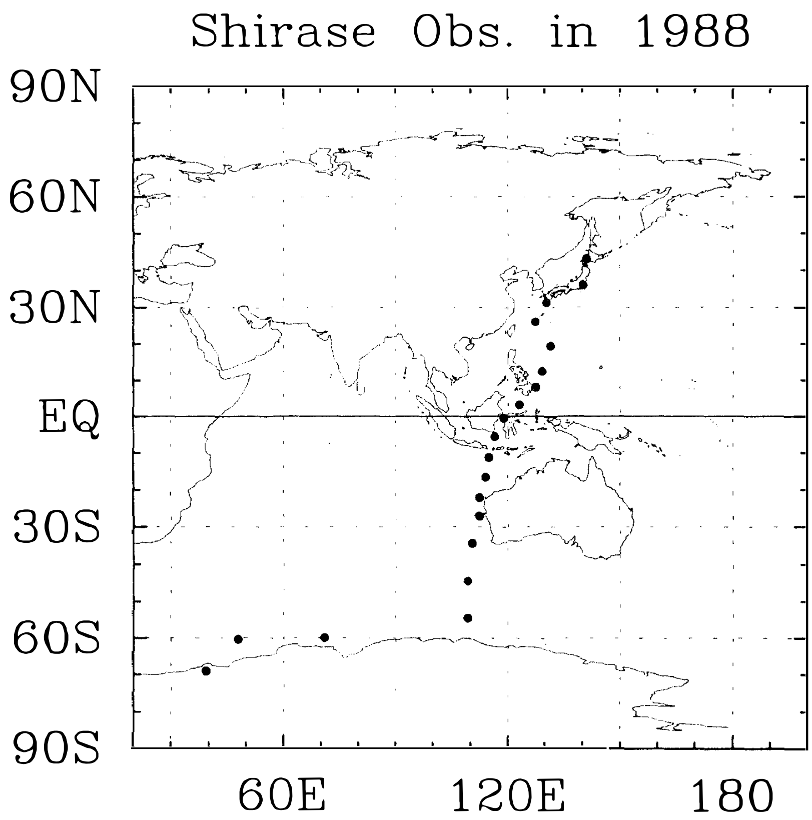

Fig. 1. Observation points along "SHIRASE" cruise in 1988. Those of routine ozonesonde observations by JMA are also plotted.

2. Data

The research vessel "SHIRASE" have travels from Tokyo, Japan to Syowa Station, Antarctica through the west Pacific Ocean and the east Indian Ocean every year during November and December. The season is quite similar to that of the "HAKUHO-MARU" cruise used in our previous study (OGINO *et al*., 1995), although the trajectory (along 110–140°E) is located to the east of the latter (along 140–160°E). In 1987–1990, extensive ozonesonde observations were carried out (preliminary results from the observation in 1987 were reported by MATSUBARA *et al*., 1991). The ozonesondes (Meisei KC-79) were launched at ~1 day intervals, which corresponds to ~5° latitudinal resolution (observation points are shown in Fig. 1). In each launch, vertical distribution of temperature and ozone were observed with 300–400 m height resolution (~1 min sampling interval). Horizontal wind was also observed only in 1987 and 1988. Adding data of routine ozonesonde observations at 4 stations (Sapporo, Tsukuba, Kagoshima and Naha) by JMA (Japan Meteorological Agency), latitudinal (60°S–42°N, roughly along 120°E) and vertical (0–30 km) distributions of temperature and ozone are obtained. In this study, we interpolate all the original data linearly at a height interval of 50 m.

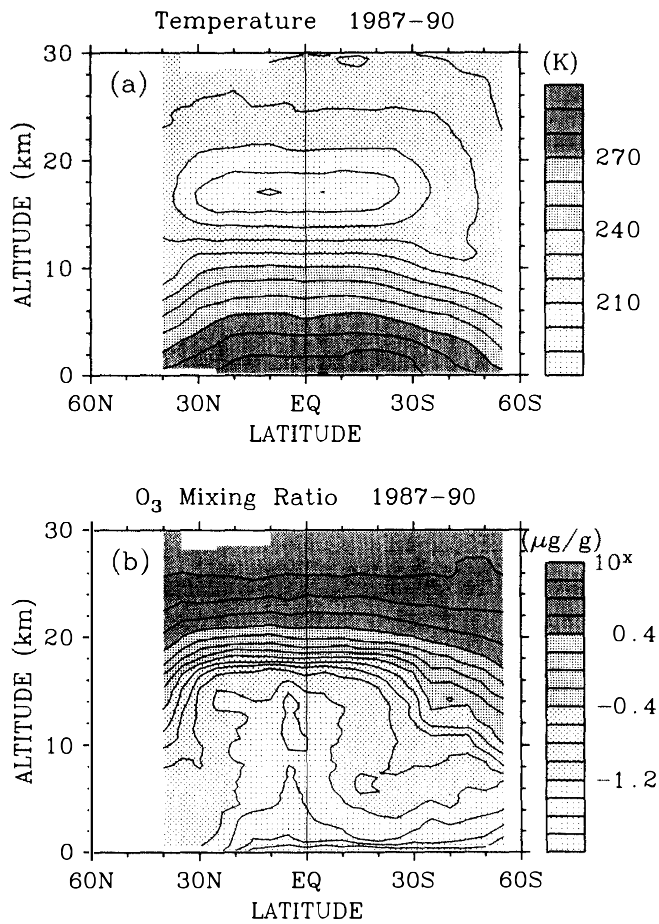

Fig. 2. Meridional cross sections of (a) temperature and (b) ozone mixing ratio averaged over 4 year observations.

Figure 2 shows meridional cross sections of temperature and ozone mixing ratio averaged over 4 year observations. The 4 year averaged value at every 10° was obtained by averaging all the data for 4 years of observations in each 10° latitude band. The tropopauses exist at about 17 km altitude in the equatorial region and lower in mid-latitudes. Ozone mixing ratio begins to increase just above the tropopause. Year-to-year variations of such background structures seem to be not large, although the data are not presented here.

Vertical profiles of fluctuations of temperature T' and of ozone mixing ratio R' are shown in Figs. 3 and 4, respectively. T' is defined as $T-\bar{T}$, where T is the observed temperature and $\bar{T}$ is a background temperature (which is defined by low-pass filtered temperature with cut-off vertical wavelength of 8 km in this study). R' is defined in the same manner. In almost all the profiles, we can easily notice that shallow wavy structures with vertical wavelength 1-4 km are dominant just above the tropopause. These fluctuations are mainly studied in this paper.

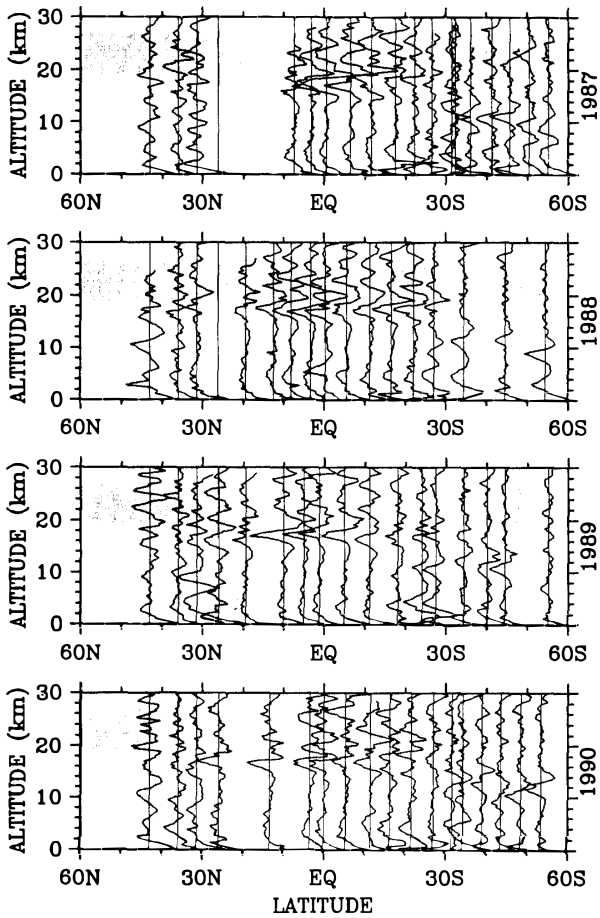

Fig. 3. All the vertical profiles of fluctuations of temperature observed with ozonesondes launched at "SHIRASE". 1° corresponds to 1.1 K. The altitude range (19-27 km) mainly analyzed in this study is indicated by shaded areas.

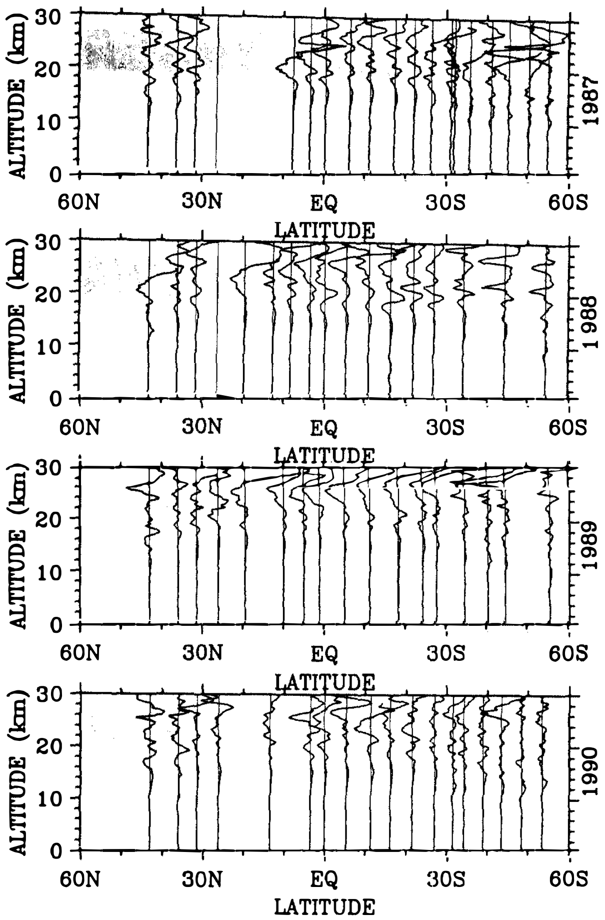

Fig. 4. *As in Fig. 3 but for fluctuations of ozone mixing ratio. 1° corresponds to 0.2 μg/g.*

3. Power Spectral Analysis

We have analyzed a vertical wavenumber spectrum for each profile of normalized temperature and normalized ozone mixing ratio. The altitude range for spectral analysis was chosen to be 19–27 km in order to avert contamination by a sharp peak at the tropopause. After removing a linear trend from an individual profile and applying a bell taper window to remove the edge effect, we employ a fast Fourier transform directly in the power spectral analysis (see YAMANAKA *et al*., 1996; OGINO *et al*., 1995, 1997).

Figure 5 shows mean power spectra of normalized temperature $T'/\bar{T}$ and normalized ozone mixing ratio $R'/\bar{R}$ averaged over all observations. The spectrum of normalized temperature and that of normalized ozone mixing ratio is converted to a horizontal wind spectrum by multiplying by $5g^2/[3N^2]$ and $5\bar{R}N^2/[3(\partial\bar{R}/\partial z)^2]$, respectively, where N is the Väisälä-Brunt frequency (averaged over 19–27 km altitude) and g is gravity acceleration, to compare the power spectral density quantitatively following a semi-empirical model of gravity wave spectra with potential to kinetic energy ratio of 3/5 (VANZANDT, 1982; OGINO *et al*., 1995). The spectra in the higher vertical wavenumbers have a spectral slope of approximately -3 (*e.g*. SMITH *et al*., 1987; FRITTS *et al*., 1988; TSUDA *et al*., 1991; ALLEN and VINCENT, 1995; YAMANAKA *et al*., 1996). However, the magnitude of the normalized

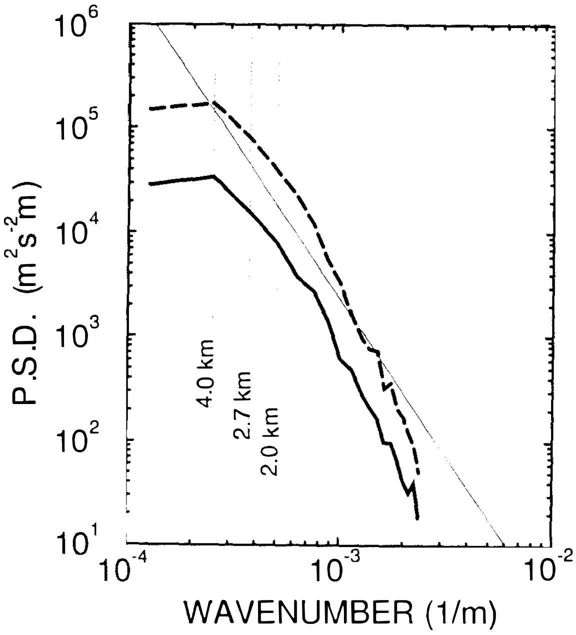

Fig. 5. Mean power spectral densities of normalized temperature (thick solid line) and normalized ozone mixing ratio (thick dashed line) observed in the 19–27 km altitude range. The thin solid line indicates the model value $N^2/[6m^3]$. The 4.0, 2.7 and 2.0 km vertical wavelength components mainly discussed in this study are indicated by thin dashed lines.

temperature spectrum seems to be somewhat smaller (1/2–1/10) than the model value ($N^2/[6m^3]$, where m is a vertical wavenumber) which is expected from linear saturation theory of gravity waves (SMITH *et al.*, 1987; FUKAO *et al.*, 1989).

4. Meridional Variation

Figure 6 shows meridional variations of power spectral densities of normalized temperature for 4.0 km, 2.7 km and 2.0 km wavelength components. We can find symmetrical distributions with maxima near the equator as the first component. This feature seems to be remarkable in the larger wavelength component. Furthermore, we can also find asymmetrical distributions with larger value in the Northern (or winter) Hemisphere as the second component. The mean value in 30°–40° in the Northern Hemisphere is about 3 times larger than in the Southern hemisphere. However, we cannot find similar distributions with equatorial maxima and asymmetry between Northern Hemisphere and Southern Hemisphere in panels of ozone mixing ratio (Fig. 7) and we can find that differences of the power spectral densities between temperature and ozone mixing ratio are larger in the mid-latitude region. This inconsistency will be investigated in the next section.

5. Consistency between Temperature and Ozone Fluctuations

It has been known that vertical profiles of ozone in the lower stratosphere have wave-like structures (*e.g.* DOBSON, 1973; EVANS *et al.*, 1979) and that both temperature and

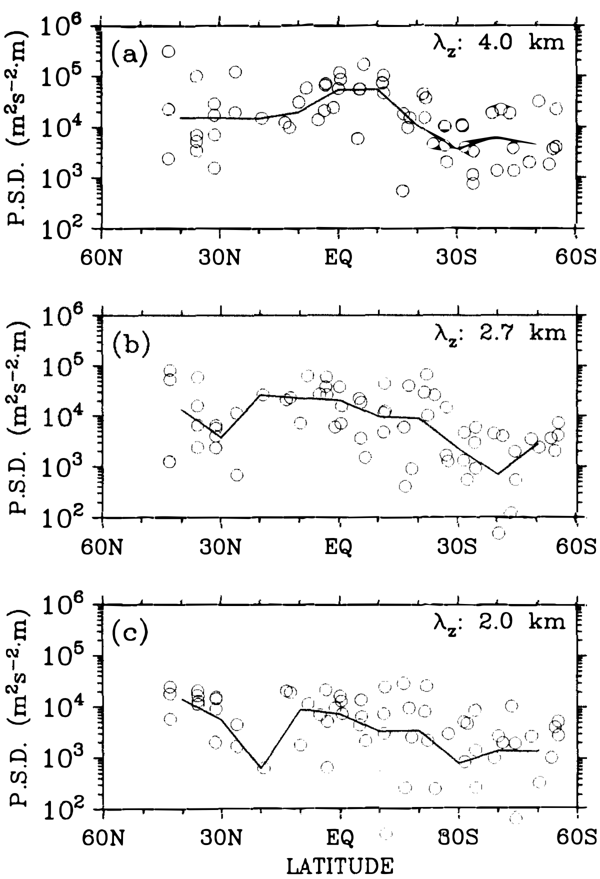

Fig. 6. Meridional variations of power spectral densities of (a) 4.0 km, (b) 2.7 km and (c) 2.0 km vertical wavelength components for normalized temperature observed in the 19–27 km altitude range. Circles indicate calculated values from individual observations. Solid lines in each panel show mean values in each 10° latitudinal band.

ozone fluctuations are often induced gravity waves (*e.g.* DANIELSEN *et al.*, 1991; TEITELBAUM *et al.*, 1994). Here, we examine the relationship between temperature and ozone fluctuations observed by "SHIRASE" to consider the results obtained in the previous section.

In the lower stratosphere, the photochemical lifetime of ozone is longer (several months or more) than periods of waves which we focus on in this study (10^0 hour-10^1 day), so that we can assume that both potential temperature θ and ozone mixing ratio R are conserved quantities:

$$\frac{\mathrm{D}\theta}{\mathrm{D}t}=0 \text{ and } \frac{\mathrm{D}R}{\mathrm{D}t}=0, \tag{1}$$

(LINDZEN, 1990). By linearization under an assumption that each physical quantity can be decomposed into a sum of a background component which is uniform in the horizontal direction and time and a perturbation component:

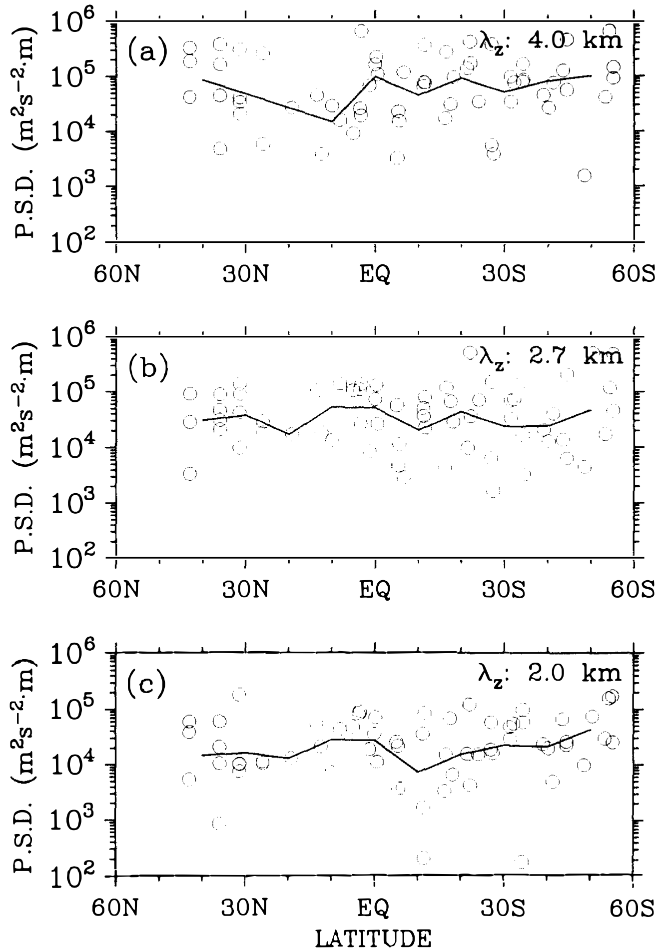

Fig. 7. As in Fig. 6 but for normalized ozone mixing ratio.

$$\begin{aligned} \theta &= \bar{\theta}(z) + \theta'(x, y, z, t) \\ R &= \bar{R}(z) + R'(x, y, z, t) \\ u &= \bar{u}(z) + u'(x, y, z, t) \\ v &= \bar{v}(z) + v'(x, y, z, t) \\ w &= \qquad w'(x, y, z, t), \end{aligned} \tag{2}$$

where u, v and w are zonal, meridional and vertical velocities, respectively, eq. (1) becomes:

$$\begin{aligned} \left(\frac{\partial}{\partial t} + \bar{u}\frac{\partial}{\partial x} + \bar{v}\frac{\partial}{\partial y}\right)\theta' + w'\frac{\partial\bar{\theta}}{\partial z} &= 0 \\ \left(\frac{\partial}{\partial t} + \bar{u}\frac{\partial}{\partial x} + \bar{v}\frac{\partial}{\partial y}\right)R' + w'\frac{\partial\bar{R}}{\partial z} &= 0. \end{aligned} \tag{3}$$

Assuming wave-like solutions of the form exp $\{i(kx+ly+mz-\omega t)\}$, we obtain:

$$\theta^* \equiv \mathrm{Real}[\theta']\left(\frac{\partial\bar{\theta}}{\partial z}\right)^{-1} = \mathrm{Real}[R']\left(\frac{\partial\bar{R}}{\partial z}\right)^{-1} \equiv R^*. \tag{4}$$

An example of vertical profiles of θ^* and R^* is shown in Fig. 8a. In the lower stratosphere, θ^* and R^* have good agreement. Another example which does not show

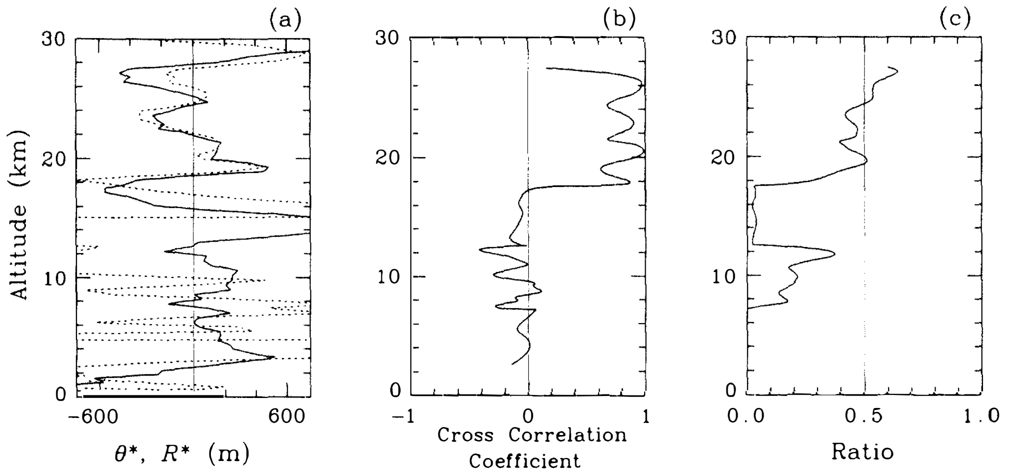

Fig. 8. Vertical profiles of (a) θ^* (solid line) and R^* (dashed line), (b) cross-correlation coefficient between θ^* and R^* and (c) amplitude ratio $V_{\theta^*}/(V_{\theta^*}+V_{R^*})$, observed at 1°S 119°E on 21 November 1987. These values were calculated by using the data 2.5 km above and below each altitude.

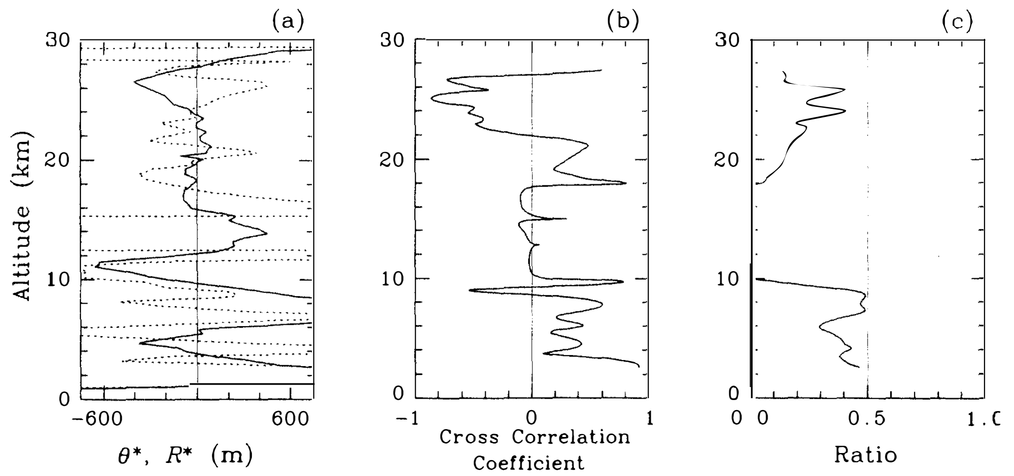

Fig. 9. As in Fig. 8 but for profiles observed at 35°S 111°E on 4 December 1988.

good agreement is also shown in Fig. 9a. In order to quantify the agreement, we have calculated the cross-correlation coefficient between θ^* and R^* (Figs. 8b and 9b) and amplitude ratio $V_{\theta^*}/(V_{\theta^*}+V_{R^*})$, where V denotes variance (Figs. 8c and 9c). These two values were calculated by using the data in an altitude range 2.5 km above and below each altitude. Figure 10 shows the meridional cross section of correlation coefficient and amplitude ratio. We find that correlation coefficients take positive values at almost all latitudes in the lower stratosphere and that θ^* and R^* correlate well to each other and take closer values in the equatorial region.

6. Discussion and Conclusion

In this study we have analyzed vertical wavenumber spectra of temperature and ozone

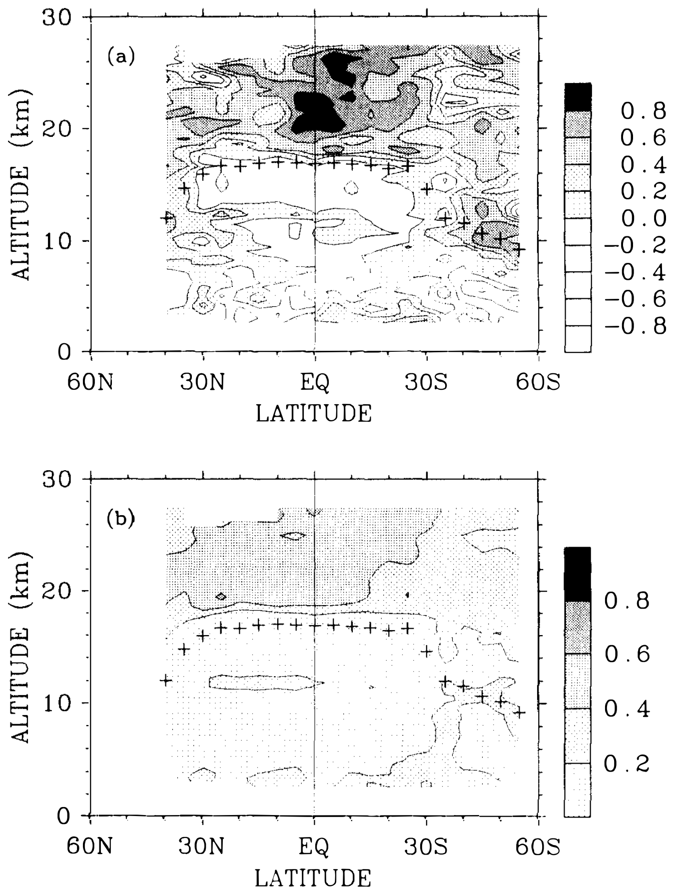

Fig. 10. Meridional cross section of (a) cross-correlation coefficient between θ^* and R^* and (b) amplitude ratio $V_{\theta^*}/(V_{\theta^*}+V_{R^*})$. These values were calculated by using the data 2.5 km above and below each altitude. Plus marks denote mean tropopause heights.

mixing ratio obtained from ozonesonde observations on the research vessel "SHIRASE" and by JMA over a wide latitudinal range (60°S–43°N) roughly along 120°E, and investigated meridional distributions of power spectral densities with vertical wavelengths of 4.0, 2.7 and 2.0 km. We have found symmetrical distributions with maxima near the equator as the first component and asymmetrical distributions with larger values in the Northern (or winter) Hemisphere as the second component in power spectral densities of normalized temperature. The equatorial maxima are consistent with our previous study (OGINO *et al.*, 1995), which strongly suggests that such distributions exist universally, at least over the west Pacific Ocean and the east Indian Ocean in the Northern Hemispheric winter. It must be noted, however, that because Kelvin waves or mixed Rossby gravity waves may exist in the equatorial region, it is open to question whether the short-vertical-scale fluctuations mainly discussed in this study are associated by gravity waves.

Several reasons must be considered to explain the asymmetrical distributions: seasonal difference, difference between observation points east of the Asian Continent and west of the Australian Continent, or difference of orographic undulations between the Northern Hemisphere and Southern Hemisphere. Further investigation of such meridional distributions will be quite important to understand the role of gravity waves in the global circulation quantitatively and to clarify the excitation source of gravity waves. So, similar observations in different seasons and different longitudes are strongly expected.

Unlike power spectral densities of normalized temperature, those of normalized ozone mixing ratio do not show remarkable meridional variations. Comparison of detailed structure of potential temperature and ozone mixing ratio shows good agreement in the low latitude region. This suggests that in the low latitude region the fluctuations of temperature and ozone can be explained only by vertical advection of air parcels. On the other hand, other photochemical or dynamical processes must be considered to explain the different structures of temperature and ozone fluctuations in the mid-latitude region. Although the reason for this inconsistency is not yet clear, one possible candidate is that meridional advection of the background field $v\partial(\bar{\theta}, \bar{R})/\partial y$, which was omitted in eq. (3), cannot in fact be neglected. Further investigation needs to determine wave structures. Routine ozonesonde observations including wind data by JMA will be helpful to clarify the inconsistency between temperature and ozone fluctuations in the mid-latitude region.

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