Equatorial Inertia-Gravity Waves in the Lower Stratosphere Revealed by TOGA-COARE IOP Data

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Abstract

Short-period disturbances in the equatorial lower stratosphere are analyzed by using radiosonde data of horizontal winds and temperature at 10 stations during the TOGA-COARE intensive observational period (IOP). The analysis is focused on disturbances whose periods are shorter than about 3 days.

Time-height cross sections of both horizontal winds and temperature show the existence of disturbances with periods of about two days and vertical wavelengths of 3-5 km. First, we made power and cross-spectral analyses. Dominant disturbances in northern [7°N-8°N] and southern [9°S-11°S] areas of the TOGA-COARE Large-scale Soundings Array (LSA) regions, propagate eastward and have similar structure in which vertical and horizontal wavelengths are 3-4 km and several to ten thousand kilometers, respectively. The phase differences between the zonal and meridional wind components at one location, and the phase differences in wind components between the northern and southern regions, exhibit the typical structure of equatorially-trapped inertia-gravity waves. In the TOGA-COARE LSA equatorial area, dominant disturbances have vertical wavelengths of 4-5 km which are a little longer than those observed in the northern and southern areas. Phase differences are clear for meridional wind components between zonally separated stations, and show that the horizontal wavelengths are three to four thousand kilometers, and that the disturbances propagate eastward. On the other hand, phase differences between zonally separated stations for zonal wind components are not significant.

Next, a composite analysis was made with a reference of convective activity in the troposphere. Short period disturbances with 3-5 km vertical wavelengths, which are consistent with the results of the spectral analysis, appear in the composite of lag-time-height sections in the lower stratosphere, indicating that these disturbances are strongly linked to the convective activity. Vertical phase propagation is downward in the upper troposphere and lower stratosphere, showing that these disturbances propagate energy upward there.

Possible equatorially-trapped modes having the wave structures revealed by the above spectral and composite analysis are estimated using the theoretical dispersion relation. It is likely that the disturbances in the northern and southern areas correspond to \( n=1 \) eastward inertia-gravity waves. The possible modes in the equatorial regions are different for zonal and meridional wind disturbances, because odd (even) modes have zonal (meridional) wind component only.

The estimated wave parameters for meridional wind disturbances are consistent with \( n=0 \) inertia-gravity waves propagating eastward. The disturbances dominant in the zonal wind component in the equatorial areas which do not show clear coherent zonal structure are probably due to a mixture of \( n=-1 \) Kelvin waves, \( n=1 \) eastward and westward inertia-gravity waves.

1. Introduction

In the latter half of the 1960’s, two kinds of equatorial waves were discovered. One is the mixed Rossby-gravity wave first discovered by Yanai and
Maruyama (1966), and the other is the Kelvin wave, discovered by Wallace and Kousky (1968). These waves were identified as the normal mode solutions on the equatorial beta plane, derived by Matsuno (1966). Following this, the detailed structure of these waves has been examined extensively by a large number of observational studies. Mixed Rossby-gravity waves propagate westward with a period of about 4–5 days, and vertical and zonal wavelengths of 4–8 km and 10,000 km. Kelvin waves propagate eastward with a period of about 15 days and vertical and zonal wavelengths of about 6–10 km and 20,000–40,000 km.

Studies of smaller-scale inertia-gravity waves in the lower stratosphere have been performed, and understanding of their contribution to the mean flow has been renewed by observational analyses and numerical simulations. Cadet and Teitelbaum (1979) analyzed the data of soundings launched from a research vessel during the GATE (GARP [Global Atmospheric Research Programme] Atlantic Tropical Experiment) and showed the inertia-gravity waves propagate westward in the easterly shear background flow. Tsuda et al. (1994) discussed the characteristics of gravity waves in the equatorial region by analyzing radiosonde measurements of wind velocity and temperature fluctuations from February 27 to March 22, 1990 in east Java, Indonesia (7.6°S, 112.7°E). They showed that the typical vertical wavelengths of the waves are 2–2.5 km and that most of them propagate eastward in the westerly shear background flow. Maruyama (1994) analyzed twice-daily time series upper-air data in Singapore (1°N, 104°E) during 1983–1993 to examine disturbances in the period of about 2 days. It was shown by his analysis that the vertical fluxes of zonal momentum are related strongly with the quasi-biennial oscillation (QBO) cycle, and that the largest flux occurs in the region where the westerly regime is descending.

Sato et al. (1994) examined temperature and horizontal wind fluctuations for periods shorter than 3 days in the equatorial lower stratosphere using data from operational rawinsonde observations in Singapore during 1978–1993. They showed that 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 and that short-period fluctuations have significant energy separated from long-period Kelvin waves and mixed Rossby-gravity waves. Extending this study, Sato and Dunkerton (1997) estimated positive and negative parts of momentum fluxes separately. They concluded that gravity waves propagate eastward and westward almost equally in the lower stratosphere. Based on numerical studies (Takahashi, 1996; Alexander and Holton, 1997), as well as these quantitative observational studies, it is considered that gravity waves may play the leading role in driving the QBO, together with Kelvin and Rossby-gravity waves (Dunkerton, 1997). However, the observational studies described above are based on data from a single observation station, so a detailed horizontal structure has not yet been clarified.

In the troposphere, the existence of quasi 2-day fluctuations has been demonstrated by recent observational studies. Takayabu (1994a,b) showed the dominance of 1.5–2.5 day period disturbances in the cloud field during December to February by utilizing three-hourly infrared equivalent blackbody temperature (TBB) data from the Japanese Geostationary Meteorological Satellite (GMS). Takayabu et al. (1996) further described the detailed structure of the quasi 2-day oscillation observed during TOGA-COARE. The quasi two-day mode has a westward-propagation speed of about 20 m s⁻¹, a horizontal wavelength of ~30° longitude and eastward phase tilt with height throughout the troposphere. The observed wind disturbance structures are consistent with those of the westward-propagating n = 1 inertia-gravity waves. Takayabu et al. (1996) focused on the phenomena only below 100 hPa, but here we pay attention to the phenomena above 100 hPa, especially in the lower stratosphere. In the stratosphere, Ogino et al. (1995) showed the meridional variations of power spectral densities for wind, using Hakuho-Maru J-COARE (Japanese Coupled Ocean-Atmosphere Response Experiment) Cruise Rawinsonde data. However, they represented only the variances, and could not investigate the interrelationship between data for other locations. Karoly et al. (1996) showed the gravity wave activity using TOGA-COARE sounding data at Santa Cruz (10°S, 165°E). But their analysis was also based on a single observational station data. In this study, we will investigate equatorial waves based on the data from stations in the TOGA-COARE region. We aim to show the horizontal structure of the short-period disturbance in the lower stratosphere using TOGA-COARE rawinsonde data at 10 stations, and to examine the relationship between these disturbances and convective activity in the troposphere. In Section 3 we plot the time series data of winds to show the existence of short-period disturbances in the lower stratosphere. In Section 4, spectral analysis is applied in order to examine the vertical and horizontal structures of the disturbances. In Section 5 we make a composite analysis to determine the relationship between the short-period disturbances in the lower stratosphere and convective activity. In Section 6, discussions are made concerning the identification of wave types observed in the data. A summary and concluding remarks are given in Section 7.
2. Data and method of analysis

2.1 Data

The data used in this study are TOGA-COARE rawinsonde data and GMS TBB data. Dense upper-air observation data during TOGA-COARE Intensive Observation Period (IOP) from November 1992 to February 1993 are utilized for analyses.

Figure 1 shows a map of the TOGA-COARE Large-scale Soundings Array (LSA). LSA denotes an area bounded by latitudes 10oS and 10oN and longitudes 140°E and 180°. Ten stations where upper-air observations were made four times a day are used for analysis in this study. In this area, OOZ corresponds to 10 A.M. local time. These stations are Chuuk (7.40°N, 151.80°E), Pohnpei (7.00°N, 158.19°E), Manus (2.1°S, 147.4°E), Kavieng (2.6°S, 150.8°E), Kapingamarangi (1.1°N, 154.8°E), Kexue #1 (4.0°S, 156.0°E), Shiyan #3 (2.3°S, 158.0°E), Nauru (0.0°, 166.9°E), Misima (10.7°S, 152.8°E), and Honiara (9.4°S, 160.0°E). Intensive Flux Array (IFA) is the inner quadrangle area surrounded by solid lines, and Outer Sounding Array (OSA) is the outer hexagon shown by broken lines.

Since characteristic features of disturbances are expected to depend strongly on latitude, we classify these 10 stations into three areas; the northern area (Chuuk, Pohnpei), the equatorial area (Manus, Kavieng, Kapingamarangi, Kexue #1, Shiyan #3, Nauru) and the southern area (Misima, Honiara).

In each launch of upper-air soundings, data were sampled every ten seconds corresponding to roughly 46 m height intervals (Ogino et al., 1995). After doubtful data are removed, linear interpolation is applied to obtain data with fixed height intervals of 100 m. The data are obtained up to about 20 km height for most of the stations (Fig. 2). We also use TBB data on a 1°X 1°grid at three-hourly intervals for the study of convective activity.

2.2 Method of analysis

We apply a power spectral analysis to wind and temperature data to examine the amplitude of short-period disturbances. A cross-spectral analysis is performed to obtain vertical and horizontal phase differences associated with the short-period disturbances. The Blackman-Tukey method is used for the calculation of the spectrum. The maximum lag number is 80 (20 days). Minimum and maximum frequencies are 0.025 cycles/day and 2.0 cycles/day, corresponding to maximum and minimum period of 40 days and 0.5 days, respectively. A spectral analysis is applied to time series data only when more than 30 % data are available.

A composite analysis is applied to obtain disturbances accompanied by the convective activity with a quasi 2-day period. For the convenience of comparison, the reference points for the composite are
chosen to be the same as used by Takayabu et al. (1996), that is, the reference time Day 0 for the composite is determined by selecting 8 minimum \( T_{BB} \) values averaged over the IFA region during the periods of December 10–16 and 21–27, 1992. It means that Day 0 corresponds to the time of the most vigorous convective activity. Time series data of winds for 2 days before and after Day 0 are used for the composite.

3. Background zonal field and existence of short-period wind fluctuation

Figure 3 shows a latitude-height section of zonal wind velocities averaged over the whole period of TOGA-COARE-IOP. In the lower stratosphere, westerlies and easterlies are prominent above and below 20 km, respectively, corresponding to the QBO-phase where westerly winds are descending. The mean tropopause level during this period is about 16.5 km; the tropopause level appears to fluctuate by superposing downward wavelike progressions with periods of about 10–15 days (not shown). Similar fluctuations are reported by Shimizu and Tsuda (1997).

Figure 4 gives time-height sections of meridional wind velocities during December 1992 in the (a) northern, (b) equatorial, and (c) southern areas. In order to see the short-period disturbances, we applied a high-pass filter with a cutoff length of 3 days at each altitude. In the lower stratosphere (17–30 km), we can find wavelike disturbances with a period of about 2 days and a vertical wavelength of 3–5 km. The vertical wavelength in the equatorial area seems to be longer than in the northern and southern areas. Downward phase propagation indicating upward energy propagation can be clearly recognized in the lower stratosphere. These short-period wavelike disturbances can also be found in the zonal wind and temperature data, and at other stations (not shown).

Both wave periods and vertical wavelengths are similar to wave structures analyzed by previous observational studies in the equatorial area (Sato et al., 1994), and in the southern area (Tsuda et al., 1994).

4. Spectral analysis of short-period disturbances

We perform spectral analysis of winds and temperature, in order to examine the horizontal and vertical structure of the disturbances. Following the classification of analysis areas described in Section 2, we will discuss the structures of disturbances over three different northern, equatorial and southern ar-
4.1 Power spectra at each station

Power spectra of meridional winds (v) at Chuuk (7.40°N, 151.80°E) in the northern area are shown in Fig. 5a. Large spectral power is seen at periods of 4–5 days in the upper troposphere (10–16 km). Large power of the 4–5 day period is also found in the lower troposphere below 5 km, which corresponds to mixed Rossby-gravity waves as analyzed by Numaguti et al. (1995). Large power amplitudes are found around the period of about 2 days in the upper troposphere (10–15 km), which synchronized with the convective activity analyzed by Takayabu et al. (1996). Spectral amplitudes with periods shorter than 3 days are dominant in the lower stratosphere above 18 km. In particular, a dominant spectral peak at periods of 2–3 days is seen at about 20 km height. Diurnal variations of v are also large in the lower stratosphere. Figure 5b shows power spectra of v at Manus (2.06°S, 147.43°E) in the equatorial area. As in the northern area, spectral amplitudes corresponding to mixed Rossby-gravity waves are dominant at periods of 4–5 days in the troposphere. Around the period of 2 days, spectral amplitudes which synchronized with the convective activity (Takayabu et al., 1996) are also dominant in the upper troposphere between 10–15 km. In the lower stratosphere from 16 km to 20 km, there are relatively large spectral amplitudes at periods of 2–5 days. Figure 5c shows power spectra of v at Misima (10.70°S, 165.80°E) in the southern area. Spectral power is large in periods shorter than about 3 days in the lower stratosphere. A dominant peak is seen in the period of 2–3 days as seen at Chuuk in the northern area (Fig. 4a). On the other hand, large power exists around 4–5 day periods in the troposphere.

Power spectra of zonal winds (u) at Chunk are shown in Fig. 6a. As for v fluctuations, spectral amplitudes of u are dominant at periods shorter than 3 days in the upper troposphere and lower stratosphere. There exists large spectral power at periods longer than 10 days in the upper troposphere and lower stratosphere (10–20 km) which may correspond to Kelvin waves. The spectral peaks of 4–5 days in the troposphere are thought to be due to mixed Rossby-gravity waves. Large spectral power is also found in the period ranges of 2–3 days in T, in the lower stratosphere between 17–22 km (not shown). Results for Manus are shown in Fig. 6b. In the zonal wind, disturbances with a period longer than 10 days due to Kelvin waves are dominant in the troposphere and stratosphere. Disturbances with 4–5 day periods which probably correspond to mixed Rossby-gravity waves are also dominant in the lower and upper troposphere. Note that Manus is located slightly away from the equator, so that Rossby-gravity waves can have nonzero amplitude of u component. Spectral peaks at periods of 2 days are seen separately.
in the upper troposphere are associated with convective activity, as shown later (Fig. 12). Large spectral power is seen in the periods of 1–3 days, as well as in the longer periods in the lower stratosphere. Figure 6c shows power spectra of $u$ at Misima. Dominant spectral peaks shorter than 3 days in the stratosphere, as in $v$ fluctuations, are also observed in $u$ component. In addition to short-period disturbances, large spectral amplitudes at periods longer than 10 days which may be due to Kelvin waves, and 4–5 days which may due to Rossby-gravity waves are conspicuous. At another station in the southern area, Honiara, similar spectral features to those at Misima are observed (not shown).

4.2 Vertical structure of the disturbances

Our next concern is the vertical and horizontal structure of the disturbances. To investigate the ver-
tical structure of the disturbances, we make a cross spectra for a time series at a reference height and at other various heights. The reference is taken to be the height where the spectral amplitude is largest near a 2-day period. In Fig. 7a the coherence and the phase difference for the 2-day-period component of meridional wind fluctuations at Chuuk are plotted as a function of height. The reference height is chosen as 21.5 km. A systematic phase-height relationship is displayed at the height in the layer 15-27 km, and the phase leads with height. From this phase structure, it is estimated that the vertical wavelength of the disturbance is 3-4 km, which is consistent with the wavelike structure seen in the time-height section of Fig. 4a. Comparatively large coherence is also found in the upper troposphere from 10 km to 13 km height. This suggests that short-period disturbances in the lower stratosphere

Fig. 5. Power spectra of (a) $v$ disturbances at (a) Chuuk, (b) Manus and (c) Misima as a function of height. The contour interval is $4 \text{ m}^2 \text{ s}^{-2}$.
are related to those in the upper troposphere. At Pohnpei, another station in the northern area, similar spectral features to those at Chuuk are observed (not shown).

The result of the coherence and phase difference of \( v \) in the vertical direction at Kexue #1 in the equatorial area is shown in Fig. 7b. The reference height is taken to be 16.6 km. The results for the 2-day period are plotted. Although the data are not available above 20 km, about one cycle of phase change can be seen in the layer between 15 km and 20 km. The estimated vertical wavelength is 4–5 km in the lower stratosphere, as seen in the time-height section of Fig. 4b. Relatively large coherences in the layer above 11 km imply that disturbances in the lower stratosphere and those in the troposphere are linked to each other. The analysis for the zonal wind also shows that the phase leads with height in the lower stratosphere, and the estimated vertical wavelength is 5–6 km (not shown).

Fig. 6. The same as Fig. 5, but for \( u \) disturbances.
Results at Misima in the southern area are plotted in Fig. 7c. The reference height is 17.5 km. A systematic phase-height relationship can be seen in the lower stratosphere, as in the northern area. The vertical wavelength of the disturbance is estimated at 3–4 km and the phase leads with height. At another station in the southern area, Honiara, a similar phase structure is observed (not shown).

4.3 Horizontal structure of the disturbances

In order to investigate the horizontal characteristics of the disturbances, we calculated cross-spectra between Chuuk and Pohnpei. Figure 8a shows coherence and phase difference of \(v\) at each height during the period of 2 days between two stations. Since we define Chuuk as a reference point, positive (negative) phase difference means that the disturbances propagate westward (eastward). Relatively large coherences are found in the stratosphere. Phase differences vary with height. But in general, they are negative in the stratosphere, indicating eastward propagation. Taking their distance of about 940 km into account, the zonal wavelength is estimated at about 2,800 km. Table 1 shows the obtained phase differences for \(v\) between Manus and 5 other stations for a 2-day period component in the lower stratosphere and corresponding zonal wavelengths. All results indicate the eastward propagation. All estimated zonal wavelengths except for Kappingamarangi are around 3,000–4,000 km.

Coherence and phase difference at each height for a 2-day period component between Misima and Honiara (9.42°S, 159.97°E) are shown in Fig. 8c. The distance between Misima and Honiara is about 780 km. Above about 19 km, where a dominant peak is seen in the power spectra, the phase difference is about −30°, indicating that the disturbances move eastward with zonal wavelengths of several thousands to ten thousand kilometers.
4.4 Phase differences between $u$ and $v$

Cross spectra between $u$, $v$, and $T$ components were also computed. Figure 9a shows the phase relationship between $u$ and $v$ at the period of 2 days at Chuuk, in the northern area. The coherence is relatively large and the phase of $v$ leads that of $u$ in time by $90^\circ$. This phase relationship is consistent with the horizontal wind structure of inertia-gravity waves which should rotate clockwise in time in the northern hemisphere (e.g., Gill, 1982). No clear phase relationship was obtained between $u$ and $T$.

At Nauru in the southern area, the phase relationship between $u$ and $v$ is opposite to that in the northern area (Fig. 9c). The phase of $u$ leads that of $v$ in time by $90^\circ$. This phase relationship is consistent with the characteristics of inertia-gravity waves in the southern hemisphere.

In the equatorial area, the coherences are relatively small, and no systematic relationship between $u$ and $v$ is seen (Fig. 9b).

4.5 The relationship between the waves in the northern area and southern areas

Figure 10 shows the phase difference of $v$ between Pohnpei in the northern area and Honiara in the southern area for a 2-day period component. In the lower stratosphere, coherence between the two locations is large and the phase difference is about $180^\circ$. This means that the disturbances in the northern and southern areas are closely linked with each other, and that they exist over the tropics having a meridional scale of at least a few thousand kilometers. However, the waves found in the equatorial area are thought to be different from those dominant in the northern and southern areas, be-
5. Composite features synchronized with the convection

In this section, disturbances synchronized with convection in the troposphere are examined by a composite analysis. We choose eight convective systems with a period of quasi 2-days for the composite, which are the same systems as described by Takayabu et al. (1996). Figure 11 shows the IFA-circumscribed rectangular area-mean $T_{BB}$ in December 1992. The reference time Day 0 for the composite was depicted by arrows. Day 0 corresponds to the minimum $T_{BB}$ time at the IFA area. The result of composite for $v$ at Chuuk in the northern area is shown in Fig. 12a. The time mean is subtracted at each height. Signals of quasi 2-day wave with phases propagating downward can be seen dominantly in the upper troposphere ($12 \text{ km} \leq z \leq 16 \text{ km}$). There are also quasi 2-day signals in the lower troposphere ($z \leq 12 \text{ km}$) whose phases are propagating upward. These characteristics in the troposphere observed in Fig. 12 are consistent with the results of Takayabu et al. (1996). In the lower stratosphere, a wave-like structure with vertical wavelengths of 3–5 km is clearly observed. The wave amplitude is 2–3 m s$^{-1}$ and phase leads with height. The phase of the stratospheric disturbances, with a period of about 2 days, is found to be synchronized with convective activity in the troposphere. It is also worth noting that the vertical wavelength and period seen in the composite are similar to those detected by spectral analysis in the previous section. Composite maps for zonal wind and temperature are also constructed (not shown). Similar to meridional wind, the zonal wind composite shows the existence of quasi 2-day

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig9.pdf}
\caption{Coherences and phase differences between u and v at (a) Chuuk, (b) Manus, and (c) Misima for the period of 2.0 days.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig10.pdf}
\caption{The same as Fig. 8, except between Pohnpei and Honiara.}
\end{figure}
disturbances in the troposphere, and the wavelike structure whose vertical wavelength is 3-5 km can be seen as fragments in the lower stratosphere. As for temperature composite, wavelike structures, as seen in u and v components, are clear in the lower stratosphere, although diurnal variability is dominant in the troposphere (not shown).

Similar features of stratospheric disturbances connecting with tropospheric convection are also observed in composite maps at other stations. Figure 12b shows a meridional wind composite at Manus in the equatorial area. Signals of wavelike structures are found in the lower stratosphere, connecting with quasi 2-day disturbances in the troposphere. Phases of the disturbances lag behind with increasing altitude in the lower and middle troposphere (z ≤ 12 km), but lead in the upper troposphere and lower stratosphere. The vertical wavelength is about 5 km in the lower stratosphere, which is also consistent with the results of the spectral analysis. A composite of the zonal wind component at Manus has similar wave structures as seen in v component, and the amplitude is much larger (about 10 m s⁻¹ as peak-to-peak amplitude; not shown).

In the southern area, a wavelike structure with vertical wavelengths of about 3 km is seen in the lower stratosphere (Fig. 12c). It is worth noting that the out-of-phase relation of v between northern and southern areas is seen in Figs. 12a and 12c as suggested by the cross-spectral analysis in Subsection 4.5, although it is not very clear.

6. Discussion

We analyzed the disturbances in the lower stratosphere using two different methods, i.e., spectral and composite analyses. Since results obtained by spectral analysis and composite analysis are consistent with each other, we can confirm the existence of the stratospheric disturbances synchronized with the tropospheric convective activity.

During TOGA-COARE IOP, we detected two types of 2-day period disturbances. One type is dominant in the northern (7-8°N) and southern areas (9-11°S), and propagates eastward having vertical and horizontal wavelengths of 3-4 km and several to ten thousand km, respectively. The other type is dominant in the equatorial area and its vertical wavelengths are 4-5 km. Phases of v component propagate eastward, having zonal wavelengths of 3000-4000 km, although such phase propagation is not clear for u component. Since zonal winds in the upper troposphere and lower stratosphere are easterlies during TOGA-COARE IOP, as shown in Fig. 2, it seems that eastward disturbances are more apt to exist than westward disturbances. This is consistent with the result by Maruyama (1994) that positive vertical flux of zonal momentum is observed in the easterly period.

The eastward propagating waves detected in the northern and southern areas are likely due to an n = 1 equatorial inertio-gravity wave as discussed below. First, it is shown that wave parameters are consistent with the dispersion relation. For inertio-gravity waves in the equatorial beta plane, the dispersion relation is,

\[
m^2 \omega^2 \frac{\beta}{N^2} - k^2 - \frac{\beta k}{\omega} = (2n + 1) \frac{\beta|m|}{N},
\]

where k and m are the zonal and vertical wavenumbers, respectively, ω the frequency and n the degree of Hermite polynomial which corresponds to the number of nodes in the meridional velocity component (Holton, 1992). We take the buoyancy frequency squared \(N^2 = 5.0 \times 10^{-4} \text{ sec}^{-2}\) as a typical stratospheric value. Since the mean zonal wind is weak around 20 km where the wave structure is clearly seen (Fig. 2), the Doppler effect of the mean wind can be ignored for the parameter estimation. Using the vertical wavelength of 3-4 km and the wave period of 2 days obtained from data at one location in the northern and southern areas, we obtain estimates of zonal wavelengths of 3200-6100 km for the n = 1 eastward inertio-gravity wave. These values are consistent with the zonal wavelengths of several to ten thousand kilometers estimated from cross-spectral analysis for time series at two separate locations. The zonal wavelengths for n = 0 eastward inertio-gravity waves are estimated at 2300-3300 km from (1), which is much shorter than the estimate from the cross spectral analysis. The other modes (n ≥ 2) cannot have the 2-day period and the 3-4 km vertical wavelengths.

The second evidence is the fact that the wave structure as seen in meridional wind in the northern and southern areas is not observed in the equatorial area. Theoretically, n = 1 eastward inertio-gravity waves have maximum v amplitude at y = \(\sqrt{\frac{N}{\beta|m|}}(\equiv y_0)\), and zero at the equator. The observed vertical wavelength of 2-4 km indicates that y₀ corresponds to the latitudes of 8°N and 8°S, which are approximately the same latitudes of the northern and southern areas defined in this paper.

The third evidence is the meridional phase structure. As shown in Fig. 10, phase difference of v between Pohnpei in the northern area, and Honiara in the southern area, is about 180° in the lower stratosphere, which is also consistent with the meridional structure of n = 1 eastward inertio-gravity wave.

On the other hand, the disturbances in the equatorial region show complicated features. The equatorial wave theory indicates that modes with maximum u (v) amplitudes have zero v (u) component at the equator. Thus, the disturbances seen in u and v components are probably due to different modes, although the observed vertical wavelength (4-5 km) and wave periods (about 2 days) are similar.
The equatorial waves having nonzero values of $v$ at the equator are even modes. The result of cross-spectral analysis of $v$ data from zonally separated locations suggested that the waves propagate eastward having zonal wavelengths of 3000–4000 km. From dispersion relation (1) for $n = 0$ eastward inertia-gravity waves, the zonal wavelength is estimated at 3300–4400 km, using a vertical wavelength of 3–4 km and wave period of 2 days estimated by data at one location. The values of zonal wavelengths from the two different methods coincide well, indicating that the $v$ disturbances observed in the equatorial area are likely due to $n = 0$ inertia-gravity waves. The other even modes ($n \geq 2$) cannot have the 2-day wave period and the 3–4 km vertical wavelength.

As for the disturbances observed in $u$ components at the equator, judging from the fact that we could not obtain a meaningful phase difference between the time series of zonally separated locations, the $u$ disturbances may be due to a mixture of various modes propagating eastward and westward. This speculation is consistent with the result by Sato and Dunkerton (1997) that positive and negative momentum fluxes ($u'w'$) associated with short period disturbances are cancelled largely at the equator. If we assume that equatorial Kelvin waves are most dominant, zonal wavelengths are estimated at 2500–3100 km from its dispersion relation:

$$\omega = -\frac{Nk}{m}, \quad (2)$$

and using the vertical wavelength of 4–5 km and the wave period of 2 days. Other candidates are $n = 1$ eastward inertia-gravity waves having zonal wavelengths of 6100–18400 km as observed in the northern and southern area, and $n = 1$ westward inertia-gravity waves having zonal wavelengths of 3800–6500 km as detected in the equatorial troposphere by Takayabu et al. (1996).

7. Summary and concluding remarks

The horizontal and vertical structure of the short-period disturbances in the equatorial lower stratosphere were examined based on the TOGA-COARE special upper-air observations. The $T_{BB}$ data from GMS were used to see the connection of these stratospheric disturbances with tropospheric convection.

The time-height sections of high-pass filtered $u$, $v$ and $T$ components at individual stations suggested the existence of waves with a period of about 2 days and vertical wavelengths of 3–5 km. Power and cross-spectral analyses were applied to estimate horizontal and vertical structures of the waves. Both wind and temperature spectra are large in the periods shorter than 3 days in the lower stratosphere.

In the northern and southern areas, the 2-day waves propagate eastward with vertical wavelengths of 3–4 km and zonal wavelengths of several to ten thousand kilometers. The phase difference between $v$ components in the northern and southern areas is 180°. Horizontal wind vectors rotate clockwise and counterclockwise in time in the northern and southern areas, respectively. The most probable candidate for the waves having these characteristic structures is the $n = 1$ eastward propagating inertia-gravity wave.

The 2-day period disturbances in the equatorial
area have vertical wavelengths of 4-5 km. They were considered to be a mixture of several kinds of waves. The disturbances seen in the $u$ component do not show systematic zonal phase propagation and are probably due to a mixture of equatorial Kelvin waves and eastward and westward propagating $n=1$ inertio-gravity waves. On the other hand, the disturbances observed in the $v$ component show clear eastward phase propagation, having 3000–4000 km zonal wavelengths. The disturbances are probably due to eastward propagating $n=0$ inertio-gravity waves.

Composite analysis was applied with a reference to convective activity oscillation with about a 2-day period. Composite time-height sections indicate the existence of short-period waves in the lower strato-

Fig. 12. Composite structures of meridional winds at (a) Chuuk, (b) Manus, and (c) Misima. Mean value at each level is subtracted. Contour interval is 1 m s$^{-1}$. 
sphere in most areas that are locked with the tropospheric convection. The wave period and vertical wavelengths are similar to those detected by spectral analysis. This result suggests that the short-period disturbances in the tropical lower stratosphere are forced by convection in the troposphere.

During the TOGA-COARE period, the QBO was in the westerly shear phase. A similar campaign with a dense radiosonde observational network is needed in the easterly shear phase, because the structure and propagation characteristics of waves in the stratosphere are strongly affected by the mean wind. Convective activity is not uniform in the troposphere. The regional difference of wave activity and characteristics is another interesting issue, which should be clarified by observations in the future. Analysis of GCM QBO simulation outputs may help in its understanding.

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References


TOGA-COARE 集中観測データに基づく
下部成層赤道慣性重力波の解析

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TOGA-COARE 集中観測期間中の 10 地点の高層データの東西風・南北風・温度ラジオゾンダ観測データを用いて、熱帯成層圏下部における波動擾乱の解析を行なった。解析は 3 日以下の短周期成分に着目した。

各地点の東西風・南北風・温度成分の時間高度断面図には、成層圏下部に時折、周期約 2 日、鉛直波長 3~5 km の波動状の擾乱が見られた。

そこで、まず、パワースペクトル及びクロススペクトル解析を行なった。

その結果、TOGA-COARE-LSA (Large-scale Soundings Array) 北部 [7°N~8°N] と LSA 南部 [9°S~11°S] には鉛直波長約 3~4 km、東西波長数 1000 km~10000 km の良く似た東進波が、同時に存在することがわかった。擾乱の東西風成分と南北風成分の一致点での位相差、北部領域と南部領域間の位相差は、擾乱が赤道域にトラップされた慣性重力波の特徴と一致する。

一方、LSA 赤道域には、鉛直波長約 4-5 km の北部南部領域とは異なる特徴を持つ東進波が存在することがわかった。東西風成分には有意な東西方向の位相差は検出できなかったが、南北風成分の位相差は、擾乱が 3000~4000 km の東西波長を持つことを明確に示していた。

次に、対流活動との関係を調べるために、GMS の TBB データを用いて対流活発時の波箱にとったコンボジット解析を行なった。ラグ時間高度断面図には、スペクトル解析の結果と良く一致する特徴を持つ、鉛直波長 3~5 km の風・温度擾乱が下部成層圏に見られた。これは熱帯下部成層圏短周期波動擾乱が対流活動に関連して発生していることを示唆する。

また、これらの波動擾乱は上部対流層及び下部成層層で位相が下向きに伝播していた。これは、波動のエネルギーが上向きに伝播していることを示している。

さらに、赤道波の分散関係式を用いて、上記のスペクトル、コンボジット解析により明らかになった波動構造 (周期、水平構造、鉛直波長) を持つモードの特定を試みた。まず、LSA 北部と南部で検出された擾乱は n = 1 東進慣性重力波である可能性が高いため、一方 LSA 赤道域で検出された擾乱は、東西風成分、南北風成分について異なるモードによる可能性がある。なぜなら、赤道において、偶数モードは南北風成分のみ、奇数モードは東西風成分のみ持つからである。南北風成分に顕著な LSA 赤道域の擾乱の構造は n = 0 東進慣性重力波と良く一致している。一方、同領域の東西風に顕著な擾乱は、東西に離れた地点間での有意な位相差が捉えられなかったことから赤道ケルビン波、n = 1 の西進及び東進慣性重力波が混在したものと推察される。

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