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Mesospheric gravity waves at Saskatoon (52°N), Kyoto (35°N), and Adelaide (35°S)

T. Nakamura, T. Tsuda, and S. Fukao
Radio Atmospheric Science Center, Kyoto University, Kyoto, Japan

A. H. Manson and C. E. Meek
Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatchewan, Canada

R. A. Vincent and I. M. Reid
Department of Physics and Mathematical Physics, University of Adelaide, Australia

Abstract. The gravity waves with periods of 10 min to 8 hours in the mesosphere (67–80 km) are studied using observations from the Adelaide MF radar (35°S), Saskatoon MF radar (52°N), and the middle and upper atmosphere (MU) radar at Shigaraki, near Kyoto (35°N). The seasonal variations of the gravity wave intensity deduced from the horizontal wind velocities showed semiannual variations with solstitcial maxima and equinoctial minima at all three locations, but the month of maximum intensity in the year depends on the locations and wave frequency. The kinetic energy due to gravity waves showed similar amplitude between Kyoto and Adelaide, but smaller at Saskatoon, which agrees well with the results of the preliminary comparison using a limited frequency range and limited observation periods by *Nakamura et al.* [1993a, b]. The horizontal propagation direction of these gravity waves showed small seasonal variations and significant dependency with wave periods at Saskatoon but showed more frequent variation without a large frequency dependency at Kyoto and Adelaide. These characteristics indicate that at the lower latitudes gravity wave activity is larger, as pointed out by *Tsuda et al.* [1994] from various observational techniques. Also, the frequent changes of the gravity wave intensities at the lower latitudes suggest that there are strong influences of the background wind variation in the middle atmosphere such as semiannual oscillation, mesospheric semiannual oscillation and other wind variations in the low latitudes.

1. Introduction

The behavior of gravity waves is very important in understanding the dynamical processes in the middle atmosphere, since they transport energy and momentum from the lower atmosphere to the mesopause region, where dissipating and saturating gravity waves release their energy and momentum [e.g., *Lindzen*, 1981; *Matsuno*, 1982; *Fritts and Rastogi*, 1985]. Fundamental mechanisms involved in these processes were clarified by observations using various remote-sensing and in situ measurement techniques [e.g., *Fritts*, 1984].

Spectral analyses of gravity waves in terms of frequency and vertical wavenumber have been applied to radar observations at various locations [*Carter and Balsley*, 1982; *Vincent*, 1984; *Frezal et al.*, 1981; *Meek et al.*, 1985; *Tsuda et al.*, 1989]. Among the various radar observations, the middle and upper atmosphere (MU) radar, an mesosphere-stratosphere-troposphere (MST) radar with quick beam steering, is a powerful instrument with which to observe the height profiles of the upward flux of horizontal momentum as well as gravity wave energy in the mesosphere. In particular, it has been demonstrated that the zonal momentum flux has a clear annual variation with the mean wind accelerations comparable with the predictions from theoretical works [*Tsuda et al.*, 1990]. However, we still have little knowledge as to where these mesospheric gravity waves are excited and how they propagate up to this region.

The latitudinal variations of the gravity wave energy and momentum give us important information to help clarify the source and propagation directions of the mesospheric gravity waves. A detailed comparison of the mesospheric gravity waves with 10–100 min periods has been carried out between observations of the Saskatoon MF radar and the MU radar, Kyoto [*Nakamura et al.*, 1993a], and very similar seasonal variations (semiannual) were found at both radar site. Also, the gravity waves have been compared for two campaign periods between Adelaide MF radar and the MU radar, Kyoto, finding a similar amplitude of gravity waves at the geophysically conjugate sites, but that the horizontal propagation directions were different between them [*Nakamura et al.*, 1993b]. *Tsuda et al.* [1994] have summarized these observations with other observation techniques such as Rayleigh lidars, radiosondes, and rocketsondes in the stratosphere and mesosphere and suggested the stronger activity of gravity waves is in the lower latitude regions.

This paper is devoted to the extension of the previous comparison between Adelaide and Kyoto and that between Saskatoon and Kyoto [*Nakamura et al.*, 1993a, b] by MF and MST radar observations. The gravity waves with 10 min to 8 hours are compared among the three stations to obtain variation over a 12-month year, in order to investigate how the results from

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Table 1. Observation Periods and Parameters of the Radars Used in This Study

	Adelaide	Kyoto	Saskatoon
Location	(35°S, 139°E)	(35°N, 136°E)	(52°N, 107°W)
Radar type	MF	MST (VHF)	MF
Wind measurement technique	spaced antenna	Doppler beam swinging	spaced antenna
Observation period	Jan.–Dec. 1992	Dec. 1985 to Dec. 1988 (4–5 days/month)	Jan.–Dec. 1989
Observation time	24 hours	daytime 0800 LT to 1600 LT	24 hours
Height range	60–98 km	60–90 km	58–109 km
Time resolution	4 min	2.5 min	5 min
Height resolution	4 km	0.6 km	3 km

the preliminary comparisons [*Nakamura et al.*, 1993a, b] are common for different frequency components and for different seasons. Also, the horizontal propagations are studied by means of covariances of horizontal and vertical wind velocities.

2. Observation and Analysis

Table 1 shows the observation periods for the comparison in this study. In order to obtain the seasonal variations of the gravity waves ranging from 10 min to 8 hours, observation databases with good time resolution and large samples of data are necessary. The Saskatoon MF radar has been working with a data-sampling resolution of 5 min [*Manson and Meek*, 1993], observing the atmosphere between 58 and 109 km. The data taken between January and December 1989 are utilized in this study. The Adelaide MF radar has improved the data sampling in December 1991 to 2 min. Horizontal wind velocities involving 4-min averages from 60 to 98 km between January to December 1992 are used for the analysis. The MU radar observations in the mesospheric mode (60–90 km) have been regularly carried out for 4–5 days a month. The Doppler velocities of vertical and four oblique beams of northward, eastward, southward, and westward directions, with an off-zenith angle of 10 deg are determined by 1-min time series with the data-sampling interval of 2.5 min. In a previous comparison between Saskatoon and Kyoto [*Nakamura et al.*, 1993a], we used 1989 MU data, (the same year as Saskatoon MF radar data). However, the 4–5 day averaged data in a month for the MU radar showed large variability. In the current analysis we used the data set obtained in 1985–1988 in order to increase the amount of data and the quality of the monthly means. Time resolutions for these observation years were 2.5 min and better than that for 1989 (3.5 min), which is useful to obtain the higher-frequency component of gravity waves.

For all data sets, a frequency spectrum at each height is calculated by the Fourier transform of the autocorrelation function of the time series of the wind velocities in the daytime, with zero weighting for the data gaps [*Nakamura et al.*, 1993a]. In order to align the data quality for the three radars, we degraded the data in two ways. First, the MU radar data with 0.6-km resolution has been averaged over 3 km. Second, only daytime data, and data between 67 and 80 km, are used for the analyses of the three radars because the MU radar can obtain significant echo power only in these height and time ranges.

The frequency spectra of the horizontal wind fluctuations are calculated for each day between 67 and 80 km altitudes and averaged over all height. Furthermore, the wind variances of the 10 frequency or period bands with periods of 8–4 hours, 5.7–2.8 hours, 4–2 hours, 2.8–1.4 hours, 2–1 hours, 1.4 hours to 42 min, 1 hour to 30 min, 42–21 min, 30–15 min, and 21–11 min are calculated by integrating the frequency spectra. The daily variances are averaged with a low-pass filter of 30 days cutoff period and used to make contour plots with regards to months of a year and wave periods.

3. Results

3.1. Wind Variance

Figure 1 shows the contour plots of the horizontal wind variance, $\overline{u'^2 + v'^2}$, at Saskatoon, Kyoto and Adelaide. The variance of the longest period band, that is, 8–4 hours band for Kyoto data were eliminated because we could not obtain enough statistical stability in this low frequency band because of small data samples.

Since the frequency band width applied to calculation of the wave variance is proportional to the center frequency as described in the previous section, this contour plot corresponds to the energy content form, and so the periods with the highest contour level in a certain month indicate the dominant wave component in that season. Because the contour corresponds to the energy content, a constant variance value with the period indicates the frequency spectra with the slope of -1 in logarithmic scale plot. So, the frequency spectra with the slope of $-5/3$, which is often observed in the frequency spectra of the observed wind velocities, would show a slight decrease of the contour variances with decreasing period in Figure 1. This is generally true in Figure 1, but the short-period component, with period shorter than approximately 30 min for Saskatoon and Adelaide and 20 min for Kyoto shows an increase of the variance with decreasing period. These large variances may be due to a contamination by horizontal variations of vertical wind velocities in the spaced antenna technique for Saskatoon and Adelaide data [*Royrvik*, 1983], and random noise due to the measurement accuracy in determining horizontal wind velocities for Kyoto data. There is also a possibility that data gaps may have enhanced the high-frequency variances. Thus these possible contaminations should be carefully considered when we look at the plots in the following parts of this paper.

It is clear in Figure 1 that the variances at Saskatoon and Kyoto clearly show equinoctial minima at the same time, that is, in early April (spring) and in September (autumn), for all the period ranges. At Adelaide the variance also shows equinoctial minima, but the months are slightly different from the other two sites in the northern hemisphere, that is, in March and November. However, March (autumn) is equivalent to September (NH), and November (spring) is equivalent to May (NH), so only the spring differs, with a later spring (1 month)

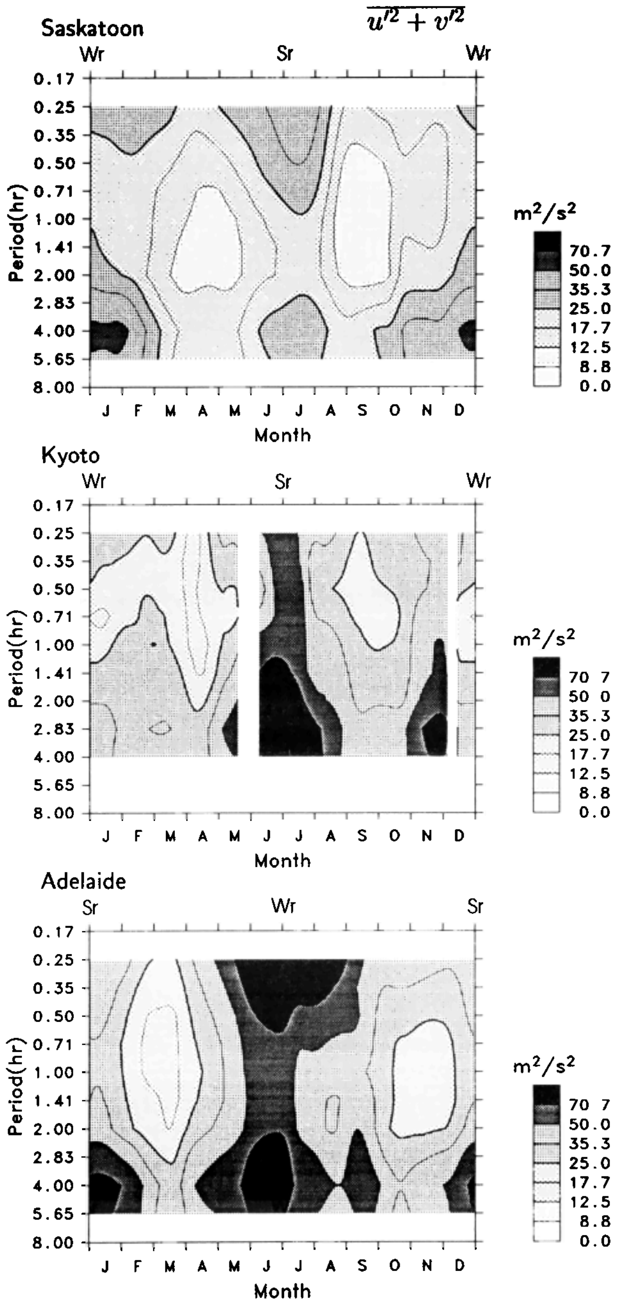

Figure 1. Contour plot of the gravity wave variance $u'^2 + v'^2$ with wave period and season observed at (top) Saskatoon, (center) Kyoto, and (bottom) Adelaide in the mesosphere (67–80 km). The variances are calculated between $0.71T$ to $1.41T$ for the central period T. Low-pass filter with 30-day cutoff was applied in time.

in the southern hemisphere. These equinoctial minima of the gravity wave activity have been observed by many precedent studies especially for short-period gravity waves [e.g., *Meek et al.*, 1985; *Manson and Meek*, 1993; *Tsuda et al.*, 1990]. However, we have found that the equinoctial minima exist at least for periods up to 8 hours at the same time. The difference of the month of the minima between the hemispheres is probably because the minima correspond to changes of the direction of zonal mean wind in the mesosphere. In fact, the spring/autumn reversals to westward/eastward flows were completed for the 67–80 km layer by mid-April/mid-September at Saskatoon [see *Manson et al.*, 1991]. (The mean winds at Saskatoon and Adelaide observed here are similar to these typical years.) This is consistent with the gravity wave intensities. At Adelaide, the seasonal (spring/autumn) reversals were completed by mid-October/early-March [*Manson et al.*, 1991]. (These are mid-April/early-September in NH seasonal terms.) Thus, while winds are quite similar seasonally to the NH, the gravity wave intensities minimize a month later than reversal in spring.

The primary peak of the variance, that is, the maximum in a year, changed with frequency bands and locations. In Saskatoon, the maximum variance in a year occurred in summer for the short period component (1 hour to 30 min), with a secondary winter peak; which has already been reported by *Nakamura et al.* [1993a]. However, the long-period component (2–8 hours) showed a maximum in winter and the secondary peak in summer. On the contrary, the variances at Kyoto had a maximum in summer for all the period range, and secondary peak in winter. The variance at Adelaide has comparable peaks in summer (January) and in winter (June) for long-period component (2–8 hours), but the short-period component (2 hours to 30 min) showed a winter maximum and a summer secondary peak.

The frequency dependency of the season of the gravity wave maximum by the Saskatoon MF radar is reported by *Gavrilov et al.* [1995]. They showed at 60–100 km altitudes annual variation is dominant for low-frequency gravity waves and the semiannual variation becomes strong for high-frequency gravity waves. In our study the height range was lower (67–80 km) and the semiannual variation was more significantly observed. This is consistent with *Manson and Meek* [1993] also. The differences in the seasonal variations of the wave variances between the different frequencies is probably due to the difference in the horizontal phase velocities of the gravity waves in different frequencies. The differences among the radar sites suggest differences in the propagation direction of the gravity waves, and perhaps sources, among the three sites.

Next, we compare the variance among the three locations. Figure 2 shows the ratio of the kinetic energy of the gravity waves, $\rho(\overline{u'^2 + v'^2})$, between the observations at two radar sites, where atmospheric density ρ, is taken from CIRA (1986). The right panels are supplementally plotted to indicate the yearly average ratio at each wave period component.

The ratio of Kyoto/Saskatoon (top panel) and that of Adelaide/Saskatoon (center panel) were significantly larger than the unity for almost all the frequency and season, indicating the gravity wave activity is weaker at Saskatoon than the other two sites. The yearly averaged ratio was 1.6 and 1.7 for Kyoto/Saskatoon and Adelaide/Saskatoon. These ratios did not change much with the wave periods for Adelaide/Saskatoon, but the Kyoto/Saskatoon ratios were larger for longer periods. This characteristic, that is, the short wave periods showing small ratios, is partly due to a possible contamination of u' and v' by horizontal variations of w' component for the spaced antenna wind data at Saskatoon. On the contrary, the yearly averaged ratio for Adelaide/Kyoto was about 1.2 and close to unity, suggesting a similar magnitude of gravity wave activity at these two locations, although the ratio fluctuated largely with season. The yearly averaged ratio again shows some frequency dependency but may be because of the influence of vertical winds associated with gravity waves upon horizontal winds (as mentioned earlier) at Adelaide for the short-period component.

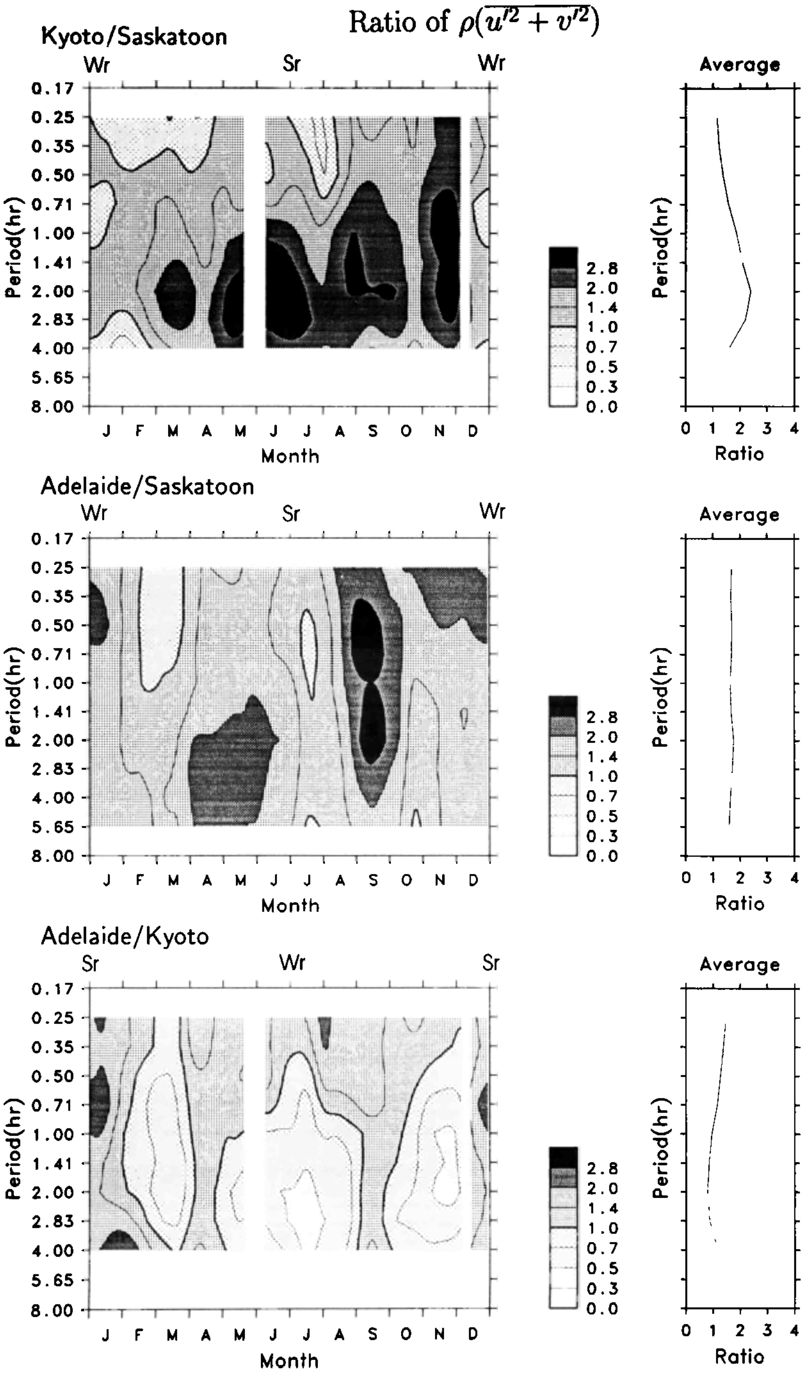

Figure 2. Contour plot of the ratios of the kinetic energy due to gravity waves $\rho\overline{u'^2 + v'^2}$ at Saskatoon, Kyoto, and Adelaide. The density ρ is taken from CIRA (1986). Other parameters are the same as Figure 1.

The effect of the reduction of wind variances due to the horizontal and vertical averages by the radar sampling volumes was discussed by *Nakamura et al.* [1993a]. In the present comparison the effect of the horizontal averaging due to the wide antenna beam could therefore cause some loss of the variance for Adelaide and Saskatoon MF radars. However, this effect is considered to be less than 20% for the wave periods larger than 10 min [*Nakamura et al.*, 1993a]. So, we can conclude that the gravity wave activity at Adelaide and Kyoto is almost of the same magnitude, but it is a little bit weaker at Saskatoon.

Preliminary comparison of the gravity wave variance only for the short-period components, 10–100 min, between Saskatoon and Kyoto [*Nakamura et al.*, 1993a] and only for campaign observation periods between Adelaide and Kyoto [*Nakamura et al.*, 1993b] showed that the gravity waves at Kyoto and Adelaide were of similar intensity, but those at Saskatoon were smaller than those in Kyoto. Our present study has confirmed that these characteristics are true for the period range (10 min to 8 hours) and in the yearly average. Thus our result supports the suggestion by *Tsuda et al.* [1994], that is, gravity wave activity is larger in the lower-latitude regions.

3.2. Covariance

Covariances of the wind fluctuation u', v', and w' contain information on propagation directions of gravity waves, and have been studied in earlier papers [e.g., *Manson and Meek*, 1993; *Tsuda et al.*, 1990; *Reid and Vincent*, 1987]. Figure 3 shows the contours of $\overline{u'v'}$ from the MF radar wind velocities observed at Saskatoon and Adelaide. At Saskatoon, $\overline{u'v'}$ becomes negative in August and September for all the period range, indicating the dominance of NW or SE propagation, and in October $\overline{u'v'}$ becomes positive, with the change of direction to NE or SW. The rest of the months showed positive and negative covariances in the shorter- and longer-period ranges, respectively. These characteristics agree well with the study using the different frequency bands of 5-min differential (10–100 min) and hourly differential (2–6 hours) filters by *Manson and Meek* [1993].

At Adelaide, the covariance $\overline{u'v'}$ was positive from December to May and negative from June to November with maximum amplitude in January and August. These features show that NE or SW propagation is dominant from December to May (summer months), but NW or SE is dominant from June to November (winter months). The variation with the frequency was not so large as that at Saskatoon, indicating the propagation direction does not change significantly with gravity wave frequency. Instead, the change of the direction with season seems to be larger than that at Saskatoon. There is perhaps a tendency for different seasonal variations, that is, midwinter is positive/negative at Saskatoon/Adelaide.

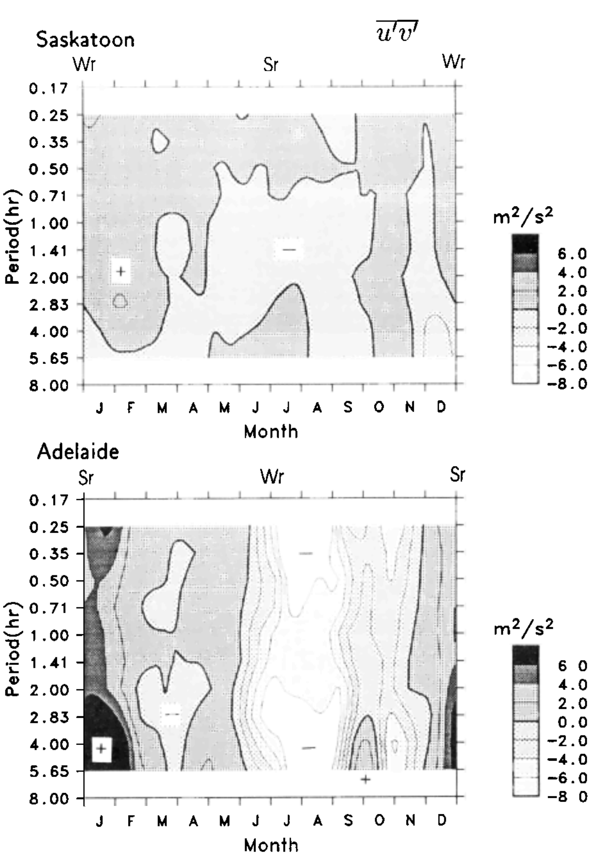

Figure 3. Contour plot of the covariance $\overline{u'v'}$, in the same format as Figure 1, for (top) Saskatoon and (bottom) Adelaide. Positive is NE-SW propagation.

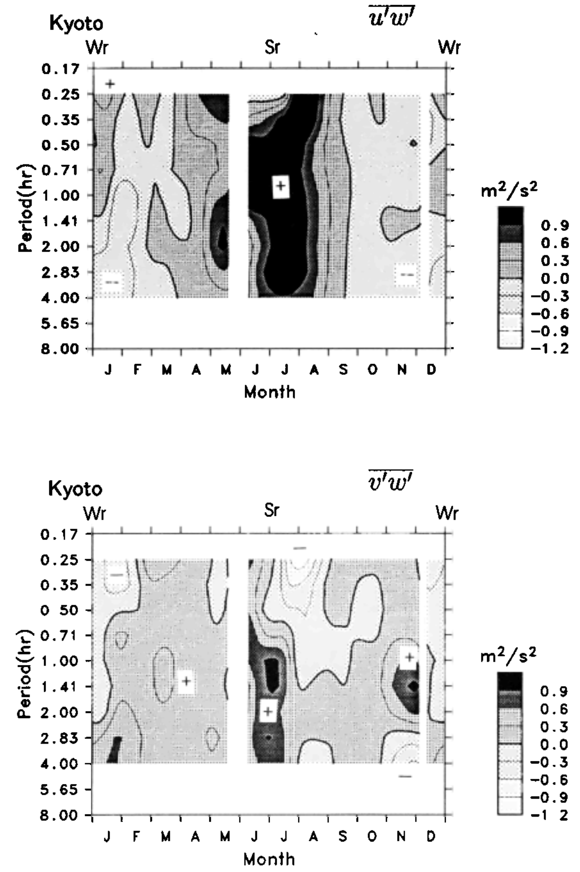

Figure 4. Contour plot of the upward fluxes of zonal momentum (top) $\overline{u'w'}$ and meridional momentum (bottom) $\overline{v'w'}$ at Kyoto. Positive is eastward/southward respectively.

Figure 4 shows the $\overline{u'w'}$ and $\overline{v'w'}$ observed at Kyoto by the MU radar. Since the MU radar observed the Doppler velocity of the radial wind component of the vertical and four oblique beams, we are not able to calculate $\overline{u'v'}$ like MF radars but can obtain $\overline{u'w'}$ and $\overline{v'w'}$ by calculating the variances of the radial wind velocities of oblique beams [*Vincent and Reid*, 1983]. The zonal momentum flux $\overline{u'w'}$ showed positive in summer from April to September and negative in winter from October to March, which agrees with the earlier results by *Tsuda et al.* [1990] and *Nakamura et al.* [1993c]. The peak of the eastward and westward flux occurred in July and January/February, respectively. The sign of the flux changed with frequency, that is, the shortest-period component (15 min) in June showed westward flux, while the wave components with periods shorter than 1 hour showed eastward flux in January. This reversal of the zonal flux for the high-frequency component was also reported by *Nakamura et al.* [1993c] in June, July, and October. The gravity waves with the horizontal phase velocity parallel and antiparallel to the mean wind have Doppler frequency shifts which makes the observed frequency higher and lower than the intrinsic frequency, respectively. This Doppler shift can change the upper limit of gravity wave observed frequency, which is the Brunt-Väisälä frequency in case of no mean wind, to be smaller and larger for antiparallel and parallel gravity waves, respectively. Thus the gravity wave spectrum in high frequencies is likely to be slightly suppressed and enhanced for antiparallel and parallel gravity waves, which can make the net momentum flux in high frequencies to be parallel to the strong mean wind.

The meridional flux in Figure 4 showed weak positive (northward) flux in general but some fluctuation with time and frequency. Especially, the momentum flux was almost always northward at periods longer than 1 hour. *Tsuda et al.* [1990] showed that the meridional momentum flux is fluctuating between northward and southward and did not have clear seasonal variation for the period of 5 min to 2 hours. It is also true for the corresponding short-period component in Figure 4, but our extended study showed dominance of northward flux in the longer-period waves. This could be due to a more active excitation of the gravity waves in the low-latitude or tropical region.

Direct comparison of the $\overline{u'v'}$ at Adelaide and Saskatoon and $\overline{u'w'}$, $\overline{v'w'}$ at Kyoto is not easy, but instead we compare a more simple parameter of $\overline{v'^2}/\overline{u'^2}$ at three locations in Figure 5, which is a parameter studied by *Vincent and Fritts* [1987]. The ratios larger and smaller than the unity correspond to the meridional and zonal directions as a preferential direction of horizontal propagation, respectively.

It is clear that at Saskatoon the shorter (<2 hours) and the longer-period components showed preferential meridional and zonal directions, respectively, except that in equinoctial months such as April and September, both were zonal. This is similar to *Gavrilov et al.* [1995] and *Manson and Meek* [1993]. However, the contours of Adelaide and Kyoto showed quite different patterns. That is, the preferential directions did not vary consistently with frequency, but the directional change with time was more frequent. At Kyoto, from May to June, in September, and from December to February the preferential direction was meridional (quite similar to Saskatoon at high frequency). However, at Adelaide meridional direction was dominant in July to August, October to January, and March to April. However, adjusting to seasons (+6 months), there are distinct similarities between the northern and southern hemispheres, with some differences in early winter (November–December in NH, May–June in SH) and in late summer (July–August in NH, January–February in SH). Although the preferential direction at Kyoto indicates less significant frequency dependence, it still has some variation with frequency from October to January, when the winter westward wind is very strong (up to 70 m/s at 70 km) [*Nakamura et al.*, 1996], that is, the shorter- (< 1 hour) and longer-period waves correspond to zonal and meridional directions. This characteristic further seems to correspond to the frequency dependency of momentum flux in December and January, as shown in Figure 4.

The difference in the variability of the changes of propagation directions at Kyoto, Adelaide and Saskatoon, that is, the gradual and less frequent change in Saskatoon and the frequent change in Kyoto and Adelaide suggests a more frequent change of the gravity wave source or the background condition such as wind fields during the propagation from the lower atmosphere near Kyoto and Adelaide. Among the background fields, the variation of the mean wind in the upper stratosphere and mesosphere is a possible reason for the difference, since the zonal mean wind at these heights is known to show annual variations dominantly in the midlatitude and high latitude but has more frequent variations (semiannual oscillation (SAO), mesospheric semiannual oscillation (MSAO), etc.) in the lower latitudes.

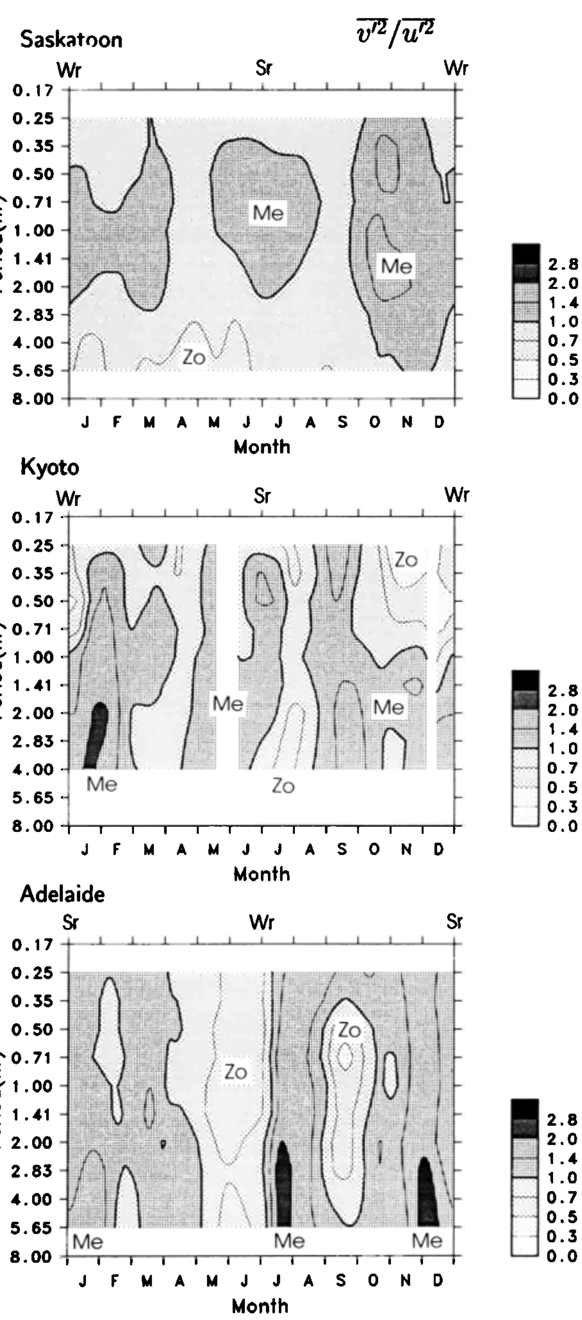

Figure 5. Ratios of $\overline{v'^2}/\overline{u'^2}$ at (top) Saskatoon, (center) Kyoto, and (bottom) Adelaide in the same format as Figure 1.

4. Discussion and Concluding Remarks

Thus in this study the seasonal variations of the gravity waves in the horizontal wind velocities are analyzed from the three radars at Adelaide (35°S), Kyoto (35°N), and Saskatoon (52°N).

The gravity waves with periods of 10 min to 8 hours at 67–80 km altitudes are compared and semiannual variations with summer and winter peaks and equinoctial minima are observed in the wind variance due to gravity waves at three locations. The minima correspond to the periods of weak mean wind in the middle atmosphere, at the transitions between summer and winter states at each hemisphere. However, the month of maximum depends on the wave periods and locations, which suggests a strong interaction with mean wind depending its horizontal phase speed.

The gravity wave variances $\overline{u'^2 + v'^2}$ are compared among the three stations. The variances were similar at Adelaide and Kyoto but smaller at Saskatoon. This is a natural extension of the results by *Nakamura et al.* [1993a, b], indicating a similar result from a limited frequency (10–120 min) and periods (two campaigns). Thus the discussion by *Tsuda et al.* [1994], that is, the stronger activity of the gravity waves at lower latitudes in the mesosphere seems to be correct by this study of a larger database and over a wider frequency range.

The covariance $\overline{u'v'}$ showed clear seasonal changes at Adelaide, but smaller seasonal variation and some frequency dependency were found in Saskatoon. The zonal momentum flux $\overline{u'w'}$ at Kyoto showed clear annual variation for all the frequency, but sometimes the short period component had opposite momentum with the longer periods. The meridional flux $\overline{v'w'}$ with periods longer than 1 hour were northward for all the year, suggesting the source in the low latitudes.

The propagation directions are compared by the variance ratios of $\overline{v'^2}/\overline{u'^2}$, which showed frequent temporal variation but less dependence on wave period at Kyoto and Adelaide, and less frequent temporal changes and significant wave period dependence at Saskatoon. This suggests that at the lower latitude, more frequent changes of back-ground mean wind in the middle atmosphere such as MSAO, SAO, and other long-period variations are possible sources of this variation.

In the stratosphere below 60 km, latitudinal difference of gravity waves has been studied using rocket observations [*Hirota*, 1984; *Hamilton*, 1991; *Eckermann et al.*, 1994]. Eckermann et al. analyzed the gravity waves in the 20–60 km altitudes from the large database of meteorological rocket measurement at 15 sites. They found that at high latitudes, wind variances showed clear annual variations with winter maxima, but in lower latitudes, semiannual or shorter variations become dominant. Also, they indicated larger seasonal variations of the characteristics of rotation direction of the wind in the profiles at lower latitudes. Thus results below 60 km are similar to our seasonal variation in the sense that both showed more seasonal variability in lower latitudes.

Some simplified modeling approaches have been done to reveal the source of the seasonal and latitudinal variabilities [*Eckermann*, 1992, 1995]. The refraction of the gravity waves by the meridional gradient of mean wind [*Eckermann*, 1992] and variations of vertical temperature structure [*Eckermann*, 1995] have been found to generate some characteristics of observed seasonal and latitudinal variations of gravity waves in the stratosphere, despite the assumption of lack of the source variations. More observations and analyses, especially observations including the lower altitudes, will be needed to ascertain whether the latitudinal variation of the gravity waves observed in this paper is due to the source variation with latitudes (and longitudes) or due to the background conditions for wave propagation.

Finally, in this paper the observation periods for three locations are chosen in different years. This is mainly because we tried to obtain data sets with high resolutions and good data quality for each observation site in order to analyze both high- and low-frequency gravity waves. Although *Gavrilov et al.* [1995] showed gravity wave activity of the frequency and height ranges studied in this paper does not show significant interannual variations at Saskatoon, further comparisons using same observation periods and more locations will be desirable in a future study.

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References

Carter, D. A., and B. B. Balsley, The summer wind field between 80 and 93 km observed by the MST radar at Poker Flat, Alaska (65°N), *J. Atmos. Sci.*, *39*, 2905–2915, 1982.

Eckermann, S. D., Ray-tracing simulation of the global propagation of inertia gravity waves through the zonally averaged middle atmosphere, *J. Geophys. Res.*, *97*, 15,849–15,866, 1992.

Eckermann, S. D., On the observed morphology of gravity-wave and equatorial-wave variance in the stratosphere, *J. Atmos. Terr. Phys.*, *57*, 105–134, 1995.

Eckermann, S. D., I. Hirota, and W. K. Hocking, Gravity wave and equatorial wave morphology of the stratosphere derived from long-term rocket soundings, *Q. J. Meteorol. Soc.*, *121*, 149–186, 1994.

Frezal, M. E., M. Glass, J. L. Fellous, and M. Massebeuf, Simultaneous meteor radar observations at Monpazier (France, 44°N) and Punta Borinquen (Puerto Rico, 18°N), III, The latitudinal variations of the energy of gravity waves (2–8 h) in the high mesosphere, *J. Atmos. Terr. Phys.*, *43*, 543–547, 1981.

Fritts, D. C., Gravity wave saturation in the middle atmosphere: A review of theory and observations, *Rev. Geophys.*, *22*, 275–308, 1984.

Fritts, D. C., and P. K. Rastogi, Convective and dynamical instabilities due to gravity wave motions in the lower and middle atmosphere: Theory and observations, *Radio Sci.*, *20*, 1247–1277, 1985.

Gavrilov, N. M., A. H. Manson, and C. E. Meek, Climatological monthly characteristics of middle atmosphere gravity waves (10 min–10 h) during 1979–1993 at Saskatoon, *Ann. Geophys.*, *13*, 285–295, 1995.

Hamilton, K., Climatological statistics of stratospheric inertia-gravity waves deduced from historical rocketsonde wind and temperature data, *J. Geophys. Res.*, *96*, 20,831–20,839, 1991.

Hirota, I., Climatology of gravity waves in the middle atmosphere, *J. Atmos. Terr. Phys.*, *46*, 767–773, 1984.

Lindzen, R. S., Turbulence and stress due to gravity wave and tidal breakdown, *J. Geophys. Res.*, *86*, 9707–9714, 1981.

Manson, A. H., and C. E. Meek, Characteristics of gravity waves (10 min–6 hours) at Saskatoon (52°N, 107°W) observation by the phase coherent medium frequency radar, *J. Geophys. Res.*, *98*, 20,357–20,367, 1993.

Manson, A. H., et al., Comparisons between satellite-derived gradient winds and radar-derived winds from the CIRA-86, *J. Atmos. Sci.*, *48*, 411–428, 1991.

Matsuno, T., A quasi-one-dimensional model of the middle atmospheric circulation interacting with internal gravity waves, *J. Meteorol. Soc. Jpn.*, *60*, 215–226, 1982.

Meek, C. E., I. M. Reid, and A. H. Manson, Observations of mesospheric wind velocities 2. Cross sections of power spectral density for 48–8 h, 8–1 h, 1 h–10 min over 60–110 km for 1981, *Radio Sci.*, *20*, 1383–1402, 1985.

Nakamura, T., T. Tsuda, M. Yamamoto, S. Fukao, S. Kato, A. H. Manson, and C. E. Meek, Comparative observations of the short period gravity waves (10–100 min) in the mesosphere in 1989 by Saskatoon MF radar (52°N), Canada, and the MU radar (35°N), Japan, *Radio Sci.*, *28*, 729–746, 1993a.

Nakamura, T., T. Tsuda, M. Yamamoto, S. Fukao, S. Kato, and R. A. Vincent, Comparison of the mesospheric gravity waves observed with the MU radar (35°N) and the Adelaide MF radar (35°S), *Geophys. Res. Lett.*, *20*, 803–806, 1993b.

Nakamura, T., T. Tsuda, M. Yamamoto, S. Fukao, and S. Kato, Characteristics of gravity waves in the mesosphere observed with the MU radar, 1, Momentum flux, *J. Geophys. Res.*, *98*, 8899–8910, 1993c.

Nakamura, T., T. Tsuda, and S. Fukao, Mean winds at 60–90 km observed with the MU radar (35°N), *J. Atmos. Terr. Phys.*, in press, 1996.

Reid, I. M., and R. A. Vincent, Measurements of mesospheric gravity wave momentum fluxes and mean flow accelerations at Adelaide, Australia, *J. Atmos. Terr. Phys.*, *49*, 443–460, 1987.

Royrvik, O., Spaced antenna drift at Jicamarca, mesospheric measurements, *Radio Sci.*, *18*, 461–476, 1983.

Tsuda, T., T. Inoue, D. C. Fritts, T. E. VanZandt, S. Kato, T. Sato, and S. Fukao, MST radar observations of a saturated gravity wave spectrum, *J. Atmos. Sci.*, *46*, 2440–2447, 1989.

Tsuda, T., Y. Murayama, M. Yamamoto, S. Kato, and S. Fukao, Seasonal variation of momentum flux in the mesosphere observed with the MU radar, *Geophys. Res. Lett.*, *17*, 725–728, 1990.

Tsuda T., Y. Murayama, T. Nakamura, R. A. Vincent, A. H. Manson, C. E. Meek, and R. L. Wilson, Variations of the gravity wave characteristics with height, season and latitudes revealed by comparative observations, *J. Atmos. Terr. Phys.*, *56*, 555–568, 1994.

Vincent, R. A., Gravity wave motions in the mesosphere, *J. Atmos. Terr. Phys.*, *46*, 119–128, 1984.

Vincent, R. A., and D. C. Fritts, A climatology of gravity wave motions in the mesopause region at Adelaide, Australia, *J. Atmos. Sci.*, *44*, 748–760, 1987.

Vincent, R. A., and I. M. Reid, HF Doppler Measurements of mesospheric gravity wave momentum fluxes, *J. Atmos. Sci.*, *40*, 1321–1333, 1983.

S. Fukao, T. Nakamura, and T. Tsuda, Radio Atmospheric Science Center, Kyoto University, Uji, Kyoto 611, Japan.

A. H. Manson and C. E. Meek, Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatchewan, Saskatoon, Canada S7N 0W0.

I. M. Reid and R. A. Vincent, Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, South Australia 5005, Australia.

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