Rocketsonde Observations of the Middle Atmosphere Dynamics at Uchinoura (31°N, 131°E) during the DYANA Campaign Part II: Characteristics of Gravity Waves

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We describe in this paper the height variations of the gravity wave characteristics in the middle atmosphere, using the profiles of wind velocity and temperature collected at 20–90 km altitude by means of a series of rocketsonde experiments and the MU (middle and upper atmosphere) radar during the DYANA campaign. The dominant vertical scales of the wind velocity fluctuations generally increased with altitude from 2–3 km in the lower stratosphere to 10–15 km in the mesosphere. The vertical wavenumber spectra of the wind velocity fluctuations, constructed in five altitude regions, showed height variations in the spectral shape, which was fairly consistent with the model spectrum based upon the saturation of gravity waves. The wind velocity variance due to gravity waves generally increased in the stratosphere, diminished just above the stratopause, greatly increased again in the lower mesosphere, and finally became nearly constant in the upper mesosphere above about 65 km. The gravity waves with relatively small vertical scales were significantly weakened just above the stratopause, suggesting the important effect of the vertical structure of the static stability on the propagation characteristics of gravity waves.

1. Introduction

A theoretical prediction, concerning the important role of the gravity waves in the middle atmosphere dynamics (e.g., LINDZEN, 1981; MATSUNO, 1982; HOLTON, 1982), has stimulated observations by means of various measurement techniques (e.g., FRITTS, 1984). In particular, MST radar and lidar observations have contributed to studies on the gravity waves due to the advantages of their good time and height resolutions in addition to the ability of continuous measurements (FRITTS *et al.*, 1988; TSUDA *et al.*, 1990; WILSON *et al.*, 1991). Moreover, *in-situ* measurements by means of a meteorological rocketsonde and a balloon-borne radiosonde have also been widely performed (HIROTA and NIKI, 1986; KITAMURA and HIROTA, 1989; TSUDA *et al.*, 1991), which can complement the MST radar profiles, that normally have data gaps in the height range of 25–60 km.

Owing to these exhaustive theoretical and observational studies, our understanding of the gravity wave characteristics has greatly increased in the last few decades, the consensus being reached that a major part of the meso-scale wind fluctuations in the middle atmosphere can be

interpreted as the superposition of many gravity waves. In order to describe the complicated structures of the fluctuations, VANZANDT (1982) introduced model spectra satisfying the linear dispersion relations of gravity waves, which were originally proposed for oceanic gravity waves.

We here concentrate on the behavior of the vertical wavenumber spectrum, $A(m)$, for which a model spectrum was assumed, for example, by GARRETT and MUNK (1975), as follows

$$A(m) = \frac{C}{(1 + m/m_*)^t} \quad (1)$$

where m_* is a characteristic wavenumber and C is a constant.

The spectral slope for $m \gg m_*$ can be approximated as t , which was experimentally found to be about -3 (e.g., FRITTS *et al.*, 1988; TSUDA *et al.*, 1989). Equation (1) also indicates that $A(m)$ for $m \ll m_*$ becomes a white spectrum, and the transition between the two asymptotic spectral shapes occurs near $m \sim m_*$. VANZANDT and FRITTS (1989) further investigated the behavior of the spectra for $m \ll m_*$, and delineated a modified form of Eq. (1), having a positive slope for $m \ll m_*$, being proportional to m .

Using a linear saturation theory for gravity waves, DEWAN and GOOD (1986) proposed a model spectrum in order to describe $A(m)$ for $m \gg m_*$, and SMITH *et al.* (1987) also derived a quantitative model, as follows

$$A_s(m) = \frac{N^2}{6m^3} \quad (2)$$

which indicates that the spectral amplitudes are limited by the saturated values, depending on the background values of the Brunt-Väisälä frequency squared, N^2 .

The model spectrum was compared with various observations, showing fairly good agreement regardless of the latitudes of the observation stations and altitude ranges (FRITTS *et al.*, 1988; TSUDA *et al.*, 1989). The height variations in the observed vertical wavenumber spectra suggested that all the components of the gravity waves are not necessarily saturated in the stratosphere, while the spectra in the upper mesosphere are described fairly well by the model spectra (SHIBATA *et al.*, 1988; WILSON *et al.*, 1990; TSUDA *et al.*, 1991; MURAYAMA *et al.*, 1992a).

It can also be delineated from the saturated spectrum model that the vertical scale of the dominant gravity waves generally increases with altitude. Through simultaneous observations of the wind motions with the MU radar, rocketsondes and radiosondes, MURAYAMA *et al.* (1992a) clarified the increase in the vertical scale of wind fluctuations with altitude, being 2–5 km in the lower stratosphere, about 5–15 km in the upper stratosphere and greater than 10–15 km in the mesosphere.

This paper is concerned with data analysis of the behavior of gravity waves, using the wind velocity and temperature profiles collected with rocketsondes and the MU radar during the DYANA campaign, whose experimental configuration and basic data are described in detail in the companion paper (MURAYAMA *et al.*, 1992b). We present in Section 2 the vertical wavenumber spectra of wind velocity fluctuations, which are further compared with the model spectrum. In Section 3, we focus on the height variations of the wind velocity variance, which

is contributed to by the gravity waves with various wavenumber ranges. Section 4 is devoted to detailed analysis of the important effects of the static stability structure near the stratopause upon the upward propagation characteristics of gravity waves. Discussion and concluding remarks are summarized in Sections 5 and 6, respectively.

2. Vertical Wavenumber Spectra of Wind Velocity Fluctuations

Examples of snapshot profiles for the eastward and northward components are shown in Fig. 1, which were collected on 17 February 1990, with a falling sphere at 18–60 km, and the MU radar in two regions at 5–25 km and 60–90 km (MURAYAMA *et al.*, 1992b). Note that the observations with the rocketsonde and the MU radar were not conducted during the same periods of a day. For instance, there is up to 9 hours difference between the profiles obtained with the rocketsonde and the mesospheric observations with the MU radar, because the latter were limited to during the daytime.

Superimposed on the fundamental structures of the wind velocity and temperature profiles, fluctuations with vertical scales ranging from a few to several km can generally be recognized, showing fairly good correlations between the zonal and meridional components. The dominant vertical scales of the fluctuations generally increased with altitude, being consistent with the saturated gravity wave theory as well as the earlier results reported by MURAYAMA *et al.* (1992a), i.e., they were 2–3 km in the troposphere and lower stratosphere, increased to about 5 km in the upper stratosphere, and then became larger than about 10 km

Fig. 1. Vertical profiles of northward (left) and eastward (right) wind velocity observed during 12:14–13:40 LT on 24 February with the MU radar (thick solid lines at 5–25 km and 60–90 km), and a Viper rocket with a falling sphere launched at 2100 LT (thin solid lines at 18–60 km), respectively.

in the mesosphere. The amplitudes of the fluctuations also increased greatly with altitude such that they were a few m/s below about 20 km, 5–10 m/s near 40 km and 20–30 m/s above 60 km.

We separated the entire height range of the DYANA results into five altitude regions, with a thickness of about 10 km, having a nearly constant N^2 value; the lower stratosphere at 17–23 km (A), the middle stratosphere at 22–32 km (B), the upper stratosphere at 33–43 km (C), the lower mesosphere at 47–56 km (D) and the upper mesosphere at 65–85 km (E). The lowest and highest regions corresponded to the MU radar observations, and the others to the rocketsonde soundings. The mean values of N^2 were 6.53×10^{-4} (A), 4.85×10^{-4} (B), 4.88×10^{-4} (C) and 3.48×10^{-4} (D) (rad/s)², respectively, which were estimated from the mean temperature profile obtained with the rocketsonde soundings and routine radiosondes. Note that N^2 in region E was assumed to be 3.45×10^{-4} (rad/s)² from the CIRA 1986 model, since a simultaneous temperature profile was not available.

The spectra were first determined in the five height ranges by using the individual profiles, and then the mean of the eight spectra was calculated, as illustrated in Fig. 2, where the straight lines, having a logarithmic slope of -3 , are the corresponding model saturated spectra obtained with Eq. (2), which were calculated by using the N^2 values in each height range. Note that the analyzed wavenumber range in the lower stratosphere was greatly different from the others because of the better height resolution and the smaller height range.

Fig. 2. Vertical wavenumber spectra of the meridional (dashed) and zonal (solid) wind fluctuations observed with rocketsondes and the MU radar. The top and bottom spectra correspond to the mean results for the entire MU radar observations during the DYANA campaign, while the middle three spectra are the means of eight determinations from the rocketsonde measurements (see text). The model spectrum is also plotted, using the observed N^2 (see text for details).

There was a large change in the spectral shape between the lowest and highest regions, but the variations seemed to be fairly well interpolated by the results for the intermediate height ranges. The spectral amplitudes for small wavenumbers, for example, $m = 2 \times 10^{-4}$ c/m (or 5 km in wavelength, λ_z) showed a clear increase with altitude, i.e., they were $2\text{--}3 \times 10^4$ (m^3/s^2) in regions A and B, increased to $4\text{--}8 \times 10^4$ and $6\text{--}8 \times 10^4$ (m^3/s^2) in C and D regions, respectively, and then finally became $2\text{--}3 \times 10^5$ (m^3/s^2) in region E.

By comparing the observed values with the model prediction, it can be suggested that the wave components with $m = 2 \times 10^{-4}$ c/m ($\lambda_z = 5$ km) were not saturated in the lower stratosphere, being one-tenth of the model value, therefore they were able to increase in amplitude with altitude in the stratosphere and lower mesosphere, and finally reach their saturation values in the upper mesosphere. On the other hand, the spectral amplitudes with larger m did not show an increase with altitude, but they were fairly constant in all the height ranges, indicating that the spectral amplitudes were limited by the saturated values, which is consistent with the theoretical prediction.

Moreover, the spectral shape varied with the wavenumber, that is, the spectral slope was generally gradual for a small m , where the gravity waves were not fully saturated, while it became steeper for a large m , approaching the model value of -3 . However, the spectral shape also changed with altitude, which can be recognized by the mean slope for $m \leq 4 \times 10^{-4}$ c/m, which was estimated to be -0.7 , -1.0 , -1.8 , -2.6 and -3.0 from the lower to higher regions in Fig. 2, respectively.

In other words, the wavenumber range of the saturated components increased with altitude. In the stratosphere only the gravity waves with a large wavenumber were saturated, while all the components within the entire observed wavenumber range seemed to satisfy the saturation condition in the upper mesosphere. The general characteristics of the spectra described above are again quite similar to the earlier results, delineated through rocketsonde and MU radar experiments in 1985–87 (MURAYAMA *et al.*, 1992a).

We now quantitatively estimate the increase in the gravity wave energy per unit mass by analyzing the integrated wind velocity variance from the spectra in the two wavenumber ranges; (i) $10^{-4} \leq m \leq 2 \times 10^{-4}$ c/m (or $5 < \lambda_z < 10$ km) and (ii) $2 \times 10^{-4} \leq m \leq 10^{-3}$ c/m (or $1 \leq \lambda_z \leq 5$ km). The wind velocity variance normalized as to the model value is shown in Fig. 3, being the mean value between the zonal and meridional components, which indicates the index of the gravity wave saturation in the corresponding wavenumber ranges (MURAYAMA *et al.*, 1992a). The integrated variance in the lower stratosphere is not shown in Fig. 3(a), because the observed wavenumbers were not extended widely enough to include range (ii).

Although the two sets of results similarly showed the exponential growth of the variance with altitude, the scale height was greatly different between the wavenumber ranges (i) and (ii), which can be estimated to be about 15 km and 25 km, respectively. Note also that the values in the upper mesosphere were close to unity in the two wavenumber ranges, suggesting that the gravity wave energy was limited by the saturated value predicted by the model.

If a gravity wave were free from any breaking processes including wave saturation, its wind velocity variance, or the wave energy per unit mass, should increase exponentially with a scale height equal to that for the density decrease (approximately 7 km in the middle atmosphere). The observed scale height in wavenumber range (ii) was obviously larger than this value, indicating that the rate of energy loss was greater for gravity waves with a smaller λ_z . Moreover, even in wavenumber range (i), the scale height was twice larger than the density scale height, suggesting that a part of the gravity waves also lost its energy in the course of the upward propagation.

Fig. 3. Height variation in the normalized variance in the two wavenumber ranges, i.e., (i) $10^{-4} \leq m \leq 2 \times 10^{-4}$ c/m (left) and (ii) $2 \times 10^{-4} \leq m \leq 10^{-3}$ c/m (right). The dot-dash lines indicate the asymptotic increase in the observed values.

3. Profiles of Wind Velocity Variance

We are interested in the fine structure of the height variations of the gravity wave energy, for which the spectral analysis presented in the previous section may not be suitable, since it requires a fairly large height range, covering the largest vertical scales in the wavenumber spectra. Therefore, we present in this section profiles of the wind velocity variance, which were calculated from the wind velocity profiles after processing with band-pass filters, having three different pass-bands of 3.5–1.5 km, 6.0–4.0 km and 12.0–6.0 km (these scale ranges are hereafter referred to as (a), (b) and (c), respectively).

The sum of the wind velocity variance between the zonal and meridional components, $\overline{u'^2} + \overline{v'^2}$, is shown in Fig. 4 for the measurements on 24 February 1990. Although the statistical results as to the wind velocity variance shown in Fig. 3 exhibited asymptotic growth, being approximated by the exponential curve with the constant scale heights, the detailed profile of $\overline{u'^2} + \overline{v'^2}$ in Fig. 4 involved great variability.

The values of $\overline{u'^2} + \overline{v'^2}$ below 20 km, detected with the MU radar, ranged up to 10 (m^2/s^2) in scale range (a), while they were about 1/3 in range (b), which is consistent with the fact that the vertical scales of the dominant gravity waves are 2–3 km there, as shown in the previous section. It is noteworthy that the considerably large $\overline{u'^2} + \overline{v'^2}$ values in range (c) and a part of (b) were reflected by the vertical structure of the jet stream, therefore, they did not fully represent the gravity wave energy in the lower atmosphere.

Although comparison of the absolute values of $\overline{u'^2} + \overline{v'^2}$ between the three scale ranges may not be very meaningful, because the bandwidths for the three ranges are not uniform, investigations of their height variations would be quite interesting. The profiles in Fig. 4 were

Fig. 4. Profiles of the wind velocity variance, $\overline{u'^2 + v'^2}$, observed on 24 February 1990 with a rocketsonde at 15–60 km and the MU radar in two height ranges, 5–20 km and 60–90 km. Before calculation of $\overline{u'^2 + v'^2}$, band-pass filters with pass-bands of 3.5–1.5 km (left), 6.0–4.0 km (center) and 12.0–6.0 km (right) were applied.

fairly continuous between the rocketsonde and the MU radar observations, suggesting the overall consistency of the profiles obtained with the two different observation techniques. The values of $\overline{u'^2 + v'^2}$ became decreased at 20–25 km in all the three scale ranges, and then showed enhancement near 30 km. They again became small near 45 km, and then increased exponentially at 45–60 km altitude, showing a continuous profile to the values in the mesosphere obtained with the MU radar. The values of $\overline{u'^2 + v'^2}$ above 60 km did not show significant height variations, instead they had a rather constant value in the entire height range. The maximum $\overline{u'^2 + v'^2}$ values in range (a) were nearly the same between the lower stratosphere and the mesosphere, while they increased by a factor of about 10 in ranges (b) and (c).

Figure 5 presents all the profiles of $\overline{u'^2 + v'^2}$, collected during the DYANA campaign, together with the mean values in each scale range, where the zonal mean temperature derived from the CIRA 86 model is also illustrated. The general characteristics of $\overline{u'^2 + v'^2}$ profile, described concerning Fig. 4, are more generally recognized by the mean profile in Fig. 5. In particular, the mean profile corresponding to scale range (b) most clearly exhibited the variations, that is, $\overline{u'^2 + v'^2}$ showed a decrease near 20 km, rapidly increased at 20–28 km, and then showed a rather gradual increase up to 40 km.

Then the values of $\overline{u'^2 + v'^2}$ decreased in the narrow height range of 45–50 km, coinciding with the stratopause height, which can most clearly be recognized in scale range (b). Although such a tendency was not so clear in the mean profile in scale range (a), the individual profile shows a fairly deep narrow valley at 40–45 km, suggesting a large change in the characteristics of the gravity waves near the stratopause.

The values of $\overline{u'^2 + v'^2}$ again exponentially increased at 50–60 km. It is striking that

Fig. 5. The same as Fig. 4 except that all the profiles were obtained during the DYANA period. The thick line indicates the mean value. A temperature profile taken from the CIRA 86 model is also illustrated.

$\overline{u'^2 + v'^2}$ exhibited constant values in the upper mesosphere above 65 km in all the three scale ranges, indicating that the wave amplitudes were limited by the wave saturation. Note, however, that such a saturated value can more clearly be recognized in the mean profiles, but considerable deviations can be seen in the individual profiles.

Comparison of the mean values between 25 and 65 km altitude shows that the increase in $\overline{u'^2 + v'^2}$ was only 6.6 in scale range (a), while it was about 12 and 18 in ranges (b) and (c), respectively, being generally consistent with the results in Fig. 3.

4. Effect of the Stratopause Structure on the Gravity Wave Propagation

We study in this section the vertical structure of the wind velocity variance, particularly, for the wave components with relatively small vertical scales, focusing on the effect of the decrease in the static stability near the stratopause on the upward propagation characteristics of gravity waves.

The profiles obtained with all the falling sphere soundings and the datasonde measurement on 20 January 1990 could not be included in the present analysis, since a temperature profile, which is essentially important for describing the underlying physical mechanism, was not obtained for any of them. Furthermore, the two cases observed with datasondes on 29 and 31 January were also not used, because the stratopause was not clearly detected. Therefore, only the two profiles obtained on 17 January and 5 February 1990 are treated in the following.

The profiles of wind velocity and temperature fluctuations, after applying band-pass filters with cut-offs at 1.5 and 3.5 km, are presented in Fig. 6 for the results obtained on 17 January. Investigation of Fig. 2 suggests that the components within the above-stated vertical scales were not fully saturated, but they seemed to be marginally saturated in the upper stratosphere. The stratopause, with a maximum temperature of about 268 K, was detected at 46 km altitude, coinciding with the sharp decrease in the N^2 values with a ratio of about 0.5.

Fig. 6. Profiles of wind velocity and temperature fluctuations observed with the rocketsonde launched at 21:10 LT on 17 January 1990. The left-most panel shows the temperature profile. The next panel shows the fine structure of N^2 with a resolution of 300 m, together with a smoothed profile after applying a low-pass filter with a cut-off of 10 km. Successive three panels show fluctuating components, after applying a band-pass filter (1.5–3.5 km), for the eastward and northward wind velocity and temperature. The right two panels show the variance of wind velocity and temperature. The horizontal thin dashed line indicates the altitude corresponding to $N^2 = 4 \times 10^{-4} \text{ (rad/s)}^2$.

The amplitudes of the zonal and meridional wind velocity fluctuations, u' and v' , in Fig. 6 linearly increased at 35–45 km, and then abruptly decreased above the stratopause. The wind velocity variance, $\overline{u'^2} + \overline{v'^2}$, in Fig. 6 decreased at 45–50 km to become 1/4 in comparison with the value below the stratopause. However, the variance of the temperature fluctuations, $\overline{T'^2}$, in Fig. 6 showed a relatively smaller decrease in amplitude in the corresponding altitude ranges.

Another example is presented in Fig. 7 for the measurements on 5 February. It can be clearly recognized that the wind velocity fluctuations suddenly stopped growing just above the stratopause, showing a decrease of $\overline{u'^2} + \overline{v'^2}$ by a factor of almost 1/10 around 45 km. Moreover, the temperature fluctuations also exhibited similar height variations accompanied with a decrease in $\overline{T'^2}$ by a factor of 1/5. Large variations in the N^2 values in Fig. 7 occurred at around 42 km, indicating the stratopause height, although the smoothed N^2 profile showed a relatively small decrease in N^2 , by a factor of about 0.6, below and above the stratopause.

In order to analyze the characteristics of the gravity waves detected in Fig. 7 in more detail, we present in Fig. 8 a hodograph for the components with $2 \leq \lambda_z \leq 4$ km. The hodograph clearly exhibits the clockwise rotation with altitude, which is consistent with a gravity wave with upward energy propagation (e.g., HIROTA and NIKI, 1986; TSUDA *et al.*, 1990). The linear polarization relations of gravity waves, applied between the wind velocity and temperature fluctuations, suggest that the horizontal propagation direction of this gravity wave was south-westward. The amplitudes of u' and v' were about 5 m/s below 45 km, while they decreased to about 2 m/s above 47 km, giving an amplitude ratio of approximately 0.4.

Figure 9 shows a hodograph for the component with relatively large vertical scales ranging from 6 to 12 km, which again showed the clockwise rotation, while the horizontal

Fig. 7. The same as Fig. 6 except that the results were obtained with the rocketsonde launched at 21:00 LT on 5 February 1990.

Fig. 8. Hodograph (left) for the gravity wave, with relatively short vertical scales, determined from the wind velocity profiles collected on 5 February 1990 by applying a band-pass filter (2–4 km). The best-fitted ellipse is also illustrated by the dotted line. The lowest data point is indicated by “S”, and the arrow indicates the rotation direction with altitude. The right panel shows the filtered profiles of the eastward (thick solid line) and northward wind velocity (dotted line), and temperature (thin solid line).

propagation was north north-westward. The height variations of the profiles were quite different from the results shown in Fig. 8, such that the amplitudes increased with an exponential growth rate of about 12–15 km, being roughly consistent with the scale height estimated for the variance profile in Fig. 3(a).

To summarize the results so far, we found that the amplitudes of the small-scale gravity waves ($\lambda_z \sim 2$ –3 km) became significantly small just above the stratopause. On the other hand, the gravity waves with larger vertical scales seemed to be insensitive to the stratopause.

Fig. 9. The same as Fig. 8 except for the gravity wave component with a larger vertical scale, obtained by changing the pass-band to 6–12 km.

5. Discussion

5.1 WKB scaling of gravity waves

We discuss in this section the effects of the decrease in N^2 near the stratopause on the gravity wave characteristics, assuming the WKB scaling of gravity waves, which is based upon the proportionality between the vertical wavenumber, m , and the background value of N as follows

$$m = -\frac{kN}{\omega} \quad (3)$$

where k and ω are the horizontal wavenumber and the wave frequency, respectively. Equation (3) further predicts that the wave energy is proportional to N (VANZANDT and FRITTS, 1989 (hereafter referred to as VF89)).

On the basis of the saturation theory, VF89 discussed the effect of the increase in N^2 , assuming the condition near the tropopause or the mesopause, on the gravity wave characteristics, and predicted that the wave energy increases by a factor of N^3 due to WKB scaling of a wave, and then the energy increase is finally limited as to N^2 because of the enhanced dissipation of gravity waves.

Although VF89 did not explicitly describe it, the WKB scaling method seems to be applicable to the opposite case, being defined as subsaturation, where the N^2 values decrease in the interface region between the atmospheric layers, as seen near the stratopause. In such a situation, the spectral amplitudes for $m \gg m_*$ decrease by a factor corresponding to the ratio of the N^3 values in the two regions above and below the stratopause.

In order to test the proportionality of m to N , as described in Eq. (3), we first investigate the case for $m \ll m_*$, as shown in Fig. 9. The values of m for the northward component in Fig. 9 can be estimated to be 1/6.7 and 1/7.9 c/km near 35 and 45 km altitude, respectively, giving

a decrease of m by a factor of about 0.85 below and above the stratopause. While the reduction in N was about $\sqrt{0.6} = 0.77$, showing reasonable agreement with the prediction of the WKB scaling. Although the WKB scaling also predicts the decrease in the wind velocity variance as N near the interface region, it was not clearly recognized because of the small height range above the stratopause in comparison with the vertical wavelength of the gravity wave.

We now apply the WKB scaling to gravity waves with $m \gg m^*$. Using the smoothed profiles of N^2 in Figs. 6 and 7, the ratio of N^3 below and above the stratopause can be estimated to be 0.35 and 0.46, respectively. While, the decreases in $\overline{u'^2} + \overline{v'^2}$, as shown in Figs. 6 and 7, were 0.25 and 0.1, respectively. The fairly large discrepancy in the decrease ratios between the prediction and the observations suggests that the gravity waves might be very sensitive to sharp changes in the static stability, as detected in the detailed profiles of N^2 in Figs. 6 and 7, so the smoothed N^3 values may not be used to estimate the decrease in the gravity wave energy.

Investigation of the statistical results in Fig. 5 shows that the values of $\overline{u'^2} + \overline{v'^2}$ in scale range (b) were about 5.0 and 2.5 (m^2/s^2) at 40 and 48 km, which gives a decrease rate of 0.5, which is reasonably consistent with that for N^3 . While in range (c), they were 12.0 and 9.0 (m^2/s^2) at 40 and 48 km, respectively, the ratio being estimated to be 0.75, which again approximately agreed with that for N . Therefore, WKB scaling can successfully explain the statistical behavior of the gravity wave variance, although it cannot fully account for the variations seen in the individual profiles.

In the case of subsaturation, the gravity waves are not saturated any more in the overlying region, thus they exponentially increase in amplitude, and finally again reach their saturation values, which is basically consistent with the profiles in Fig. 5.

5.2 General behavior of the profile of gravity wave energy

We describe here general characteristics of the kinetic energy of gravity wave per unit volume, $E = 1/2\rho(\overline{u'^2} + \overline{v'^2})$, using the results in Fig. 5, where ρ was taken from the CIRA 86 model. Figure 10 clearly shows that E almost monotonously decreases through the entire height ranges, although the detailed structures were different depending on the scale ranges.

In scale range (b), E was fairly constant in the lower stratosphere below about 30 km, rather gradually decreased up to 45 km, then showed a rapid decrease at 45 km, and became fairly constant at 45–60 km. Above 65 km, E again exponentially decreased at the scale height of ρ . The general characteristics were almost the same in scale ranges (a) and (c). However, the behavior of E at 45–60 km was not clearly recognized for scale range (a) because of the data gap between 50 and 60 km.

It is noteworthy that the behavior of E at 45–60 km, being located just above the stratopause, was quite interesting, which strongly suggests that the gravity waves conserved their energy there, being quite different from the behavior in other height ranges. As a result, the dynamical coupling between gravity waves and the mean winds, which can be represented, for example, by the drag force due to wave breaking, seemed to cease in the lower mesosphere, and such a mechanism becomes predominant in the upper mesosphere.

The values of E at 65 km can be estimated to be 1.5×10^{-3} , 1.5×10^{-3} and 5.0×10^{-3} (J/m^3) for scale ranges (a), (b) and (c), respectively, the sum of which is 8.0×10^{-3} (J/m^3). Since E in the upper mesosphere approximately decreases as ρ , the empirical model of the E profile can be proposed to be $8.0 \times 10^{-3} \exp(65-h/6.5)$ (J/m^3), where h is the height in km. Because the vertical scale corresponding to m^* in the upper mesosphere seems to be close to or slightly

Fig. 10. Profiles of $E = 1/2\rho(\overline{u'^2} + \overline{v'^2})$ determined by using the profiles in Fig. 5.

larger than the maximum height coverage of the current observations, the total gravity wave energy seems to be a few times larger than the proposed model value.

To summarize the above discussion, the height variations of the wind velocity variance are related to the vertical structure of the static stability profiles, which produces the changes in the gravity wave characteristics due to WKB scaling at the interface region with the decrease in N^2 . The quantitative explanations of the observed phenomena were, however, not completely confirmed. Nevertheless, it seems obvious that the propagation characteristics of the gravity waves were largely affected by the temperature structure near the stratopause, or more explicitly by the height variations of the static stability there.

The current study lead to the important idea that the amount of the gravity wave energy, passing through the stratopause into the mesosphere, can be controlled by the stratopause structure. Therefore, the large time variations in the gravity wave activity in the mesosphere, detected with radar observations (e.g., VINCENT and FRITTS, 1987), might be correlated with variations in the stratopause structure. Stratospheric warming accompanied by the enhanced activity of planetary waves, for instance, is known to produce large time variations in the temperature structure in the stratosphere and even in the mesosphere (MURAYAMA *et al.*, 1992b). In such an event, the gravity wave energy reaching the mesosphere could be modulated in response to the disturbed temperature structure near the stratopause.

6. Concluding Remarks

In this paper we have presented analysis of the gravity wave characteristics, using the wind velocity profiles at 20–90 km obtained through a series of the rocketsonde experiments and simultaneous MU radar observations.

We summarize in the following the main conclusions as to the analyzed characteristics of the gravity waves, and their interpretation in terms of the saturated gravity wave theory.

(1) The amplitudes of the wind fluctuations due to gravity waves were 2–3 m/s in the lower stratosphere, increased to about 5–10 m/s near the stratopause, and became about 20–30 m/s in the mesosphere.

(2) The vertical scales of the dominant component of gravity waves increased with altitude, being 2–3 km in the troposphere and lower stratosphere, about 5 km in the upper stratosphere, and greater than about 10 km in the mesosphere.

(3) Vertical wavenumber spectra of the wind velocity fluctuations showed large height variations, which is consistent with the saturated gravity wave theory and the earlier observations. The spectral analysis also showed that only a part of gravity waves, having small vertical scales, was saturated in the lower stratosphere, but the wavenumber range of the saturated gravity waves expanded with altitude, and finally all the components within the observed wavenumber range became saturated in the mesosphere.

(4) Case studies showed that the small scale gravity waves ($\lambda \sim 2\text{--}3$ km) were abruptly weakened just above the stratopause, while the components with larger scales were not very sensitive to the stratopause.

(5) The kinetic energy of gravity wave, E , generally decreased in the stratosphere and upper mesosphere, while it was fairly constant in the region just above the stratopause, indicating that E was conserved there.

(6) The behavior of the small scale gravity waves near the stratopause, including the structure of E , was basically explained by the WKB scaling of gravity waves, being dependent on the N^2 profile.

(7) The wind velocity variance was fairly constant in the upper mesosphere, indicating that it was limited by the wave saturation, and therefore, E exponentially decreased as $8.0 \times 10^{-3} \exp(65-h/6.5)$ (J/m³).

(8) Since the propagation characteristics of the gravity waves were very sensitive to the profile of the static stability near the stratopause, it can be suggested that the amount of E emitted into the mesosphere through the stratopause can be controlled by time variations in the stratopause structure, which are often due to stratospheric warmings and planetary waves.

Although we mainly used in this paper results obtained with rocketsondes launched in Japan, further analyses, including results collected through other observations at different locations, should be conducted in order to elucidate the entire behavior of gravity waves in the middle atmosphere during the DYANA campaign period.

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