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Coordinated observations of the dynamics and coupling processes of mesosphere and lower thermosphere winds with MF radars at the middle-high latitude

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The Communications Research Laboratory (CRL) has operated the Wakkanai MF radar since September of 1996, and Yamagawa MF radar since August of 1994. Recent observation results on variations of mean wind, wind spectra and diurnal wind oscillations during a strong eastward wind, comparison experiments with the MU radar and rockets, and D-region electron density measurements by MF radar are summarized briefly. The spectra comparison of two MF radar observations show a high degree of spatial and temporal variability in a winter mesosphere in Northern and Southern Japan. Differences of mean wind in 1997 between both sites are shown for the periods of solstices and equinoxes. It is suggested that the propagation of the diurnal tide from the mesosphere into the dynamo region is disturbed by the sudden enhancements of the strong eastward wind.

1. Introduction

The CRL constructed an MF radar at Wakkanai (45.4°N, 141.7°E) in September 1996, in addition to the Yamagawa MF radar (31.2°N, 130.6°E). A new MF radar is under construction at Poker Flat, as a collaboration project between the CRL and the Geophysical Institute, University of Alaska. The main objectives of these radars are to study the dynamics and coupling processes in the lower thermosphere and mesosphere at the middle-high latitude of mean winds, tides, planetary waves, and gravity waves. Simultaneous observations of winds have been conducted by using the Wakkanai MF radar and the Yamagawa MF radar, with the MU radar. The first comparison results of winds between the Yamagawa MF radar and the MU radar found reasonable agreement at 80–92 km. The results of the Yamagawa MF radar winds, which tended to show smaller velocities than the MU radar winds, suggest signal saturation effects above 92 km (Igarashi *et al.*, 1996). The variability and anisotropy of mesospheric wind spectra have been reported, and the results of the two MF radars have been compared (Hocke and Igarashi, 1997). The temporal evolution of the meridional and zonal wind spectra during the winter period suggest resonant interactions between planetary waves (a 2-day wave), tides, and gravity waves as a reason for the observed variability. The seasonal variations of mean winds were also compared at both radar sites in 1997 and compared with the HWM93 wind model (Hocke and Igarashi, 1998a). Diurnal and semidiurnal oscillations during the strong eastward winter jet period were discussed in relation with the propagation of the diurnal tide (or tidally modulated gravity wave flux) from the mesosphere into the dynamo region (Hocke and Igarashi, 1998b). The Wakkanai MF radar can make the observations for obtaining on the electron density profile in the ionospheric D-region by using a differential absorption technique. The electron density variations in the D-region obtained during the solar eclipse on 9 March 1997 is a good example of it's capability. In this paper the recent observation results by the MF radars are summarized briefly in order to investigate study items for future coordinated observations in the PSMOS (Planetary Scale Mesopause Observing System) program.

2. Experimental Arrangements

The locations of the MF radars and the antenna arrangements are shown in Fig. 1. The radar system parameters are given in Table 1. The Wakkanai MF radar alternatively observes winds from 60 km to 98 km for 2 minutes and then observes for D-region electron density profiles for 2 minutes. The Yamagawa MF radar only observes winds from 60 km to 98 km every 2 minutes. This radar will be upgraded for measuring electron density.

As the CRL is constructing a new MF radar at Poker Flat, a test experiment of measuring only electron density was conducted for about half year from November, 1997 at the former Poker Flat MST radar site (Igarashi *et al.*, 1999).

3. Comparison of MF Radar Results at Wakkanai and Yamagawa

3.1 Mean winds

For mean wind comparisons between Wakkanai and Yamagawa hodograph methods were applied. Averaged winds were compared with the empirical HWM93 wind model (Hedin *et al.*, 1996). Figure 2 shows the comparison between the mean winds at Wakkanai and Yamagawa (Hocke

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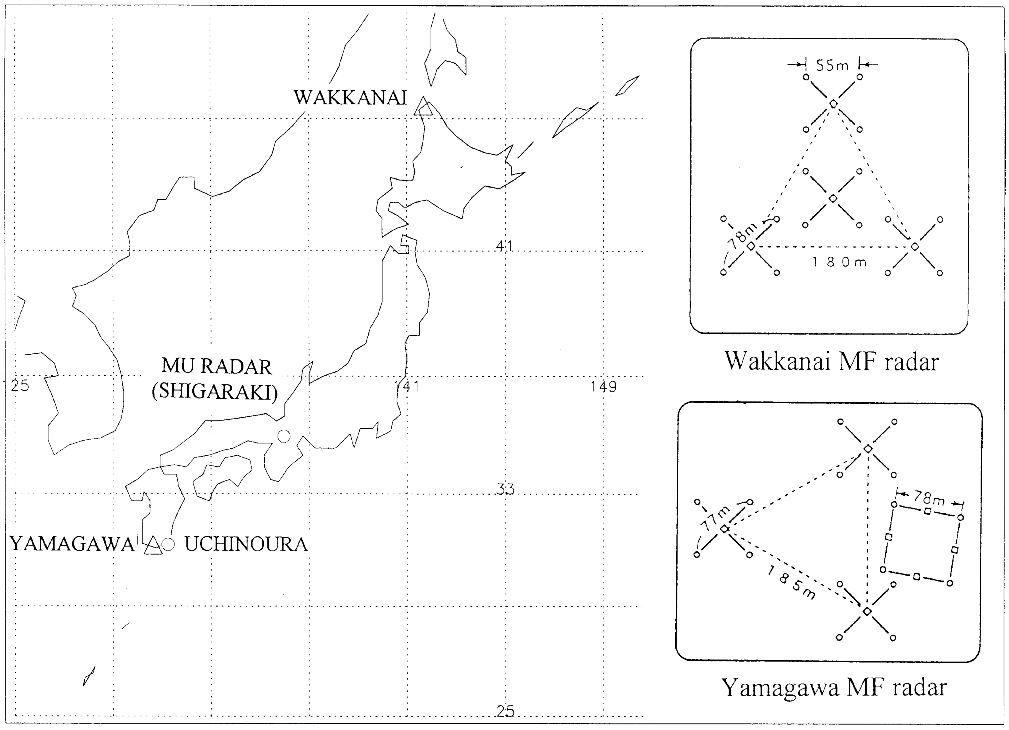


Fig. 1. Locations and antenna configurations of the Wakkanai and Yamagawa MF radars, including the MU radar at Shigaraki.

Table 1. Specifications of MF radars at Wakkanai and Yamagawa.

Parameters	Yamagawa	Wakkanai
Location	31.2°N, 130.6°E	45.4°N, 141.7°E
Peak envelope power	50 kW	50 kW
Operating frequency	1.9550 MHz	1.9585 MHz
Half power pulse width	48 μsec (since Sep. 12, 1996)	48 μsec
	27 μsec (Aug. 26, 1994–Sep. 11, 1996)	
Sampling interval	2 km	2 km
Observation modes	FCA	FCA, SCA, DAE, DPE
	FCA, DAE (since Sep. 13, 1998)	
Operated period	since 26 August 1994	since 19 September 1996

and Igarashi, 1998a). The observation time interval was one year from 7 November 1996. The daily winds were averaged for the periods of December solstice, March equinox, June solstice, and September equinox. The meridional winds at Yamagawa were a lot stronger than at Wakkanai during the December solstice. At 78 km the meridional winds were around 0 m/s at Wakkanai while they were about 15 m/s northwards at Yamagawa. For the March and September equinox southward winds at 98 km at Yamagawa were significantly stronger than at Wakkanai. The zonal wind shear from westward winds of 30 m/s at 78 km to eastward winds of 30 m/s at 98 km were stronger during the June solstice at Wakkanai than at Yamagawa, and weak westward winds occured at lower heights at Yamagawa. The longitudinally averaged winds of the empirical HWM93 wind model which were less than 5 m/s were weaker than the observed meridional winds over Yamagawa (see figures 5 and 6 in Hocke and Igarashi, 1998a). The zonal winds of the HWM93 model are in good agreement with the observed zonal winds at Yamagawa and Wakkanai within 10 m/s. But the observed meridional winds were significantly stronger than those of the empirical HWM93 wind model, as shown in Fig. 3. This suggests that the meridional wind circulation at mesospheric heights are underestimated by the HWM93 model. We will continue the observations and make a comparison study with wind models for a long-term investigation on the variability

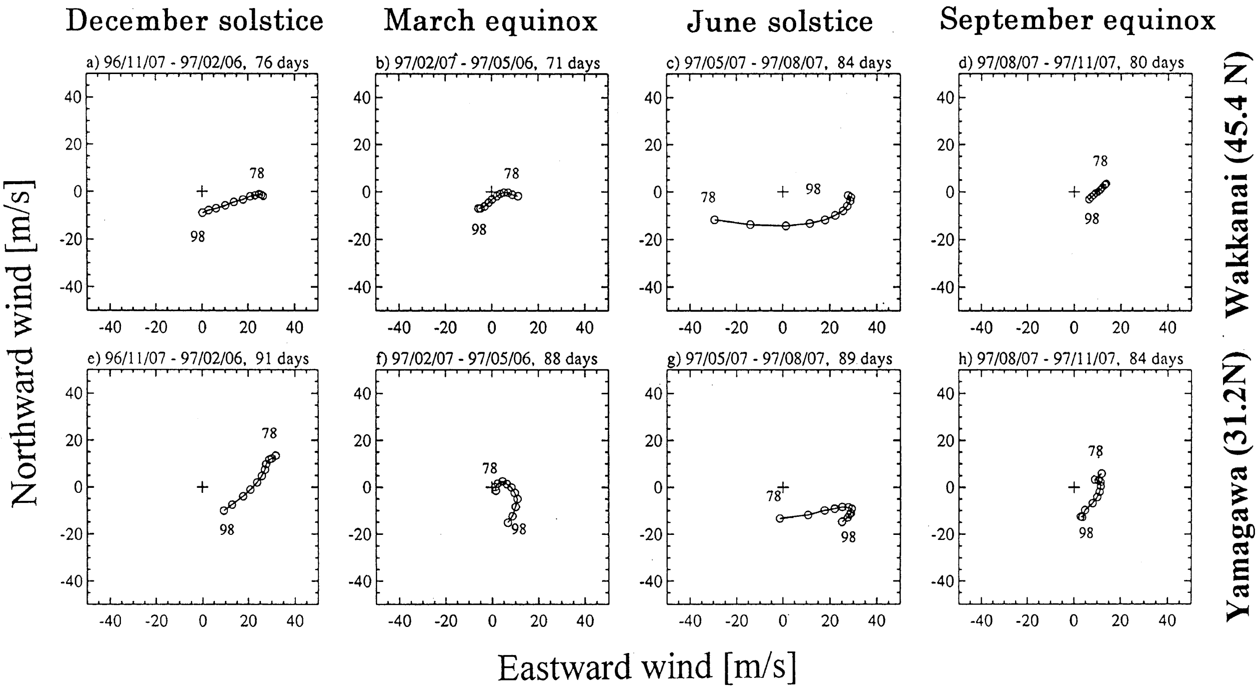


Fig. 2. Comparison of observed mean winds at Wakkanai (45.4°N) and Yamagawa (31.2°N) (after Hocke and Igarashi, 1998a).

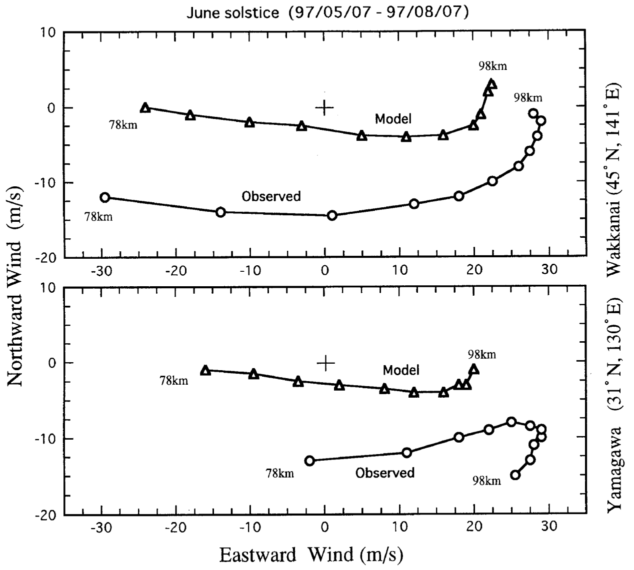


Fig. 3. Comparison of wind hodographs derived from hourly wind values of the HWM93 model, and the mean observed winds at Wakkanai and Yamagawa during the June solstice (after Hocke and Igarashi, 1998a).

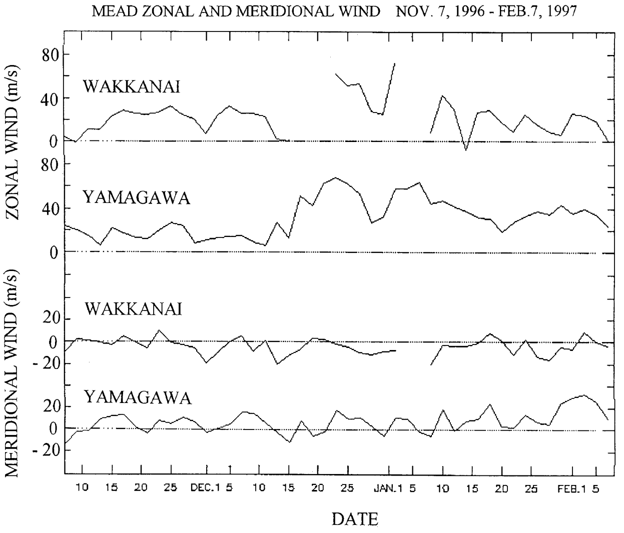


Fig. 4. Mean zonal and meridional winds averaged over 2 days at 86 km in altitudes at Wakkanai and Yamagawa from 7 November 1996 to 7 February 1997.

of mesospheric and lower thermospheric winds in mid-high latitudes.

Solar radiation and solar wind data of the first half of 1996, before and around solar minimum, were compared with geomagnetic activity indices, magnetograms, magentospheric particle fluxes, and the horizontal neutral winds at mesospheric heights measured by the Yamagawa MF radar, Collm LF wind profilers, and the Saskatchewan MF radar in northern hemisphere (Hocke *et al.*, 1998c). The correlation between the westward winds at each radar site and the geomagnetic activity Kp was investigated, and a good correlation was obtained for the Yamagawa MF radar results. This finding suggests that the mesosphere at mid-latitudes reacts to particle precipitation and ionospheric current variations in high latitudes which are obviously caused by solar winds. Geomagnetic influences on the wind fields in the mesosphere or lower thermosphere have been studied in several places by different evaluating methods (e.g., Singer *et al.*, 1994). During 1998–2002 of PSMOS program solar activity will be

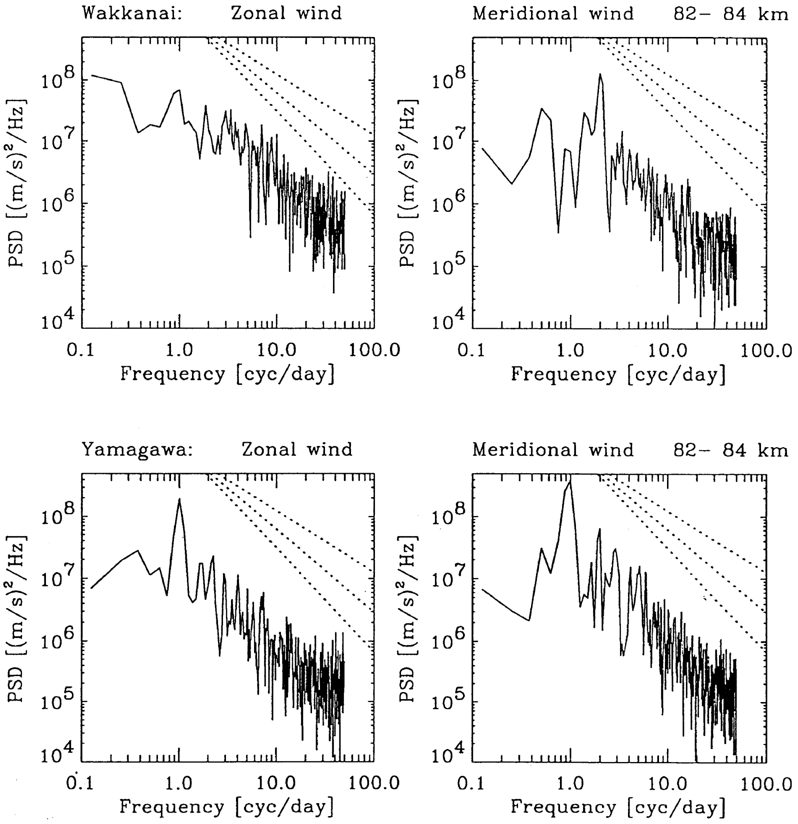


Fig. 5. Wind power spectra of the 8-day time interval of 24–31 December 1996 (after Hocke and Igarashi, 1997).

in an increasing phase. So further studies of the relations between geomagnetic activities and mesospheric winds are necessary in order to analyze the influences of geomagnetic storm effects on wind fields.

3.2 Mesospheric wind spectra, 24 hour and 12 hour wind oscillations during a time of strong eastward winds

The temporal evolution of the meridional and zonal wind spectra obtained from Wakkanai and Yamagawa around the winter solstice period of 24–31 December 1996 were compared. This period was during a time of strong eastward winds as shown in Fig. 4. These wind spectra suggest resonant interactions between planetary waves (a 2-day wave), tides, and gravity waves as the reason for the observed variability (Hocke and Igarashi, 1997). The dynamic spectra were applied to the resonant interaction condition in order to see if they fulfilled, $k_1 + k_2 + k_3 = 0$ and $\omega_1 + \omega_2 + \omega_3 = 0$, the condition (see figures 3 and 4 in Hocke and Igarashi, 1997). Wind power spectra for the 8-day December interval are shown in Fig. 5. Significant differences between the meridional and zonal frequency spectra were found. At Wakkanai the power spectral density of the zonal winds shows a very low peak level in the frequency range of semidiurnal tides. This feature appears in the higher mid-latitude during the strong winter jet period in the upper mesosphere. The power spectral density of the high frequency range (>3 cycles/day) of the zonal wind spectrum is around two times greater than that of the meridional component. The spectral peak of a 2-day wave appears in the meridional component. The 2-day wave component is the minimum zonal component in Wakkanai. At Yamagawa the diurnal component of the meridional wind spectrum is greater than that of the zonal component. The power law relations (f^{-k}, where $k = 5/3$, 4/3, and 1) are shown in Fig. 5 as dashed lines. The $k = 1$ slope fits the best. The $k = 1$ slope does not fit well for the zonal wind spectrum at frequencies higher than 3 cycles/day at Wakkanai and for all spectra at frequencies higher than 12 cycles/day. These results show a winter mesosphere in Northern and Southern Japan with a high degree of spatial and temporal variability.

Figure 6(a) shows phases of the semidiurnal wind oscillation at 86 km high at Wakkanai and phases of the diurnal wind oscillation at 86 km high at Yamagawa as a function of time from 7 November 1996 to 7 February 1997. At Yamagawa the meridional phase comes 6 hours before the zonal phase in the diurnal tide. The phases show daily variations. At Wakkanai the meridional phase comes around 3 hours before (90°), but the phase time series is more complicated than one at Yamagawa. This could be due to high tidal variability and interaction of the semidiurnal tide with a planetary wave during this winter period (Hocke and Igarashi, 1999). Figures 6(b)–(d) show phase height profiles before the onset (day 40), at the maximum (day 48) and after the first decrease (day 54) of the mean eastward winds during a strong eastward wind of the winter jet. The phase height profile of diurnal tide suggests wave reflection (phase reversal at 90 km height) by a strong eastward wind on December 25 (day 48) at Yamagawa, as shown in the lower panel of Fig. 6(c).

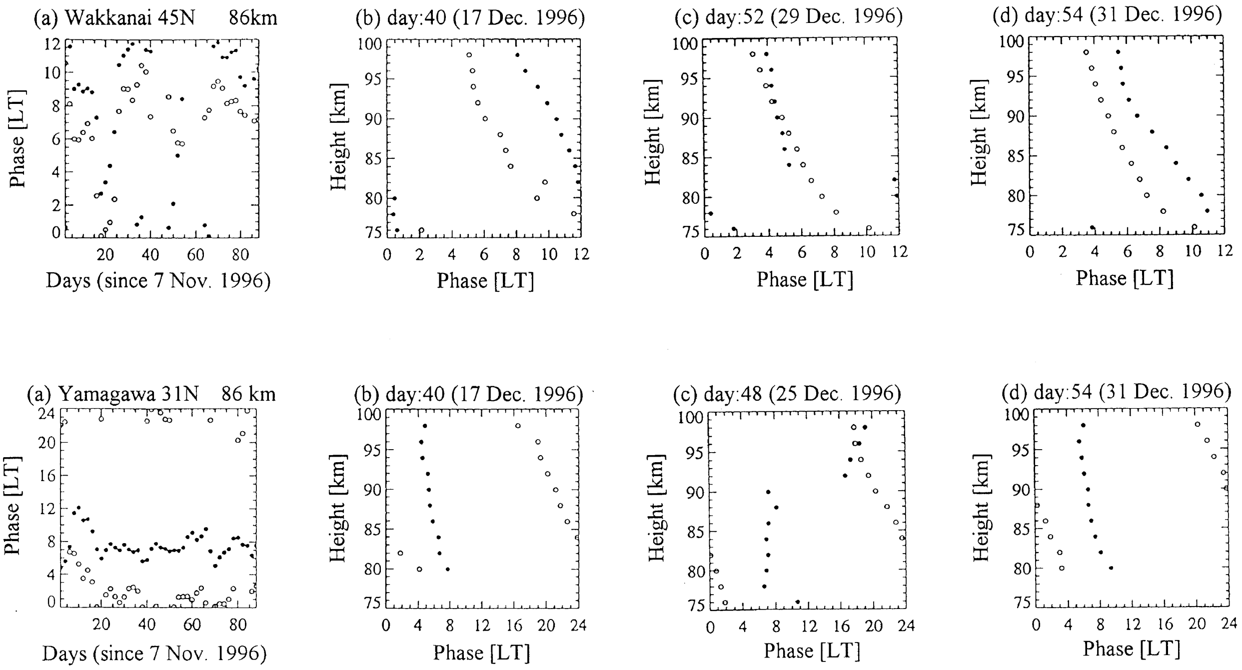


Fig. 6. (a) Phases of the semidiurnal wind oscillation at 86 km high at Wakkanai (upper panel) and phases of the diurnal wind oscillation at 86 km high at Yamagawa (lower panel) from 7 November 1996 to 7 February 1997. (b)–(d) Phase height profiles of the meridional wind oscillation at Wakkanai (upper panel) and phase height profiles of the diurnal wind oscillation at Yamagawa (lower panel), derived with a data window of four days at 86 km high on days 40, 52, and 54 for Wakkanai, and on days 40, 48 and 54 for Yamagawa. Open circles denote the meridional oscillation and full circles denote the zonal oscillations (after Hocke and Igarashi, 1998b).

On December 29 (day 52) a phase reversal of the semidiurnal tide also occured between 82 and 84 km at Wakkanai, as shown in the upper panel of Fig. 6(c). The phase reversal of the zonal component of the 24-h wind oscillation at 90 km and 82–84 km high suggests interference effects of tidal modes or wave reflection. It is noteworthy that the phase of the meridional 24-h wind oscillation seems to be not effected by the onset of the eastward winter jet.

Figure 7 shows contours of amplitudes of 24-h and 12-h wind oscillations at Yamagawa. The sudden increase of zonal wind on 22 December 1996 (day 45) was accompanied by a sudden decrease of the zonal amplitude of the strong 24-h oscillation (Hocke and Igarashi, 1998b). On the other hand, the meridional amplitude remained strong. The amplitude decrease of 24-h oscillation of zonal winds on 22 December 1996 was correlated with a strong amplitude decrease in the diurnal oscillation of the geomagnetic declination D at Kanoya (31°N). The clear correlation between the 24-h oscillation of the mesospheric zonal wind at Yamagawa and the geomagnetic declination in the E-region at Kanoya near Yamagawa leads us to the assumption that the propagation of the diurnal tide (or tidally modulated gravity wave flux) from the mesosphere into the dynamo region was significantly disturbed by the onset of the winterjet (see figure 3 in Hocke and Igarashi, 1998b).

3.3 Wind comparisons of the MU radar and rocket experiments results

It was suggested that there is a possibility of signal saturation in the high altitudes above 90 km in the first comparison experiments of Yamagawa MF radar and the MU radar results (Igarashi *et al.*, 1996). Figure 8 shows the comparison results of variances after removing the DC component and trend for zonal and meridional winds of the MU radar and Yamagawa MF radar in order to compare the amplitudes of the wind fluctuations. In this comparison the period of noticeable gravity wave activity was excluded. The variance of the MU radar seemed to increase at heights above 92 km, while below 92 km the variance profiles of the MU radar and the Yamagawa MF radar remained the same. This results similar to a trend for height variations of wind velocity variance which were compared between the high resolution Doppler imager (HRDI) on the Upper Atmosphere Research Satellite (UARS) and various MF radar observations (Burrage *et al.*, 1996) In order to validate these effects foil chaff experiments by micro-rockets were conducted at Uchinoura near the Yamagawa MF radar site (Murayama *et al.*, 1999). Wind fields of chaff and MF radar generally agreed well at 80–88 km. Above this height winds at Yamagawa were not obtained due to a strong interference during this foil chaff rocket experiment. Further experiments are necessary in order to validate saturation effects in the MF radar wind measurements by a foil chaff rocket experiment and a collocated meteor radar. In order to clear effects in processing MF radar signals the wind estimation by the Full Correlation Analysis (FCA) method was investigated by changing the signal clipping levels and the antenna combination (Yamazaki *et al.*, 1999). As a conclusion of this paper, a severe signal saturation caused by a limited dynamic range in the receiver of the MF radar did not affect wind velocity estimates as much as expected. Please note this conclusion was obtained within a limited set of several hours. During the SEEK (Sporadic-E Experiment over Kyushu) campaign lower thermospheric winds and meso-

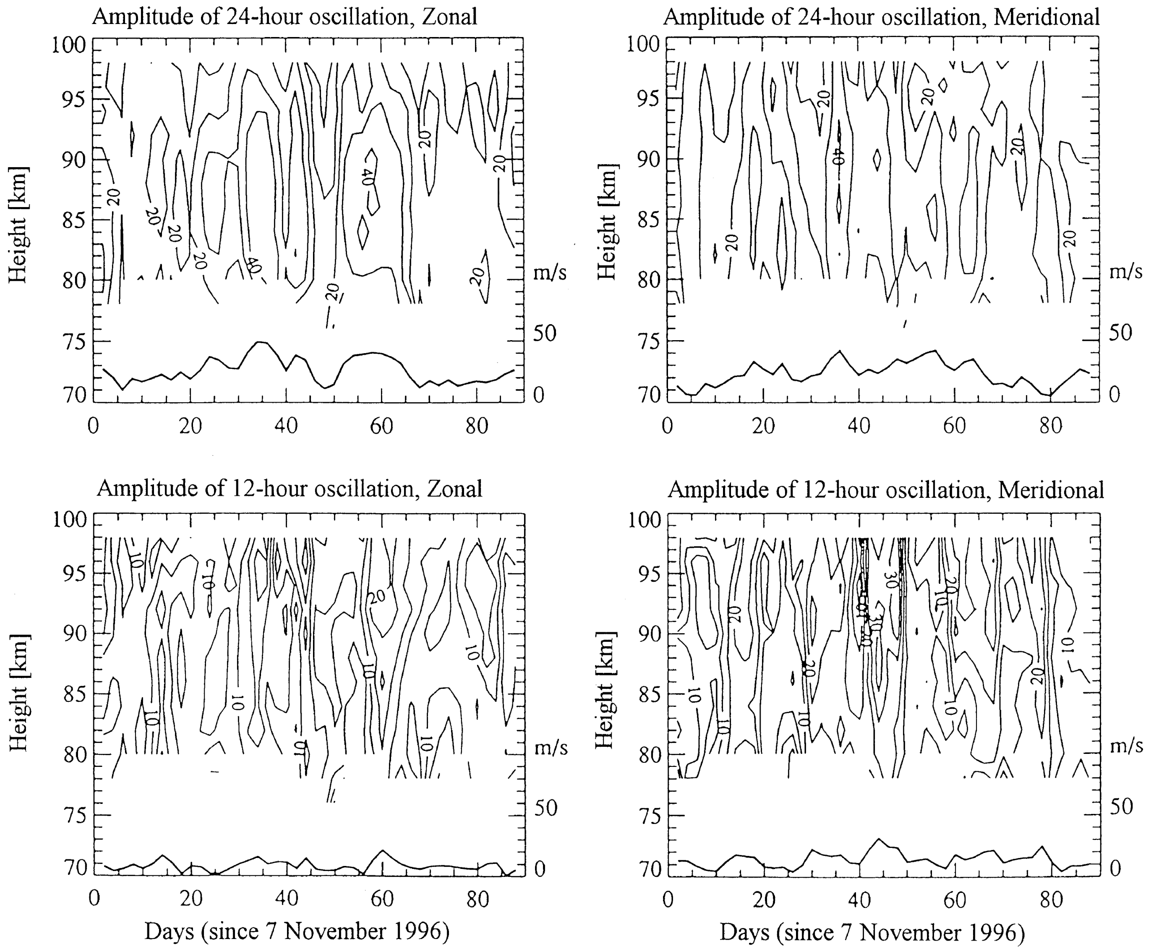
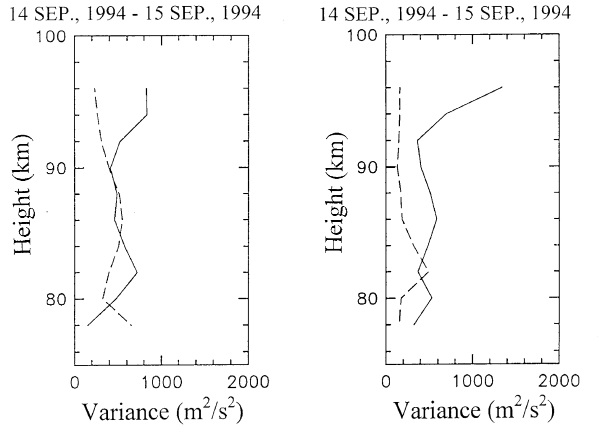


Fig. 7. Contours of 24-h and 12-h wind oscillations at Yamagawa (31°N) from 7 November 1996–7 February 1997 which were derived with a sliding data window of 10 days. At the bottom of the graphs the amplitude at 86 km high are shown. The anticorrelation of the mean eastward wind and the zonal diurnal amplitude is around day 48 (25 December 1996) (after Hocke and Igarashi, 1998b).



(a) Zonal component (b) Meridional component

Fig. 8. Variances for the zonal and meridional winds for the periods from 8:00 LT on 14 September to 7:00 LT on 15 September 1994. The solid and dashed lines respectively denote the MU radar and Yamagawa MF radar (after Igarashi *et al.*, 1996).

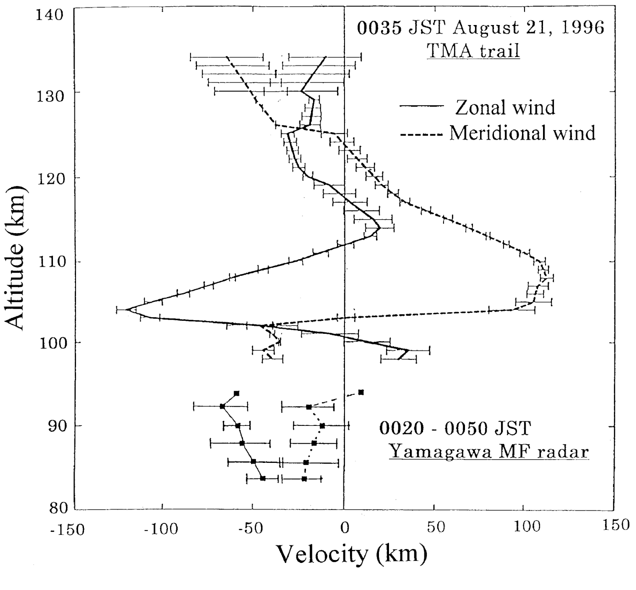


Fig. 9. Combined wind profiles derived from the Yamagawa MF radar (82–94 km) and TMA trail observations (98–134 km) for the S310-26 rocket experiment on 21 August 1996. Horizontal bars indicate a standard deviation (after Igarashi *et al.*, 1998).

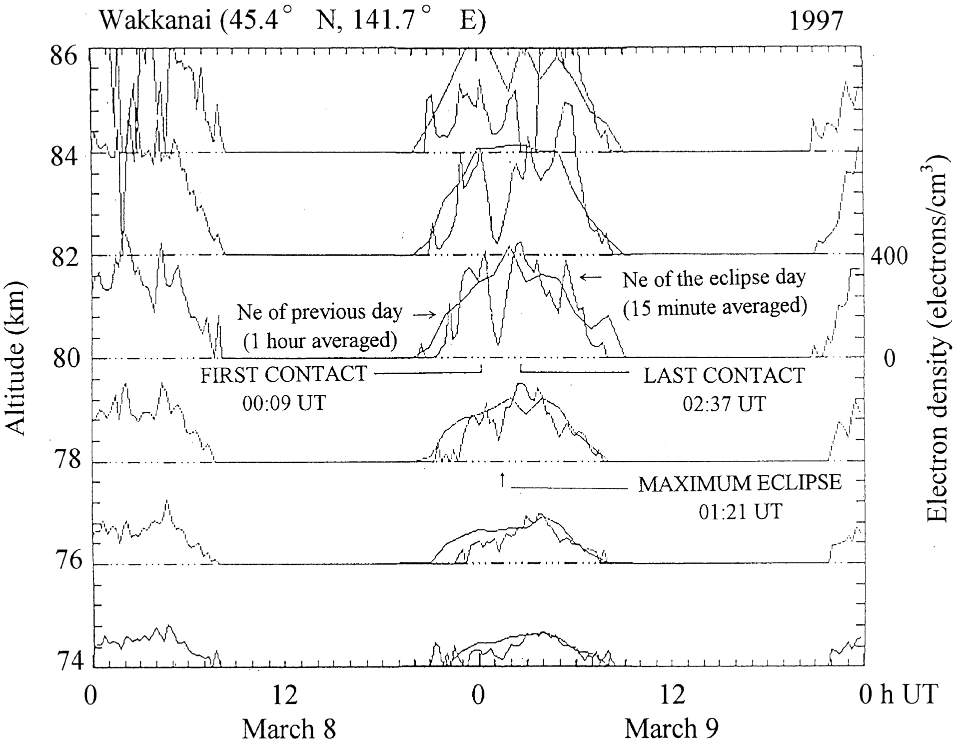


Fig. 10. Variations of the electron density profile during the partial solar eclipse which was observed by Wakkanai MF radar on 9 March 1997.

spheric winds were simultaneously measured by combining Yamagawa MF radar observations and TMA trail observations (Igarashi *et al.*, 1998; Larsen *et al.*, 1998). Figure 9 shows combined wind profiles derived from the Yamagawa MF radar (82–94 km) and TMA trail observations (98–134 km) for the S310-26 rocket experiment. This experiment showed an existence of a strong wind shear below the wind maximum and a reversal of wind direction below 100 km in altitude. The occurrence of quasi-periodic (QP) echoes with a period of 5 days from midlatitude sporadic E was interpreted in terms of effects produced by a planetary wave (Tsunoda *et al.*, 1998). In this paper wind spectra of the Yamagawa MF radar with around a 4–6 day period was compared in order to investigate the role of planetary waves in the dynamo region. Further comparison experiments should be continued in order to validate the MF radar observations and to further study the coupling between the mesopause region and the lower thermosphere region.

4. Measurement of D-region Electron Density Profile during the Partial Solar Eclipse

At Wakkanai the differential absorption technique is applied for obtaining an electron density profile, in addition to wind measurements. Igarashi *et al.* (1999) measured the D-region electron density by MF radar and compared it to the ionospheric model IRI-95. Figure 10 shows a special event of the D-region electron density variation in the altitude of 74–86 km during the partial solar eclipse at Wakkanai on 9 March 1997. The first contact was at 9:09 LT (0:09 UT), the maximum eclipse of 79% was at 10:21 LT, and the last contact was at 11:37 LT. A rapid decrease of electron density during the solar eclipse was clearly found. The minimum electron density was near the time of maximum eclipse. The change of electron density reached 74 km. The daily asymmetry in the variation of electron density also appeared in Fig. 10 (Bilitza, 1998). The difference in the averaged electron density of the previous day and the eclipse day is about 300 elecrons/cm^3 at the time of maximum eclipse at 80 km in altitude. This first result of D-region electron density during the solar eclipse is a good example for investigating the differential absorption method. The process of influence of tidal winds on the distribution of electron density in the D-region of the ionosphere is also an interesting study subject for the PSMOS program. It is necessary to make further comparison experiments of D-region electron density of MF radar measurements and in-situ rocket experiments for validating the differential absorption method. The Yamagawa MF radar will be improved to be able to measure the D-region electron density.

5. Concluding Remarks

The CRL have started an observation of mesospheric winds at both sites of Wakkanai and Yamagawa from September 1996. In this paper the comparison results of these two radars and other coordinated observations, including from rockets, were summarized briefly. Spectral variations, mean winds, 24-hour and 12-hour oscillations of winds were compared during the strong winter jet in the upper mesosphere. Spatial and temporal variability of the wind spectrum suggest resonant interactions between planetary waves, tides, and gravity waves. The spectra comparison of two MF radar observations showed a high degree of spatial and temporal variability in the winter mesosphere in Northern and Southern Japan. Differences of mean winds in 1997 were shown for the periods of solstices and equinoxes by hodographs. The zonal winds of the HWM93 model are in good agreement with the observed winds at Yamagawa and Wakkanai. But the observed meridional winds at Yamagawa and Wakkanai were significantly stronger than the averages of the empirical HWM93 wind model. MF radar observations showed that the propagation of the diurnal tide from the mesosphere into the dynamo region is probably disturbed by the sudden increase of the eastward wind. Further study is necessary for understanding the coupling processes between the mesosphere and the dynamo region. The influence of geomagnetic activity on the wind field of the mesosphere and lower thermosphere is also an important subject during the increasing phase of solar activity. A D-region electron density profile was obtained by the Wakkanai MF radar by using a differential absorption method during the solar eclipse. The process of influence of tidal winds on the distribution of electron density in the D-region of the ionosphere is also interesting study subject. A further comparison experiments of rocket in-situ measurements, Yamagawa MF radar observations and colocated meteor radar observations should be conducted in order to validate the MF radar observations and for the coupling study of the mesosphere and lower thermosphere. The CRL is constructing a new MF radar at Poker Flat (65.1°N, 147.5°W) due in October, 1998, collaborating between the CRL and the Geophysical Institute, University of Alaska Fairbanks. These MF radars at the middle-high latitude will contribute to the PSMOS program by taking part in coordinated observations with the mesosphere and lower thermosphere (MLT) radar networks.

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