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Characteristics of Gravity Waves in the Mesosphere Observed With the Middle and Upper Atmosphere Radar
1. Momentum Flux

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We observed wind motions from 60- to 90-km altitudes with the MU radar (35°N, 136°E) in the four observation periods: October 1986, June 1987, July 1990, and January/February 1991. Mean wind profiles were fairly consistent with results of Kyoto meteor radar observations (35°N, 136°E) collected in 1983–1985 at 80- to 110-km altitudes, and zonal mean winds generally agreed well with CIRA 1986 except for the profiles below 70 km in January/February 1991, although discrepancy of amplitudes sometimes ranged up to 10 to 20 m/s. Characteristics of frequency spectra of radial wind velocities were basically similar among results determined in four observation periods. That is, oblique spectra had a logarithmic slope of about −5/3 in the frequency range lower than 4–5 × 10^{-4} s^{-1}. Gravity waves with periods longer than 20–50 min to 5 hours (the lowest limit of the spectral analysis) were found to carry a large part of the zonal momentum flux, while a dominant frequency component was not detected for the meridional flux. Zonal and meridional drag of mean winds induced by the gravity wave with periods from 5 min to 8–10 hours were +51 m/s/d and −4 m/s/d in June at 75 km and −4.0 m/s/d and +7.4 m/s/d in October at 70 km, respectively. The major part of the drag force was also found in the wave component with periods larger than 30 min. The day-to-day variation in the zonal momentum flux showed a good correlation with the vertical shear of the zonal mean wind, which suggests effects of the gravity wave activities on mean wind fields, or the effect of shear variation on the gravity wave activity.

1. INTRODUCTION

Theoretical studies have proposed an important role of upward propagating gravity waves in the middle atmosphere dynamics in transporting the wave energy and momentum from the lower atmosphere to the mesosphere and lower thermosphere. [*Houghton*, 1978; *Lindzen*, 1981; *Matsuno*, 1982; *Holton*, 1982, 1983; *Fritts and Rastogi*, 1985]. The basic mechanisms of these processes have been clarified by observations involving various remote sensing and in situ measurement techniques [e.g., *Fritts*, 1984].

Among the various observations, Doppler radar measurement has become a very useful technique for determining the upward flux of the horizontal momentum [*Vincent and Reid*, 1983], which enabled us to measure the momentum deposition from gravity waves to the background mean flow. *Fritts and Vincent* [1987] found that about 70% of the momentum flux is due to gravity waves with periods of less than 1 hour. *Reid and Vincent* [1987] found that the amplitudes of momentum flux showed a semiannual variation with maxima occurring at the solstices and that zonal mean flow accelerations have typical values of 50–80 m/s/d near 85 km. *Tsuda et al.* [1990*a*] studied gravity waves with periods of 5 to 120 min and found that zonal momentum flux showed eastward and westward maxima in July/August and in December and February, respectively, and further determined the zonal acceleration for some cases to be 7–13 m/s/d and −8 to −11 m/s/d at heights of 66–79 km in summer and winter, respectively.

Climatological studies of gravity wave characteristics in the mesosphere are, however, not yet fully conducted because of a lack of a comprehensive data base. This study is devoted to clarify characteristics of gravity waves at the 60- to 90-km altitudes by the observational data collected by means of the middle and upper atmosphere (MU) radar (35°N, 136°E) during four observation campaigns of the mesospheric observations in October 1986, June 1987, July 1990, and January/February 1991. The data obtained in October 1986 were already reported by *Tsuda et al.* [1990*b*], and hence in the present paper we extend the data bases by adding the three other observation periods and discuss with the results in October 1986.

The basic experimental setup of the MU radar is described in section 2. Profiles of mean winds during the observation periods are presented in section 3. Frequency spectra of radial wind velocity and momentum flux are discussed in section 4. Vertical structure of momentum flux is described in section 5. Day-to-day variations of the gravity wave activity are shown in section 6.

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2. MIDDLE AND UPPER ATMOSPHERE (MU) RADAR OBSERVATIONS

The basic observation technique and analysis procedures for the mesospheric observations with the MU radar were described by *Tsuda et al.* [1990*b*], which are briefly summarized here. The antenna beam was steered for each transmission pulse sequentially in the vertical and four oblique directions declined from the zenith by 10° in the north, east, south, and westward. Binary phase modulation with the 8-bit complementary code with a 4-μs subpulse width was used. The received signal was oversampled every 2 μs, although the range resolution was determined by the subpulse length to be 600 m. From each Doppler spectrum obtained on 1-min observation, radial wind velocity and spectral width were determined by using a nonlinear Gaussian fitting.

TABLE 1. Observation Periods of the MU Radar in the Present Study

Month	Oct. 1986	June 1987	July 1990	Jan./Feb. 1991
Days	19	24	21	15
LT	0800–1600	0700–1700	0600–1800	0700–1700
Time resolution, s (no. of days)	60 (14)/145 (5)	60 (10)/145 (14)	185	130 (5)/185 (10)
Good data, no. of days	16	15	11	13

MU, middle and upper atmosphere.

It is noteworthy that part of the Doppler spectra were contaminated by radio interference due to other communications or broadcasting. For such a spectrum the ordinal Gaussian fitting was sometimes unable to be successfully applied. In June 1987 and July 1990, significant interference was often observed, and part of the data in January/February 1991 were also contaminated by weak interference. By using a more complicated algorithm, parameters of the Doppler spectra could be appropriately estimated. However, in this study we exclusively used data not influenced by interference.

Although the observation parameters were the same during the four observation periods, the time intervals between successive spectra were different, as summarized in Table 1, because other observations in the lower height ranges were interleaved between the successive mesospheric observations. As a result, the time resolution was better in the two observation periods of October 1986 and June 1987.

Turbulent scattering in the mesosphere is normally detected during only daylight hours, so that the durations of the observations were 10 and 12 hours in June 1987 and July 1990, respectively. Although the observation interval was also extended to 10 hours in January/February 1991, the echo power was not strong enough in the early morning and late afternoon, causing shorter coverage of the observation interval than in summer.

Figure 1 shows the hourly rate of the successful wind determinations by Doppler wind spectra as a time height cross section in the four campaign periods. Note that the data with significant interference were removed before the calculation of the data rate, so that in June 1987 and July 1990 the probability of determinations was smaller than that shown in Figure 1 due to the interference. The wind velocities were determined most frequently in October 1986 and less frequently in January/February 1991. The height range of the data rates of larger than 40% were 63–80, 65–78, 67–80, and 66–74 km in October 1986, June 1987, July 1990, and January/February 1991, respectively. In July 1990, wind data at 80–85 km were also taken at the rate of 40% in the afternoon, probably because of the high electron density due to high solar activity which reached maximum in 1989 to 1990. On the contrary, in January/February 1991 the duration of the wind data determination of 40% was limited between 1000 and 1500 LT, in the small height range around 70 km. Therefore we mainly utilized the data obtained between 68 and 80 km for the analysis of time series, such as frequency spectra of the wind velocities and momentum flux.

Because of the difference in the wind determination rate, the time resolution of the observation and the occurrence of the radio interference, the data quality is better for the former two periods: October 1986 and June 1987. So, in sections 5 and 6, data are more closely analyzed for these observation durations.

3. Mean Winds

We present in this section profiles of mean winds determined during the four observation periods, which are important to define the background condition of the gravity wave characteristics. Figures 2 and 3 show mean profiles of eastward and northward wind velocity, respectively. In Figures 2 and 3, mean wind profiles observed by the Kyoto meteor radar in the corresponding months in 1983–1986 are also illustrated for comparison. Furthermore, zonally averaged mean winds provided by the COSPAR International Reference Atmosphere (CIRA) 1986 model are plotted in Figure 2.

The MU radar results sometimes showed a wavelike structure in the mean wind profiles plotted in Figures 2 and 3, which were evident in the meridional component in June 1987 and in the both components in October 1986. *Tsuda et al.* [1990*b*] discussed that these features seemed to be spurious affected by long-period gravity waves that were not fully averaged out due to a relatively short duration of the MU radar observations on each day. So that it is rather difficult to argue fine structures of the mean wind profiles, but we need to focus on the overall structure of the profiles.

It is noteworthy that the mean winds by the MU radar were deduced by averaging profiles collected only during daylight hours; therefore the effects of diurnal tides might not be fully removed. According to the Kyoto meteor radar observation in 1983–1985, amplitude and phase of the eastward component of diurnal tides at 82 km altitude were 8 m/s and 1200 LT in summer and 2 m/s and 2000 LT in winter, respectively [*Vincent et al.*, 1988]. Consequently, the mean eastward winds in summer at around 80 km could be biased by several m/s from the values shown in Figure 2, if the averagings were limited to the daylight hours, which can account for a part of the discrepancy between the two profiles. If we assume the amplitudes of tidal winds in the altitude lower than 80 km is smaller than that at 82 km, no significant tidal influence is expected in winter and the discrepancies smaller than several meters per second are expected at the altitude below 80 km in summer. The discrepancy of the eastward wind around 80 km in January/February 1991 data is probably due to the effect of the variability of the mean wind in this season of the year. The large year-to-year variation shown in the meteor radar data at 82 km also suggests this point. General characteristics of the seasonal variation of the reversal height, that is low altitude in summer and high altitude in winter, agreed well

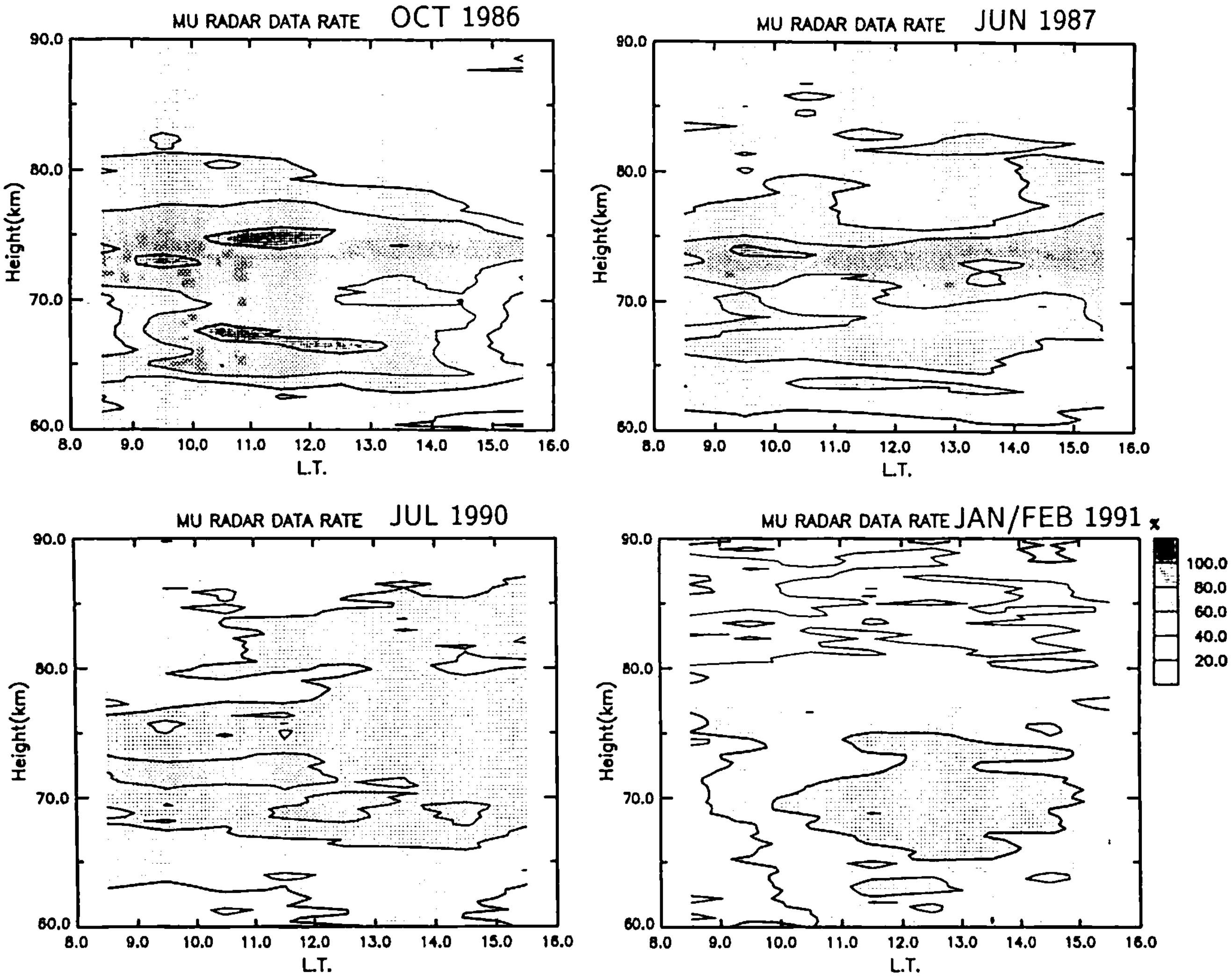

Fig. 1. Time-height cross section of the hourly rate of the wind determinations for the vertical beam of the middle and upper atmosphere (MU) radar in October 1986, June 1987, July 1990, and January/February 1991. After data screening of the wind velocity, percentage of successful wind determinations by one spectrum (almost 60 s) among the spectra collected in 1 hour is plotted.

with many other radar observations [e.g., *Manson et al.*, 1990].

The mean winds observed by Kyoto meteor radar and the MU radar at the 80- to 110 and the 60- to 85-km altitudes were fairly continuous. For the zonal mean wind the agreement is better in October 1986, while discrepancy about 10 m/s is found at around 80 km in June 1987 and July 1990. Discrepancies were also up to 20–35 m/s in January/February 1991, although the error bars of the mean wind with the MU radar above 75 km were large.

The MU radar observations showed the westward winds in summer in the mesosphere, which had maximum values of about 35 m/s at the altitudes of 74 km in June 1987 and 69 km in July 1990, respectively. The westward winds rapidly decreased with height above 75 km, then they were reversed to the eastward at 84 km and 83 km in June 1987 and July 1990, respectively.

In winter the eastward winds were observed with the peak of about 40 m/s at the altitudes of 74 km in January/February 1991. The amplitudes of the eastward wind rapidly decreased below this peak. The profile of zonal wind in October 1986 was similar to those detected in winter such that it showed an eastward peak of 40 m/s at 69 km altitude. It can be suggested that the background condition during the observation period in October 1986 was rather winterlike than summerlike.

The mean meridional winds in Figure 3 show more excellent continuity of wind fields between the MU radar data below 85 km and meteor radar data above 82 km than those of zonal components. Basic characteristics of the mean meridional winds shown in Figure 3 can be classified into summer and winter patterns between 70 and 90 km, with summer southward and winter northward wind. Meridional winds in summer collected in June 1987 and July 1990 were southward above 70 km, while they became northward below 70 km. Amplitudes of the southward winds were 10 m/s at 75–85 km and 15 m/s at around 80 km in June 1987 and July 1990, respectively.

Profiles in October 1986 and January/February 1991, which represent the winter condition, showed northward winds between 65 and 80 km, where the peak values were larger than 20 m/s at around 77 km in October 1986 and 10

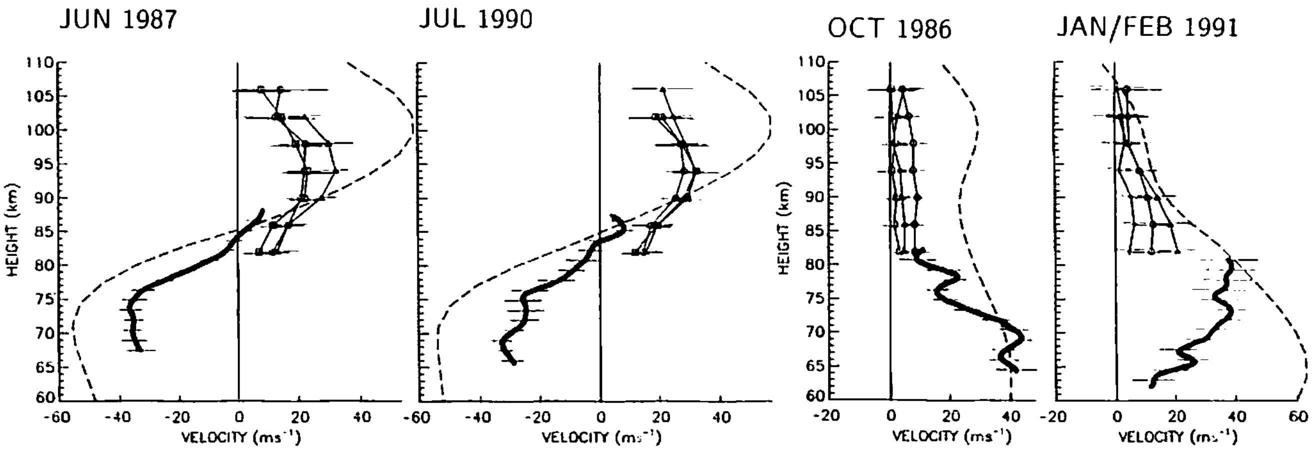

Fig. 2. Mean zonal wind observed with the MU radar on June 1987, July 1990, October 1986, and January/February 1991 (solid curves). Bars show reliable range of the mean wind. Dashed curves are zonally averaged zonal mean wind from COSPAR International Reference Atmosphere (CIRA) 1986 at 35°N. Curves with squares (1983), circles (1984), triangles (1985), and crosses (1986) are the mean winds observed by Kyoto meteor radar in 1983–1986, which are calculated by the corresponding 30-day data of the year determined by the harmonic analysis of diurnal and semidiurnal tides and mean wind [*Tsuda et al.*, 1987]. Bars indicate the reliability of the mean wind estimation.

m/s at 75 km in January/February 1991. However, above about 85 km the mean meridional winds were mainly southward for all four observation periods, except for in June above 100 km, and simple summer and winter change does not seem to happen at this altitude range. These characteristics are consistent with other radar observations [e.g., *Manson et al.*, 1990].

Here we discuss comparison of the observed results by both the MU radar and the Kyoto meteor radar with the CIRA 1986 model. Although the CIRA model gives that the maximum amplitude of the westward winds is about 55 m/s at about 71 km altitude in June and July, the MU radar observations showed 30 to 40 m/s at the corresponding altitudes, which were smaller than the model values by 15–25 m/s. A similar discrepancy can also be recognized in the region above the reversal, that is, the mean eastward wind ranged 20–35 m/s from the Kyoto meteor radar observations, again smaller than the model by about 30 m/s. When a smoothed profile of the zonal wind is constructed by connecting the profiles of the MU radar and Kyoto meteor radar observations, the reversal height of the wind direction from westward to eastward can be inferred at slightly lower than 82 km in both June 1987 and July 1990, while the CIRA 1986 model indicates it at 85 km.

In October 1986 we observed eastward winds at about 70 km altitude to be 40 m/s, showing a good agreement with the CIRA 1986 model. However, above about 75 km the observed zonal winds were as small as 10–20 m/s, which was significantly smaller than the model.

In January/February 1991 the observed eastward winds at around 80 km altitude were similar to the model. But discrepancy is remarkable below 74 km altitude such that the observed winds decreased rapidly to almost 10 m/s at 62 km, while the CIRA model shows a broad maximum with over 60 m/s centered at 65 km altitude. It is reported that from the end of January to the middle of February in 1991 a strato-

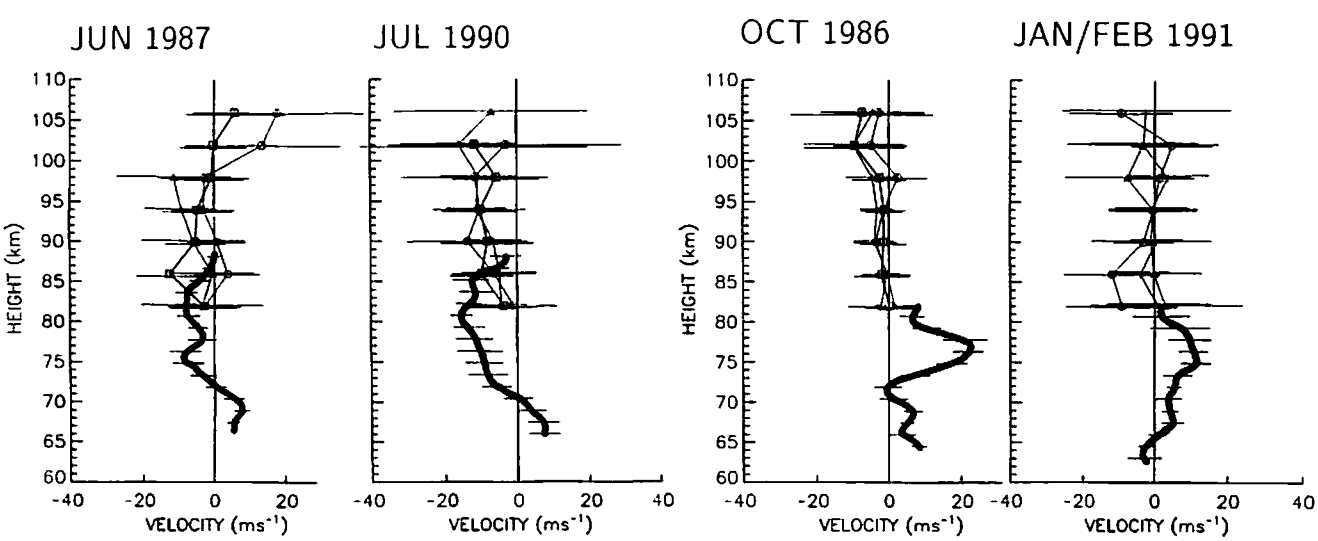

Fig. 3. The same as Figure 2 except for mean meridional winds.

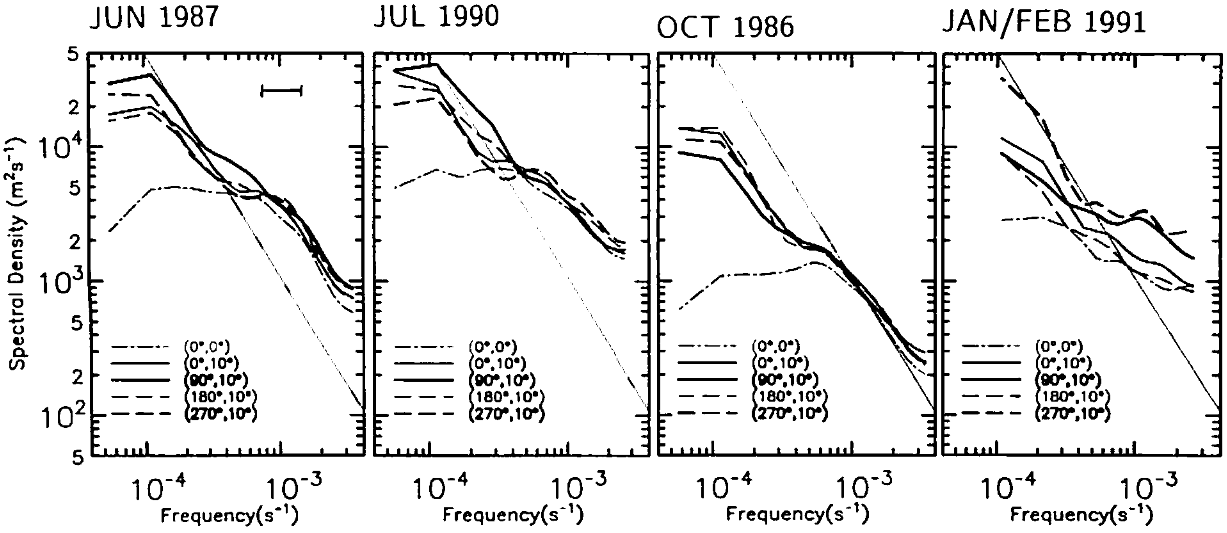

Fig. 4. Frequency spectra of radial wind velocities observed on June 6–29, 1987; July 2–21, 1990; October 13–31, 1986; and January 21 to February 8, 1991. The thin chained lines are of vertical beams and the other lines are of oblique beams: thin solid lines (northward), thin dashed lines (southward), thick solid lines (eastward), and thick dashed lines (westward), respectively. The thin straight lines indicate the spectral slope of $w^{-5/3}$.

spheric sudden warming occurred [*Naujokat et al.*, 1991]. *Tsuda et al.* [1987] pointed out that even at the latitude of 35°N the mean zonal wind at 90 km can sometimes be reversed from eastward to westward direction during a stratospheric warming. *Murayama et al.* [1992] also showed that the correlation between the stratospheric sudden warming and the weak eastward mean wind in the upper stratosphere by the rocketsonde observation in the DYANA campaign. Therefore the discrepancy in winter reported above could be caused by the effects of the stratospheric warming.

4. Frequency Spectra

We first analyze in this section frequency spectra of vertical and radial wind velocity and then further derive frequency spectra of momentum flux.

4.1. *Vertical and Radial Wind Velocity*

We analyzed a frequency spectrum by adopting the procedure described by *Tsuda et al.* [1990*b*], except that the maximum lag of an autocorrelation function (ACF) was set equal to 150 min for the results in June 1987, July 1990, and October 1986, while it was 80 min in January/February 1991 because of the lack of data in the early morning and late afternoon. We restricted the height range for the spectral analysis to 68–80 km, since the time series were most continuously obtained at these altitudes.

Figure 4 shows frequency spectra of vertical wind velocity as well as those for radial wind velocity obtained in the four oblique directions during the four observation periods. Note that the spectral density at the lowest frequency point shown in Figure 4 tends to be smaller than the real value because of the removal of the linear trend in the time series and the Hanning window multiplied to the ACF of the time series [*Tsuda et al.*, 1989]. The spectra of high frequency components are smoothed with a spectral window of a raised cosine of the logarithmic frequency, where the resulting spectral resolution becomes approximately ±35% at any specified frequency, as indicated in the figures. Thus the reliability of the spectral density at the high frequency component was significantly improved but the frequency resolution became worse than the original spectrum. The 95% confidence intervals of the spectral stability at each frequency are generally 14% and 4% for the frequencies of 1×10^{-4} s^{-1} and 1.7×10^{-3} s^{-1}, respectively. However, the confidence intervals are about twice larger for the data in January/February 1991 because of the low data acquisition rate.

The general structure of the oblique spectra was similar among determinations in the four observation periods. The logarithmic slopes of the oblique spectra were approximately $-5/3$ in the frequency range of 10^{-4} s^{-1} to 3×10^{-4} s^{-1}, suggesting that the oblique spectra were mainly contributed by the projection of horizontal wind components. On the other hand, the spectra for frequency components larger than 4–5 $\times$ 10^{-4} s^{-1} were enhanced, which seems to be caused by the effects of vertical winds. However, in the frequency range of 7–8 $\times$ 10^{-4} s^{-1} the spectra in June 1987, July 1990, and October 1986 again showed a slope of about $-5/3$, which could be explained by the Doppler shift effects on the spectrum of vertical winds [*Fritts and VanZandt*, 1987; *Tsuda et al.*, 1990*b*], i.e., the frequency spectra of radial wind with no background mean wind would show a peak at Brunt-Väisälä frequency and no energy would be found in the higher frequency region, but the Doppler shift by a background mean wind can cause a shift of peak to the lower frequency and the spectral slope with $-5/3$ for higher frequency. In January/February 1991 the spectral slope was fairly gradual in the entire frequency range larger than 4–5 $\times$ 10^{-4} s^{-1}, and it did not show the bend at 7–8 $\times$ 10^{-4} s^{-1} detected in other three periods. The determination rate of the Doppler velocity in January/February 1991 was lower than those in the other observation periods because of the low signal to noise ratio (SNR) in winter and the large interval between successive Doppler spectra due to the

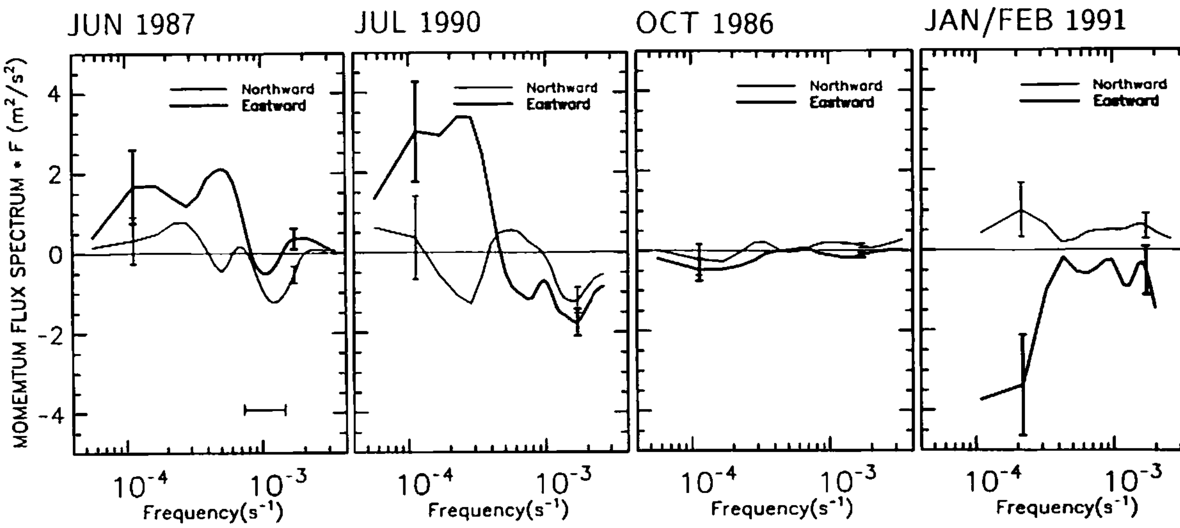

Fig. 5. Frequency spectra of zonal (thick) and meridional (thin) momentum flux observed on June 6–29, 1987; July 2–21, 1990; October 13–31, 1986; and January 21 to February 8, 1991. Note that curves are plotted in an area preserving form. The error bars indicate the confidence intervals of 95%.

interleaving of other observations. Such a condition might cause the noisy spectra in January/February in 1991, especially at the high frequency components.

A discrepancy in the spectral amplitudes among the four oblique directions was recognized in the results, which was most conspicuously seen for frequency components smaller than about 5×10^{-4} s^{-1}, where the horizontal component had a more dominant contribution to the oblique spectra. It is noteworthy that in January/February the spectral amplitudes for zonal components were larger than the meridional ones, which can be recognized in the frequency range above 5×10^{-4} s^{-1}.

It is appreciable that in October 1986 the spectral amplitudes for the eastward component were smaller than those in the other three directions for frequencies lower than 3×10^{-4} s^{-1}. In June 1987 the spectrum for the eastward component showed largest values in the frequency range of lower than 8×10^{-4} s^{-1}. Spectra in July 1990 also showed larger values for the eastward winds in the low frequency range. The azimuthal anisotropy of the oblique spectra can be interpreted in terms of the anisotropy in the distribution of gravity wave propagation [*VanZandt et al.*, 1990], which can further be related to the dominant direction of the wave-induced momentum flux.

For the vertical wind component the spectral slope was nearly zero but showed some variation with months for the frequency range of 1×10^{-4} s^{-1} to $4\text{–}5 \times 10^{-4}$ s^{-1}, where the slope can be estimated to be −0.05, 0.05, 0.15, and −0.4 in June 1987, July 1990, October 1986, and January/February 1991, respectively.

The spectral amplitudes for both vertical and oblique components were generally larger in summer months. That is, the density of oblique spectra in June 1987 and July 1990 were 3 and 3.5 times larger than in October 1986, respectively, in the frequency range between 1×10^{-4} and 2×10^{-3} s^{-1}. The spectral amplitudes in January/February 1991 were smaller than the summer results but were larger than those in October by 1.5 to 2.5 times in the frequency range of 2×10^{-4} to 1×10^{-3} s^{-1}.

These comparisons suggest that the gravity wave energy in the mesosphere exhibits a semiannual variation with the smallest values at the equinoxes, which is identical to the seasonal variation of the activity of mesospheric gravity waves with periods of 2 hours to 5 min at 60–90 km in 1985–1988 reported by *Tsuda et al.* [1990*a*] and is consistent with other radar observations [*Vincent and Fritts*, 1987; *Meek et al.*, 1985].

4.2. *Momentum Flux Spectra*

We discuss here the frequency spectra of momentum flux at 68–80 km altitude. We subtracted spectral densities between a pair of oblique frequency spectra collected by using antenna beams pointed at the opposite azimuth angles. Then, we derived a frequency spectrum of momentum flux by dividing the resultant spectral density by $2 \sin 2\theta$ (θ: zenith angle of the oblique beam). That is,

$$F_{u'w'}(\omega) = \frac{F_{V(90°)}(\omega) - F_{V(270°)}(\omega)}{2 \sin 2\theta} \qquad (1)$$

$$F_{v'w'}(\omega) = \frac{F_{V(0°)}(\omega) - F_{V(180°)}(\omega)}{2 \sin 2\theta} \qquad (2)$$

where $F_{V(0°)}(\omega)$, $F_{V(90°)}(\omega)$, $F_{V(180°)}(\omega)$, and $F_{V(270°)}(\omega)$ are spectra of the radial wind velocity at 0°, 90°, 180° and 270° azimuth angle, and θ represents the zenith angle of the oblique antenna beam direction, i.e., 10° in this study.

Figure 5 shows the observed momentum flux spectra, $F_{u'w'}(\omega)$ and $F_{v'w'}(\omega)$, for the northward and eastward components, respectively. Note that momentum flux spectra are plotted in an area preserving form, so that the area surrounded by the curve and horizontal axis is proportional to the integrated momentum flux in the corresponding frequency range. The error bars indicate the confidence intervals of 95% of the spectral stability.

There is a clear seasonal variation in that the zonal momentum flux was eastward in summer and westward in winter, which has already been reported by *Tsuda et al.* [1990*a*]. We here discuss the frequency distribution of the momentum flux. In June 1987 the zonal momentum flux was largely enhanced in the eastward direction in the frequency range lower than 8×10^{-4} s^{-1}, corresponding to the wave period of about 20 min. On the other hand, the meridional momentum flux was generally northward and southward in the lower and higher frequency ranges than 4×10^{-4} s^{-1} (40 min in period), respectively, but it did not show clear enhancement in the observed frequency region. The zonal momentum flux was fairly small in the frequency range above 8×10^{-4} s^{-1}.

In July 1990 the large eastward momentum flux was detected in the frequency range lower than 4.0×10^{-4} s^{-1}, that is, about 40 min in wave period. For the frequency range higher than 4.0×10^{-4} s^{-1} the momentum flux was westward, being opposite to that for the lower frequency components. The meridional flux fluctuated near zero, and it did not show a clear tendency of dominant directions.

On the other hand, the zonal momentum flux in January/February 1991 showed large values in the westward direction in the frequency range lower than about 4×10^{-4} s^{-1}, or 40 min in wave period. For the higher frequency component the zonal momentum flux was weakly westward. The meridional flux was generally northward in the entire frequency region, although the amplitudes were fairly small. These results support the theoretical prediction that the zonal momentum flux should be reversed between summer and winter months [e.g., *Lindzen*, 1981].

In October 1986 the amplitudes of both the zonal and the meridional momentum were fairly small in the entire observed frequency range. However, the zonal momentum flux was generally westward in the frequency range lower than 3.5×10^{-4} s^{-1} (about 50 min in wave period), which is consistent with the results in winter months, again suggesting that the condition in October 1986 was more winterlike than summerlike.

Meek et al. [1985] reported, using Saskatoon medium-frequency (MF) radar observations, that gravity waves with periods shorter than 1 hour mainly contribute to the acceleration of the mean wind. *Fritts and Vincent* [1987] and *Reid and Vincent* [1987] pointed out, using Adelaide MF Doppler radar observations, that about 70% of the momentum flux was due to the components with periods of less than 1 hour. *Fritts* [1984] theoretically discussed the contribution of high and low frequency components of gravity waves to the momentum flux by a dispersion relation and concluded that more than two thirds of the total flux is due to the waves with periods less than 2 hours if the frequency spectral slope of horizontal wind velocity fluctuation is −5/3. Our results, however, show that the amplitudes of the zonal momentum flux were considerably large for gravity waves with periods between 1 and 2.7–5 hours. It can be suggested that the gravity waves with periods longer than 2.7–5 hours can also be important in carrying momentum flux, which, however, was not clarified in this study due to the limited minimum frequency of the spectral analysis.

5. Profiles of Momentum Flux

In this section we present vertical profiles of momentum flux. Observations in June 1987, July 1990, and October 1986 were analyzed because enough wind velocity data in these 3 months were collected to analyze the vertical profile. The data were analyzed in the same way as by *Tsuda et al.* [1990*b*] except for the band-pass characteristics of the filter. For each range bin and each day, a linear trend was subtracted from the 10-hour (or 8-hour) time series of radial wind velocities. Then, the fluctuating radial wind components were separated into two frequency ranges by using low-pass and band-pass filters with a cutoff period of 30 min and a band-pass of 30–5 min, respectively. We hereafter refer to the two bands as the 8- to 0.5-hour and 30- to 5-min components, respectively. By subtracting the variances of radial wind velocity observed in each range gate by using a pair of oblique beams, we obtained profiles of both zonal and meridional momentum flux.

The values of the momentum flux in each range bin were averaged over a height range of 4.5 km, and then the profiles of $\rho\overline{u'w'}$ and $\rho\overline{v'w'}$ were determined, as shown in Figures 6–8, where ρ was taken from the CIRA 1986 model. Note that for the data in July 1990, the 30- to 5-min component was not deduced because the Nyquist period determined by

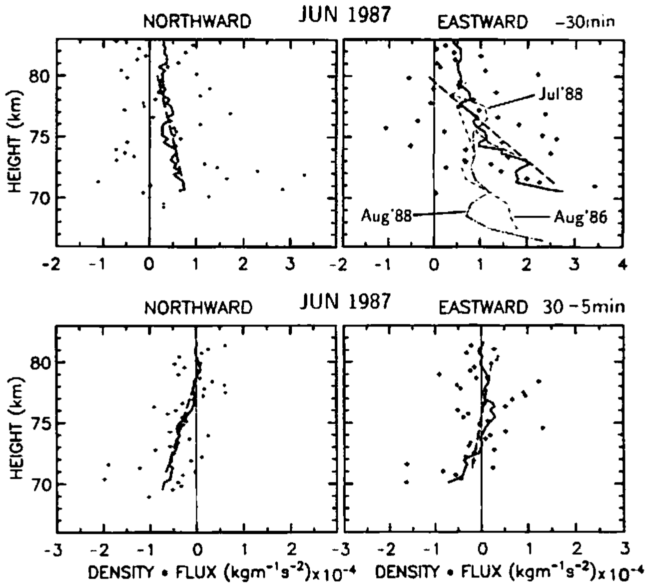

Fig. 6. Vertical profiles of (left) northward and (right) eastward components of momentum flux in June 1987. The top and the bottom panels correspond to the components with periods of more than 30 min and 30–5 min, respectively. The solid line shows the 4.5-km average of the momentum flux. The dashed lines are best fit lines between 71 and 80 km. In the top right-hand panel, the momentum flux observed in August 1986 and 1988 and July 1988 for the waves with periods of 2 hours to 30 min is also plotted as thin lines as a reference [*Tsuda et al.*, 1990*a*].

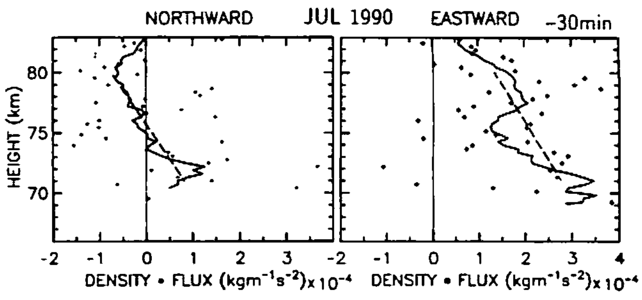

Fig. 7. The same as Figure 6 except for the data in July 1990. Only the component with periods larger than 30 min is deduced.

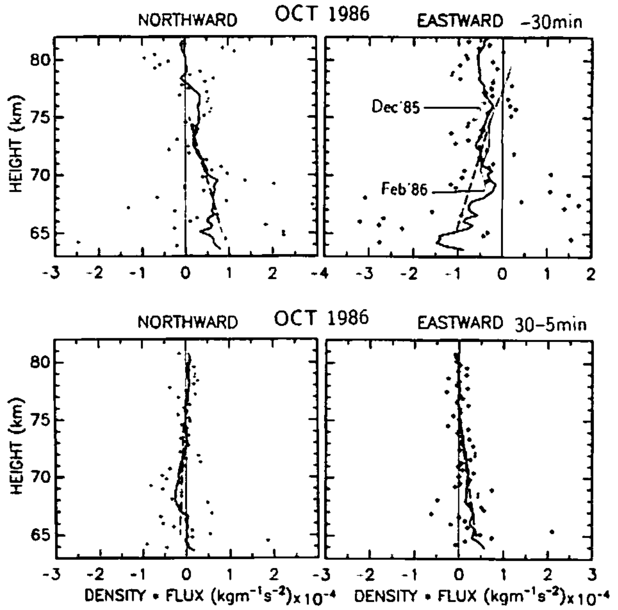

Fig. 8. The same as Figure 6 except for the data in October 1986. The dashed lines are the best fit lines between 65 and 75 km. The momentum flux observed in February 1986 and December 1985 for the waves with periods of 2 hours to 30 min is also plotted as thin lines as a reference [*Tsuda et al.*, 1990*a*].

the interval of the Doppler spectra was larger than 5 min and the band-pass filter could not be composed.

All the profiles showed that the momentum flux decreased with height, except for those of the 30- to 5-min component of zonal flux in June 1987 and the 8- to 0.5-hour component of meridional flux in July 1990. It is remarkable that the eastward momentum flux of the 8- to 0.5-hour component in June 1987 and July 1990 was conspicuously larger in comparison with other profiles at the altitudes of 71–77 km. At 71 km the eastward flux for the 8–0.5-hour component was 2×10^{-4} kg m^{-1} s^{-2} and 3×10^{-4} kg m^{-1} s^{-2} in June 1987 and July 1990, respectively, while other components were about 0.5×10^{-4} kg m^{-1} s^{-2}.

The eastward flux of the 8- to 0.5-hour component in June 1987 and July 1990 decreased rapidly with height indicating strong eastward drag force, while the 30- to 5-min component in June 1987 was small in all the height ranges. Other determinations based on the MU radar observations by *Tsuda et al.* [1990*a*] are plotted in Figure 6, which were deduced for the wave periods of 2 hours to 30 min. They showed smaller momentum flux in comparison with the results in June 1987 and July 1990 by a factor of 2/3 to 1/2, although the general behavior was quite similar. The discrepancy seems to be due to the additional momentum flux of the wave component with periods of 2 to 8 hours. The meridional component in June 1987 shows northward and southward flux in the 8- to 0.5-hour and 30- to 5-min ranges, respectively, which is also recognized in the frequency spectrum of momentum flux in Figure 5. The meridional component in July 1990 shows northward and southward momentum flux below and above 75 km, resulting in a total northward drag at around 75 km.

In October 1986, as shown in Figure 8, the zonal component was westward and eastward in the 8- to 0.5-hour and 30- to 5-min ranges, respectively. The amplitude of the zonal flux due to the 8- to 0.5-hour component was about 5×10^{-5} kg m^{-1} s^{-2} at 70 km, which was larger than that for the 30- to 5-min components by a factor of about 2. Therefore the resultant total flux seemed to be westward. The earlier results in December 1985 and February 1986 reported by *Tsuda et al.* [1990*a*] shown in Figure 8 showed a similar amplitude of westward momentum flux at 68–78 km altitude. However, *Tsuda et al.* [1990*a*] picked up the wave component with periods of 2 hours to 30 min, so that if they are compared as the momentum flux of 8-hour to 30-min components, the amplitude in October would be significantly smaller than those in December and February. The meridional component in October 1986 also shows different directions between the 8- to 0.5-hour and the 30- to 5-min components, northward and southward flux for the 8- to 0.5-hour and 30- to 5-min frequency components, respectively, although the amplitude of the latter was small.

According to the theoretical study by *Fritts* [1984] the ratio of momentum flux with periods of inertia period to 30 min and 30 min to Brunt-Väisälä period is estimated to be 1:1.1, by using a linear dispersion relation of gravity waves and the assumption of spectral slope of $\omega^{-5/3}$. Our momentum flux observation of 8-hour to 30-min and 30- to 5-min component showed that *Fritts* [1984] overestimated of the contribution of high-frequency gravity wave, which is also shown in the frequency spectral analysis for the component with periods less than 5 hours in the previous section.

The most reliable profiles of momentum flux were estimated at 71–80 km in June 1987 and July 1990 and at 65–75 km in October 1986, respectively. Therefore that part of the momentum flux profiles was fitted by a linear curve, as indicated in Figures 6–8. Then, we estimated the mean flow accelerations, or drag force, F_E and F_N, for the zonal and meridional components, respectively, from the vertical derivative of the momentum flux profiles as

$$F_E = -\frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{u'w'}) \qquad (3)$$

$$F_N = -\frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{v'w'})$$

The values of F_E and F_N can be regarded to be taken at 75 km in June 1987 and July 1990 and at 70 km in October 1986, respectively. The resultant values of F_E and F_N are summarized in Table 2.

The zonal mean winds plotted in Figure 2 showed a decrease with height above 74, 75, and 69 km in June 1987, July 1990, and October 1986, respectively; thus the results of F_E and F_N shown in Table 2 were determined at 71–80 km for June 1987 and July 1990 and 65–75 km for October 1986.

In June 1987 the eastward mean flow drag due to 8- to 0.5-hour waves was as large as 61 m/s/d, while the 30- to 5-min component showed westward drag of only 10 m/s/d, so that in total an eastward drag of 51 m/s/d resulted. The meridional acceleration in June 1987 was northward and southward for the 8- to 0.5-hour and 30- to 5-min ranges, respectively. The amplitudes were about 15 m/s/d in both cases. As a result, the drag forces due to the 8- to 0.5-hour and 30- to 5-min components canceled each other out. Thus the total acceleration became as small as −4 m/s/d. The zonal drag in July 1990 of the 8- to 0.5-hour component also showed eastward drag as high as 33 m/s/d. The northward

TABLE 2. Mean Flow Drag Due to the Gravity Waves

Month	Direction	Drag 8 hours–30 min	30–5 min	Total	Remarks
June 1987	zonal	+61 m/s/d	−10	+51	at 71–80 km
	meridional	+13	−17	−4	
July 1990	zonal	+36			at 71–80 km
	meridional	+33			
Oct. 1986	zonal	−8.7	+4.3	−4.4	at 65–75 km
	meridional	+8.4	−1.0	+7.4	
Aug. 1986	zonal	+7.2 (2 hours to 30 min)			at 70–77 km
July 1988	zonal	+12.8 (2 hours to 30 min)			at 73–79 km*
Aug. 1988	zonal	+9.4 (2 hours to 30 min)			at 66–75 km*
Feb. 1986	zonal	−7.6 (2 hours to 30 min)			at 70–78 km*
Dec. 1985	zonal	−11.0 (2 hours to 30 min)			at 73–77 km*

**Tsuda et al.* [1990*a*].

drag also reached up to 36 m/s/d, although the 30- to 5-min component, which was not determined in the present study, may cancel the strong meridional flux, as is the case of June 1987. In October 1986 the westward and northward acceleration for 8- to 0.5-hour component was 8.7 and 8.4 m/s/d, respectively, which was partly canceled out by the 30- to 5-min component, causing a small acceleration.

To summarize, the contribution of the low frequency components (8–0.5 hours) was large to not only the momentum flux itself but also to their vertical gradient, i.e., mean flow drag. And the high frequency component (30–5 min) had relatively smaller effects except for the meridional component in June 1987. The zonal drag by the gravity waves with periods from 2 hours to 30 min was also reported by *Tsuda et al.* [1990*a*], which is also shown in Table 2. They observed that the zonal momentum flux in summer was 7–13 m/s/d at about 70–75 km altitude. Our result here shows that the eastward drag was larger than their result by a factor of 3–7 times, which is probably because our results were calculated for waves with periods extending to 8–10 hours, and also the height range was higher, from 71 to 80 km. For the winter months, Tsuda et al. observed two cases in February 1986 and December 1985 which showed the westward drag of 7.6 and 11.0 m/s/d at 70–78 km for the wave periods of 2 hours to 30 min. These values are comparable with the westward flux observed for the periods of 8 hours–30 min in October 1986. However, if the direction of the drag does not change between the wave components with periods larger and smaller than 2 hours, as suggested from Figure 5, the drag by the wave periods of 8 hours to 30 min, i.e., the major component of the zonal drag, can be estimated to be larger in winter than in October.

The momentum flux and mean flow drag in October 1986 have also been already reported by *Tsuda et al.* [1990*b*], who showed momentum flux due to the wind fluctuation with periods longer than 10 min. They calculated the westward and northward drag to be 5.1 and 4.0 m/s/d, respectively, indicating a difference with the present results of 0.7 and 3.4 m/s/d, respectively. This difference is considered to be caused by small westward and comparatively large northward momentum flux with periods of the 10- to 5-min components, which can be seen in Figure 5.

The consistency of the current observations with the previous studies with the MU radar [*Tsuda et al.*, 1990*a*, *b*] suggests that the momentum fluxes obtained in the present study are typical values in the seasonal variation.

Reid and Vincent [1987] reported that gravity waves with periods ranging from 8 min to 8 hours induced zonal mean wind acceleration at 80–98 km between 50 and 80 m/s/d as a typical value and sometimes almost 200 m/s/d. They further showed a good agreement of the observed acceleration with Coriolis torque due to mean meridional wind, while they showed disagreement when planetary waves were enhanced. *Meek and Manson* [1989] also investigated $\overline{u'w'}$ at 60–110 km and found that zonal acceleration by gravity waves with periods of 10–100 min was 10–50 m/s/d in summer and winter, which was also consistent with Coriolis torque. Although our results are limited to only three campaigns and at a low altitude (75 km in June 1986 and July 1990 and 70 km in October 1986), they do not contradict other observations. Moreover, the corresponding Coriolis torque from the meridional wind shown in Figure 3 was −50 m/s/d at 75 km in June 1987, −55 m/s/d at 75 km in July 1990, and +12 m/s/d at 70 km in October 1986, which agree well with the zonal drag presented in this section except for the larger value than the observed drag in July 1990, where the drag due to the waves with periods of 30–5 min was not determined, as described above.

6. Day-to-Day Variation of Gravity Wave Activity

In this section we describe day-to-day variations of gravity wave activity during the two observation campaigns: June 1987 and October 1986. As we report in section 4, frequency spectra suggested that gravity waves with periods longer than 20–50 min produced a major part of the zonal momentum flux. Furthermore, in section 5 the momentum flux due to gravity waves with periods longer than 30 min was found to be dominant in accelerating mean wind. Therefore we study the variance and momentum flux induced by gravity waves with periods of 30 min to 4 hours.

The top panels in Figure 9 show the daily mean variance of radial wind fluctuations in the vertical and four oblique directions with periods of 4 hours to 30 min. Data with significant gaps in daytime were excluded from the figure. Note that the vertical axis of the figures are adjusted to the magnitude of variance in each month, so that the scale is larger for June 1987 than for October 1986. The bottom

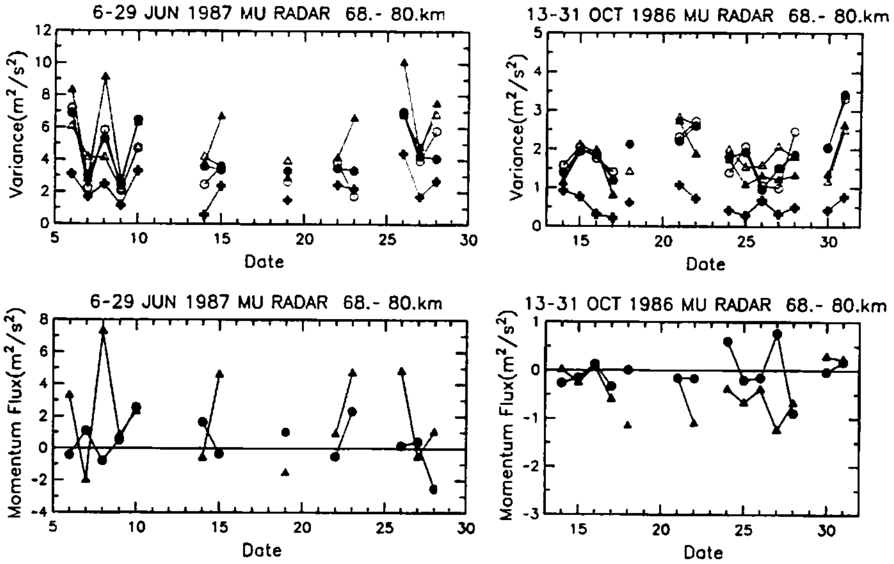

Fig. 9. (Top) Day-to-day variations of the daily mean variance of the radial wind fluctuations and (bottom) momentum flux, respectively. (Top) Pluses, solid circles, open circles, solid triangles, and open triangles show variance of vertical, northward, southward, eastward, and westward beams, respectively. Left and right panels are for observations in June 1987 and October 1986, respectively. Wind fluctuations with periods between 30 min and 4 hours are extracted. (Bottom) Day-to-day variations of zonal (triangles) and meridional (circles) momentum flux with periods between 30 min to 4 hours.

panels in Figure 9 show day-to-day variation of the momentum flux. In June 1987 the eastward momentum flux showed large day-to-day variation, that is, it quite often became as large as about 5 m^2/s^2, while it became close to zero on other days. There were no cases that showed westward flux larger than 2 m^2/s^2.

Northward momentum flux also showed similar characteristics, although the magnitudes of northward momentum flux were smaller than the eastward components. It is noteworthy that there seems to be some correlation between the enhancement of zonal and meridional components, but it did not always coincide.

In October 1986 the zonal momentum flux was generally westward, but it sometimes reversed to become eastward with small amplitudes. On the other hand, the meridional flux was distributed in both northward and southward directions.

Reid and Vincent [1987] determined momentum flux and mean flow drag every 3–4 days and found that the direction and magnitude of the flux and mean flow acceleration showed considerable variations between successive observation periods. Our results of the daily determination of momentum fluxes also showed a similar variability in amplitude and direction. These variations suggest that the propagation directions of gravity waves change frequently.

Next, we examine the relation between the day-to-day variation of the momentum flux and the variability of the mean wind field. The left panel in Figure 10 shows the daily mean zonal wind velocity averaged over the height range between 70 and 85 km as well as the mean zonal wind shear in the same height region, which is calculated by using a linear fitting of daily mean wind velocity profile. Although the mean wind and shear determined by daytime mean of a single day may be affected by a large internal gravity wave activity, the effect of the inertia gravity waves with vertical wavelength smaller than 10–15 km, which are often observed as a dominant component, would be small, because each mean wind and shear here are deduced by the data of 15-km altitude range.

The amplitudes of both mean wind and wind shear showed large day-to-day variations. There seems to be a fairly good correlation between the variations of momentum flux and wind shear, except for the results on June 26–28, 1987, while the variation of the mean wind amplitudes was somewhat different from these variations. The cross correlation between the zonal momentum flux and the zonal wind shear and between the zonal momentum flux and the mean zonal wind are plotted as scatter diagrams in Figure 10. The correlation coefficient was 0.69 between the zonal wind shear and the zonal momentum flux, while it was −0.37 between the zonal wind amplitude and the momentum flux. Therefore the former correlation, i.e., the correlation between the zonal wind shear and the zonal momentum flux, is relatively significant. The meridional momentum flux did not show a good correlation with either the mean meridional wind amplitude or the meridional wind shear.

Figure 11 shows similar comparison of observations in October 1986, where the height range for the calculation of the zonal wind and wind shear was 65–75 km. It again showed a good correlation between zonal momentum flux and zonal wind shear, while zonal mean wind amplitude did not show a good correlation with zonal momentum flux. The wind shear and the momentum flux showed large day-to-day variations, having large negative values between October 18 and 28, while the mean wind showed longer-period variations with a minimum eastward wind at October 17 and then almost monotonously increased up to 60 m/s until October 31.

The correlation coefficients between the zonal wind shear and the zonal momentum flux and between the zonal mean wind and the zonal momentum flux were 0.52 and 0.09,

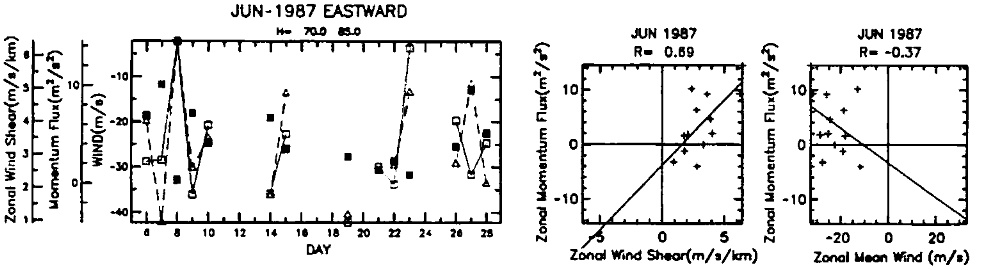

Fig. 10. (Left) Day-to-day variation of the daily mean zonal wind (solid squares) and mean shear of the mean wind (open squares) at 70–85 km in June 1987. Zonal momentum fluxes at 68–80 km are also plotted as triangles. Scatter diagrams of mean shear and zonal momentum flux and mean wind and zonal momentum flux are shown in the middle and right panels, respectively.

respectively. The meridional flux again did not show a good correlation with meridional mean wind or wind shear.

The correlation between the mean zonal wind shear and the zonal momentum flux can be explained as due to the strong eastward momentum flux accelerating the mean zonal wind eastward by losing a part of the momentum flux, i.e., these day-to-day variations in wind shear are caused by the day-to-day variation of momentum flux caused by gravity waves.

The day-to-day variations of the momentum flux could also be generated by the variation of the mean wind intensity in the mesosphere, which modulates the effect of the gravity wave saturation due to convective instability. That is, the gravity waves propagating in the same direction as the mean wind are attenuated by the increase in mean wind amplitude. This could also cause the fluctuation of momentum flux. However, the mean wind variation in that situation has to show a better correlation with the momentum flux variation than the shear variation does, because the absolute amplitude of mean wind is concerned with the interaction with gravity waves. In the present results the variation of zonal mean wind showed less correlation with momentum flux than the variation of zonal shear. In this case it can be considered that the shear and its variability are larger than the variation of mean wind at 70–85 km, and when the shear becomes large, gravity waves with the opposite propagation of the net momentum flux are more effectively absorbed. But this situation can be considered when the variations of shear and wind fluctuation variance have positive correlation and hence can be a reasonable interpretation for the case of October 1986, but is not appropriate for June 1987, as shown in Figures 9–11.

Thus the day-to-day variation of the zonal shear of mean wind in the present study is explained that it is caused by the day-to-day variation of zonal momentum flux carried by gravity waves or the shear variability caused the day-to-day variation of zonal momentum flux.

7. Concluding Remarks

We studied the characteristics of gravity waves in the mesosphere at 60–90 km observed by means of the MU radar in four periods: June 1987, July 1990, October 1986, and January/February 1991.

The mean winds are compared with the Kyoto meteor radar observations at 80–110 km in 1983–1985, showing reasonable overall continuity at 80–90 km. Some discrepancies from the CIRA 1986 model were pointed out such that the observed winds were smaller by 10–35 m/s below 80 km in summer and above 75 km in October 1986. The eastward winds below 70 km observed in January/February 1991 were smaller than the CIRA 1986 by 20–50 m/s, which could be caused by the effects of a stratospheric sudden warming. The reversal height in summer was observed as 83–84 km in 1987 and 1990, showing good agreement with CIRA 1986 model, although the reversal height can be estimated as about 82 km when the MU radar results and Kyoto meteor radar results in 1983–1986 are averaged. The mean meridional wind in June and July showed southward maxima at around 80 km with 10–15 m/s, while the southward peak was found to be 10–20 m/s at 75–80 km in October and in January/February.

The frequency spectra of the radial wind velocity determined at 68–80 km during the four observation periods had a slope of about $-5/3$ for frequencies smaller than about 4×10^{-4} s^{-1}, while vertical spectra showed a slope of $+0.15$ to -0.4. The spectral densities at the frequency of 2×10^{-4} s^{-1} were the largest in June 1987 and July 1990, i.e., $1.5\text{–}2 \times 10^4$ m^2 s^{-1}, became $6 \times 10^3 - 1.5 \times 10^4$ m^2 s^{-1} in January/

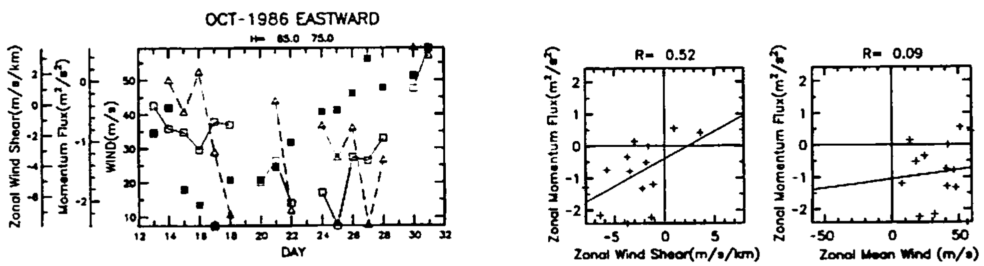

Fig. 11. The same as Figure 10 except for the data in October 1986. Zonal mean wind and shear were calculated for 65–75 km.

February 1991, and showed the smallest values of 4×10^3 $m^2 s^{-1}$ in October 1986.

Analysis of the frequency spectra of momentum flux was performed for the wave period range of 5 hours to 5 min and clarified that zonal momentum flux was predominantly contributed to by gravity waves with periods longer than 20 min in June 1987, 40 min in July 1990, 50 min in October 1986, and 40 min in January/February 1991, respectively. The meridional momentum flux did not show clear components that were dominantly detected in the momentum flux spectra, instead it rather fluctuated around zero.

The vertical profile of momentum flux, $\overline{u'w'}$ and $\overline{v'w'}$, in June 1987, July 1990, and October 1986, when the data acquisition rate was fairly good, showed that the mean flow drag by low-frequency waves (wave periods, 8 hours to 30 min) was larger than that due to high frequency components (5–30 min) for both zonal and meridional components, except that the meridional component in June 1987 was comparable to the zonal one. The directions of the drag of the high and low frequency components were opposite, causing cancelation between different frequency components. The total zonal and meridional acceleration observed in the daytime duration was +51 and −4 m/s/d in June 1987 at 75 km and −4 and −7 m/s/d in October 1986 at 70 km, respectively. Since the momentum deposition by waves with different frequency components is often of different directions, it is important to observe the dominant frequency component of the momentum flux, such as the waves with periods longer than 30 min. The zonal mean flow drag observed above showed good correspondence with Coriolis torque of the mean meridional wind observation.

The day-to-day variation in the gravity wave activity was larger in June 1987 than in October 1986. These variations in zonal momentum flux seem to show good correlation with the shear of zonal mean wind each day, suggesting these mean wind fields were accelerated and changed with the day-to-day variation of the gravity wave activity, while it is also possible that day-to-day variation of the gravity waves are caused by the variation of wind shear.

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