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MU radar observations of the aspect sensitivity of backscattered VHF echo power in the troposphere and lower stratosphere

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By using the fast beam steerability of the MU radar, we have studied the characteristics of the aspect sensitivity of the VHF backscattered echo power in the troposphere and lower stratosphere. The tropopause clearly divides the altitude range into regions with and without large aspect sensitivity. In the stratosphere, large aspect sensitivity occurs in the entire altitude region and is clearly correlated with the echo power received in the vertical direction. From investigation of the Doppler spectra, it is found that the aspect sensitivity of the echo power is correlated with the zenith angle dependence of the spectral width. Fairly large aspect sensitive echoes are also received from intense scattering layers in the troposphere, although their time-height variation is large. Because of the large aspect sensitivity of the stratospheric echo power, the effective zenith angle of the antenna beam is smaller than the bore sight angle, so that the horizontal wind velocity can not be estimated correctly from the radial wind velocity measurements done at small zenith angles.

1. INTRODUCTION

Several models are proposed to explain scattering or reflection mechanisms which give rise to the MST radar echoes in the middle atmosphere [e.g., *Gage and Balsley*, 1980]. Isotropic turbulent echoes are received from irregularities of the refractive index structure with a length scale of half of the radar wavelength [*Booker and Gordon*, 1950]. On the other hand, recent MST radar observations done in the VHF frequency band have shown large enhancements of the stratospheric echo power in the vertical direction relative to the oblique [*Gage and Green*, 1978; *Röttger and Liu*, 1978; *Fukao et al.*, 1979; *Röttger et al.*, 1981].

Doviak and Zrnić [1984] explained the zenith angle dependence of the echo power in terms of anisotropic scattering from actively turbulent regions. On the other hand, Fresnel reflection from a stably stratified atmosphere has been considered as a primary mechanism of the aspect sensitivity of the echo power [*Röttger and Liu*, 1978]. As a possible mechanism in the middle atmosphere *Röttger* [1980] further introduced the concept of diffuse reflection from a rough boundary between laminar and turbulent regions. *Gage et al.* [1981] considered the incoherent addition of reflected signals from many layers filling the volume illuminated by the radar beam, and termed the mechanism Fresnel scattering. The original Fresnel scattering model contained an improper treatment of the pulse length dependence of the echo power, and it has been revised by *Hocking and Röttger* [1983] and *Gage et al.* [1985]. The new model predicts a linear relation between the pulse length and the echo power, which has been experimentally tested by *Green and Gage* [1985].

Obviously, all of these various kinds of scatterings and reflections contributes to the MST radar echoes. It is important to determine the primary mechanisms responsible for MST radar echoes in order to interpret them in terms of the underlying physical processes. These mechanisms may be distinguished by investigating (1) the zenith angle dependence of the backscattered echo power, (2) the time and space coherence of the received signal [*Rastogi and Röttger*, 1982], and (3) the characteristics of the echo power spectra.

The newly constructed MU radar [*Kato et al.*, 1984] has a great capability for studying the zenith angle dependence of the backscattered echo power in the troposphere and lower stratosphere. By using the fast beam steerability of the MU radar, observations in 16 different directions have been simultaneously carried out. This paper reports some characteristics of the aspect sensitivity of the echo power, and its effect on the wind velocity extimation by the DBS (Doppler beam swinging) method.

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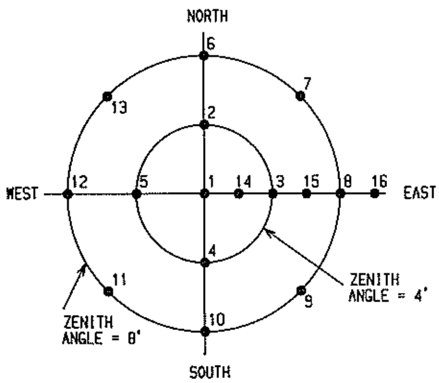

Fig. 1. Schematic top view of the antenna directions.

2. EXPERIMENTAL TECHNIQUE

The MU radar is a monostatic pulsed Doppler radar with an active phased array system operating at 46.5 MHz with a maximum transmitted power of 1 MW. The effective antenna area with 475 crossed yagis is 8,330 m^2. The one-way 3-dB beam width of the MU radar is 3.6°. The antenna gain decreases by approximately 10 dB at 3° off the antenna bore sight. *Fukao et al.* [1985*a*, *b*] described details of the MU radar. It was completed in 1984 after three years of construction. Observations of the troposphere and the stratosphere have been reported by *Kato et al.* [1984] and *Sato et al.* [1985].

Observations were carried out twice on December 20–21, 1984, and February 5–6, 1985, for about 4.5 and 8 hours, respectively. The antenna direction of the MU radar was changed every 400 μs of the interpulse period from the zenith to 15 oblique directions whose configuration is shown in Figure 1. The aspect sensitivity of the backscattered echo power has mainly been investigated from the signals received in the eastward direction. The transmitted pulse was phase-modulated by a 16-bit complementary code with a subpulse width of 1 μs. The duty ratio of a measurement in each direction was 1/400. The received echo was sampled at ranges from 5.4 to 14.85 km at intervals of 150 m, then transferred into Doppler spectra using a 128-point FFT after coherent integration of 16 times in each antenna direction. The bandwidth of the Doppler spectrum was 9.77 Hz. The radial wind velocity and the echo intensity were derived from the Doppler spectra.

3. ASPECT SENSITIVITY OF THE ECHO POWER

3.1. *Mean height profiles*

Received echo power can be expressed as

$$P_r = (\mathrm{S/N}) \cdot kBT_e/d \qquad (1)$$

where S and N correspond to the signal and noise power estimated from the Doppler spectrum, and k, B, T_e and d are the Boltzmann constant, the bandwidth of the Doppler spectra, the effective noise temperature and the duty ratio, respectively. Now, we define the range-corrected relative echo power as

$$P_\chi = (r(\mathrm{km})/10\ \mathrm{km})^2 \cdot S \qquad (2)$$

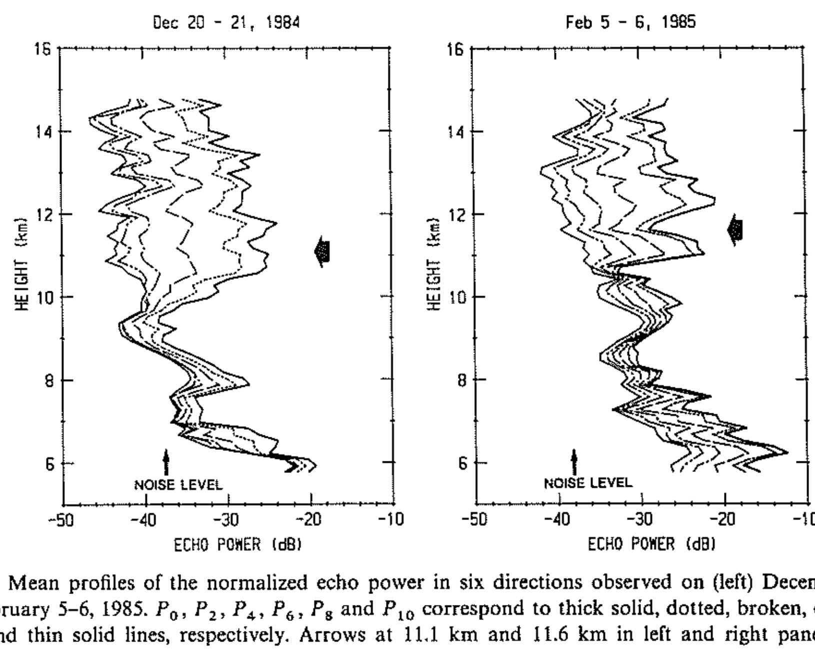

Fig. 2. Mean profiles of the normalized echo power in six directions observed on (left) December 20–21 and (right) February 5–6, 1985. P_0, P_2, P_4, P_6, P_8 and P_{10} correspond to thick solid, dotted, broken, chained, doubly chained and thin solid lines, respectively. Arrows at 11.1 km and 11.6 km in left and right panels, respectively, indicate the tropopause observed by a rawinsonde at Shionomisaki.

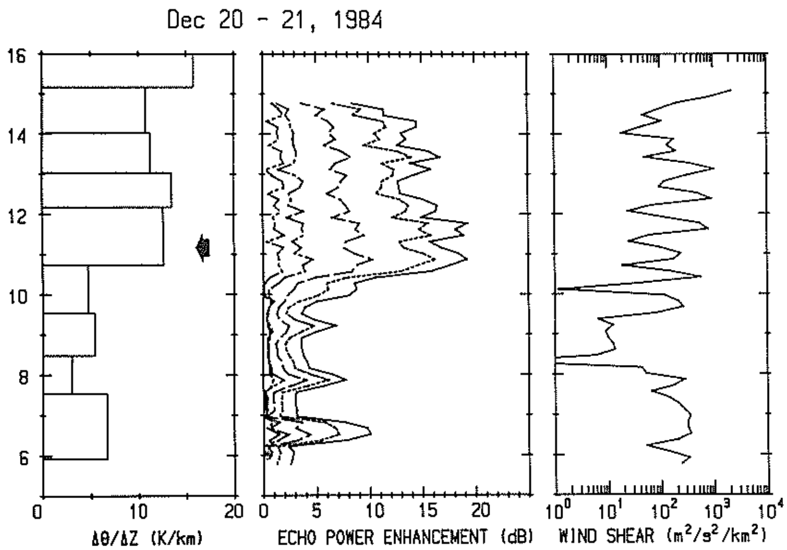

Fig. 3. The vertical profiles of (left) the potential temperature gradient, (center) the enhancement of the normalized echo power relative to P_{10}, and (right) the intensity of the vector wind shear observed on December 20–21, 1984. P_0/P_{10}, P_2/P_{10}, P_4/P_{10}, P_6/P_{10} and P_8/P_{10} correspond to solid, dotted, broken, chained and doubly chained lines, respectively.

where r and χ are the range in kilometers and the zenith angle, respectively. In Figure 2, P_χ in the vertical and oblique directions are plotted for the two observations. The power reflection coefficient $|\rho|^2$ can be defined as [*Gage and Green*, 1978]

$$|\rho|^2 = 4\lambda^2 r^2/(\alpha^2 P_t A_e^2)\cdot p_r$$
$$= 4\lambda^2/(\alpha^2 P_t A_e^2)\cdot kBT_e/(Nd)\cdot 10^8 \cdot P_\chi \qquad (3)$$

where α and λ are the antenna efficiency and the radar wavelength, respectively. As indicated in Figure 2, the mean values of N for the two observations were 1.8×10^{-4} and 1.55×10^{-4}. Thus, by assuming $\alpha = 0.8$ and $T_e = 8000$ K, and by substituting system parameters, $|\rho|^2$ can be estimated as

$$|\rho|^2 = 9.12 \times 10^{-16}\cdot P_\chi/\cos^2\chi \qquad \text{Dec. 1983}$$
$$= 10.6 \times 10^{-16}\cdot P_\chi/\cos^2\chi \qquad \text{Feb. 1984} \qquad (4)$$

The tropopause heights also shown in Figure 2 were measured at 2100 LT on December 20, 1984, and February 5, 1985, by a rawinsonde at the Shion-

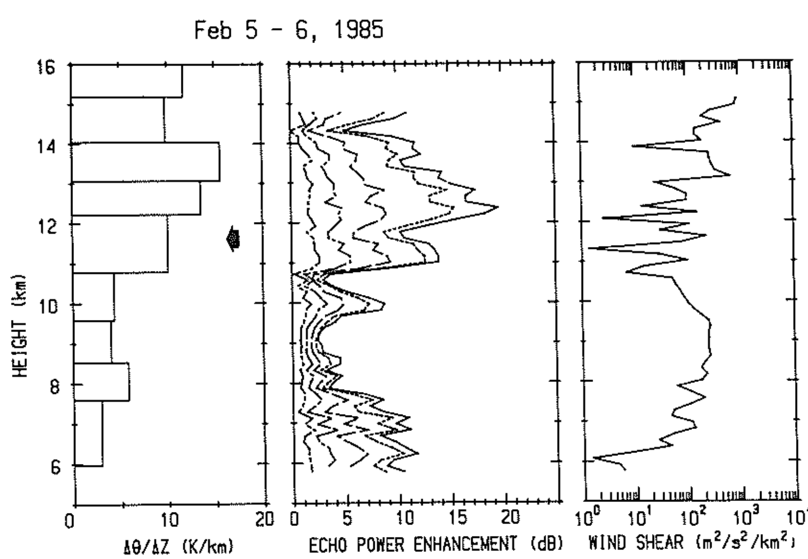

Fig. 4. The same as Figure 3 except for observations on February 5–6, 1985.

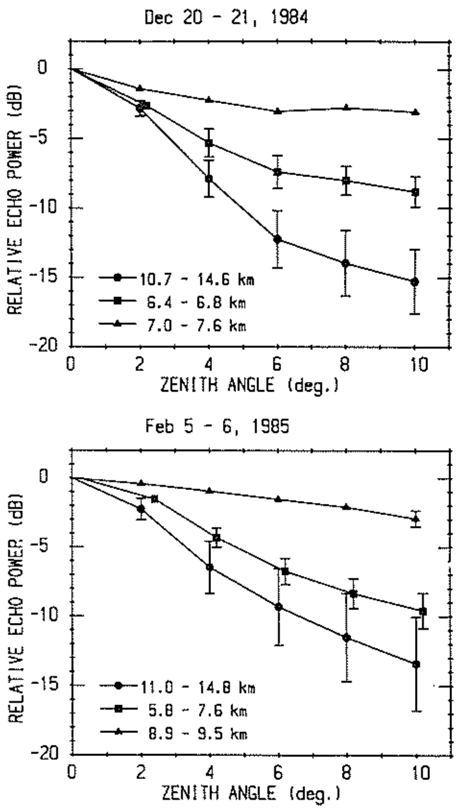

Fig. 5. The zenith angle dependence of the echo power averaged in three altitude ranges observed on (top) December 20–21, 1984, and (bottom) February 5–6, 1985. A solid circle, a square and a triangle correspond to the average in the stratosphere, the troposphere with a relatively large aspect sensitivity, and the troposphere with a small aspect sensitivity.

omisaki meteorological station located about 150 km south of the MU radar. P_0 is the largest echo power throughout the observed altitudes. Although there are some intense scattering layers, the tropospheric echo power generally tends to decrease with height. In the troposphere on December 20–21, 1984, there is not a large difference among profiles at different zenith angles, while on February 5–6, 1985, relatively large difference can be recognized in the enhanced scattering layers below 8 km. P_0 becomes large near the tropopause [*Gage and Green*, 1978; *Röttger*, 1980]. The height variation of P_0 in the stratosphere is rather larger in the February results than in the December observations, as shown in Figure 2. The aspect sensitivity of the stratospheric echo power is conspicuous in all of the observed altitudes. At large zenith angles P_χ is severely attenuated relative to P_0, although the height variation is similar in all six profiles. Echo power profiles received at the larger zenith angles do not show large variations versus height above the tropopause.

In order to investigate the aspect sensitivity more clearly, the echo power ratio relative to P_{10} is plotted in Figures 3 and 4 for the December and February observations, respectively, accompanied by the potential temperature gradient calculated from the rawinsonde measurement and the intensity of the wind shear which is defined as the sum of square of zonal and meridional shears. The tropopause clearly divides the altitude region between those with and without large aspect sensitivity. The intensity of the aspect sensitivity in the stratosphere seems to be roughly correlated with the atmospheric stability, which can be estimated by the potential temperature gradient [*Gage and Green*, 1978].

The mean zenith angle dependence of P_χ/P_0 has been calculated in Figure 5 for the stratosphere and two typical tropospheric regions with and without a large aspect sensitivity. On December 20–21, 1984, P_χ in the stratosphere decreases rapidly until the zenith angle becomes as large as 6°, then its angular dependence becomes small. That on February 5–6, 1984 decreases more slowly versus the zenith angle.

In the 7.0–7.6 km and 8.9–9.5 km altitude regions in the December and February observations, respectively, where P_0 is not enhanced relative to the surrounding altitudes, the aspect sensitivity is small, in that P_{10} is attenuated only by 3 dB relative to P_0. On the other hand, the echo power received from the 6.4–6.8 km altitudes in December 1984 and 5.8–7.6 km region in February 1985, where the echo power is locally enhanced, shows a fairly large aspect sensitivity. Thus, there seem to exist two different types of scattering regions in the troposphere: relatively thin intense scattering layers with a large aspect sensitivity, and the non–aspect sensitive regions.

3.2. *Fine structures*

For observations on February 5–6, 1985, Figure 6 shows a height time section of P_0 and P_0/P_{10}. Intense vertical echoes are received from thin stably stratified layers above 11 km. Below about 8 km, there also exist tropospheric scattering layers as thin as those in the stratosphere. The downward motion and the vertical spacing of these layers seem to be a manifestation of low frequency waves such as inertial gravity waves [*Fritts*, 1984]. The intense scattering layer in the 8–11 km altitude range propagating downward more rapidly than the other layers could be attributed to the passage of a cyclone accompa-

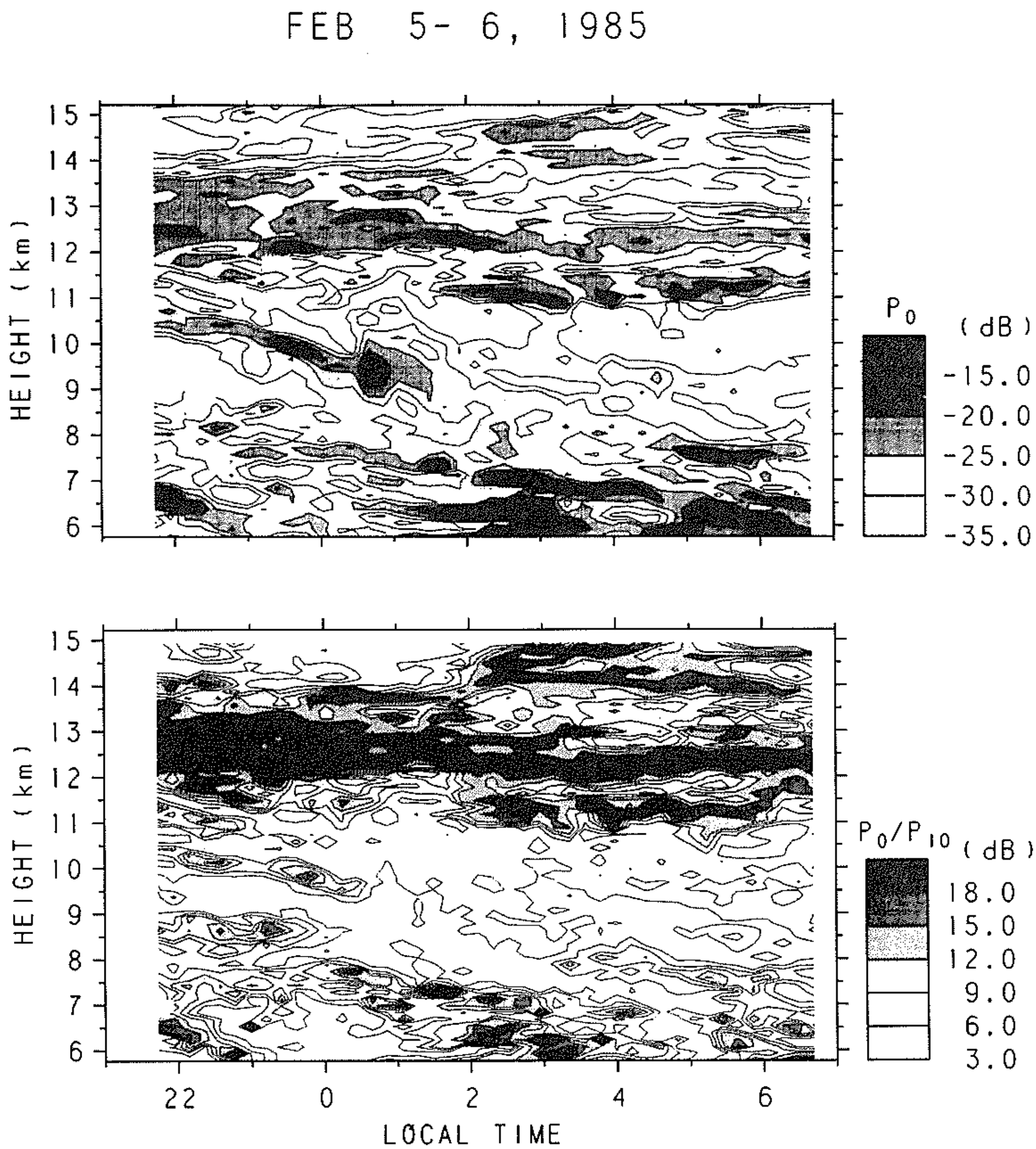

Fig. 6. Time height contour of (top) P_0 and (bottom) P_0/P_8 observed on February 5–6, 1984.

nied by a front approximately 400 km south of the MU radar [*Röttger*, 1979].

Figure 6 shows a clear correlation between P_0 and P_0/P_{10} in the stratosphere. The P_0 profiles in the troposphere have similar features in that they are stratified, and as thin as those in the stratosphere. Nevertheless, intense p_0 is not necessarily accompanied with the large aspect sensitivity represented by P_0/P_{10}.

Tropospheric echoes with a large aspect sensitivity seem to be restricted to vertically thin regions, and characterized by a short duration. Intense isotropic echoes without significant aspect sensitivity are sometimes detected in the troposphere. A typical example can be seen in the echoes received from the thick layer centered at 0045 LT and 9.5 km altitude shown in Figure 6. Although there is an abrupt increase of P_0 within a period not longer than half an hour, P_0/P_{10} does not show a corresponding enhancement. The echo power spectra had relatively

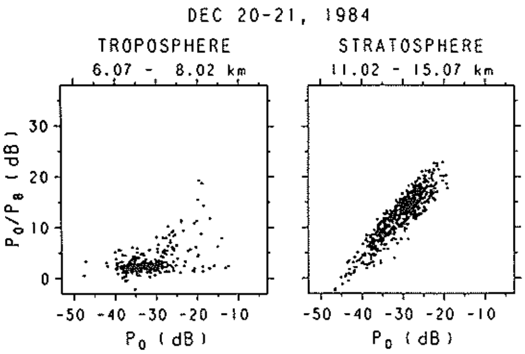

Fig. 7. P_0/P_8 versus P_0 (right) in the stratosphere and (left) in the troposphere observed on December 20–21, 1984.

large spectral widths, and did not include echoes from precipitating particles [*Fukao et al.*, 1985*c*]. The intense echo from this limited region has no aspect sensitivity, although the layer at the 10-km altitude prior to the intense echo had a zenith angle dependence of the echo power. Thus, it seems likely that the intense isotropic echo is scattered from a highly active turbulent region.

3.3. P_0 *vs.* P_0/P_8

As has been recognized from Figure 2, the height variation of P_χ at large zenith angles is much smaller than that for P_0. Figures 7 and 8 show a relation between P_0 and P_0/P_8 detected every 12 min at each altitude in the stratosphere and the troposphere. Note that the altitude region of the stratospheric echoes is restricted to less than 13.5 km in Figure 8, because a "second tropopause" at 15.9 km was detected by the rawinsonde measurement. Since the atmosphere in the vicinity of this altitude is not so stable, the characteristics of the echo power might resemble that in the troposphere.

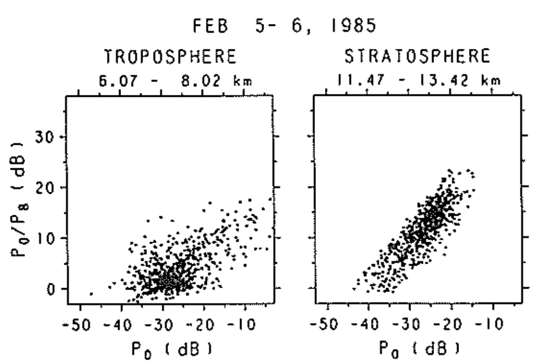

Fig. 8. The same as Figure 7 except for the results on February 5–6, 1985.

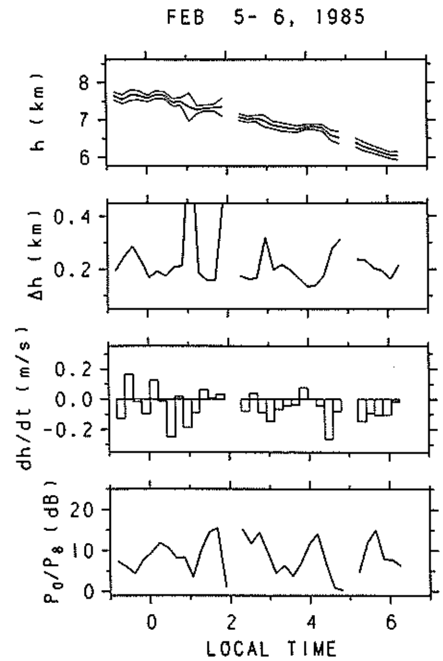

Fig. 9. Mean height (h), thickness (Δh) and time derivative of the mean height (dh/dt) of the scattering layers in the troposphere in comparison with P_0/P_8.

A relation between P_0 and P_0/P_8 in the stratosphere can be approximated by a linear curve with a slope of one. This relation suggests that P_8 is nearly constant versus altitude, and P_0 is enhanced above

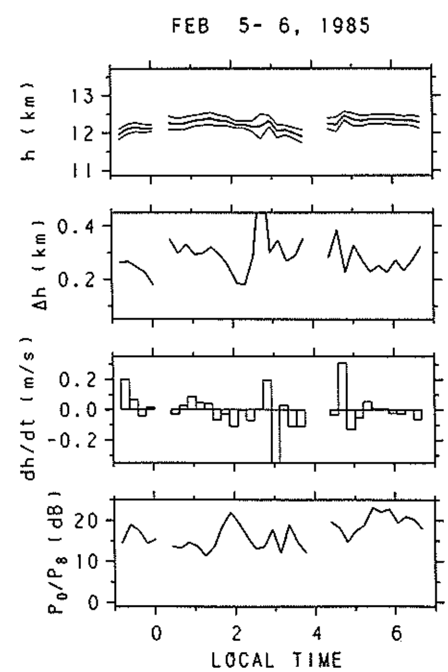

Fig. 10. The same as Figure 9 except for the stratospheric layer.

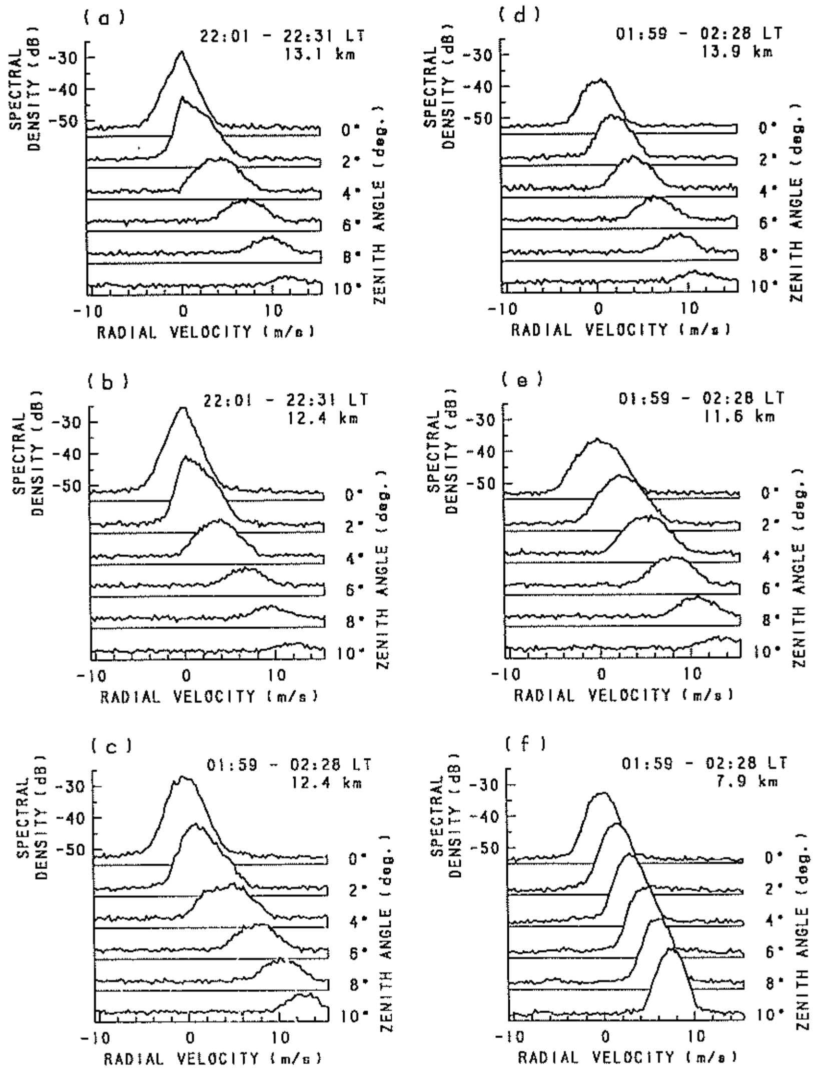

Fig. 11. Typical echo power spectra observed at the zenith angles of 0°, 2°, 4°, 6°, 8°, and 10° at several altitudes on February 5–6, 1984. Ground clutters are removed.

the constant level. The deviation of each point from the linear relation is due to the time and height fluctuations of P_0 and P_8.

On the other hand, there is not a simple relation for the enhancement of the tropospheric echo power. As can be seen from Figure 7, P_0/P_8 in the troposphere mostly has a constant value of approximately 2 dB independent of the intensity of P_0. P_0/P_8 occasionally exceeds 10 dB, but the statistical nature of its enhancement is not clear. In Figure 8, enhancement of P_0/P_8 observed in February is more frequent than in December, but its statistical behavior can not be simply described.

Isotropic echoes independent of the zenith angle are detected only in the troposphere. In other words, the stratosphere is filled with aspect sensitive echoes. Therefore, the mechanism producing aspect sensitivity must exist in the entire stably stratified region. The difference in the characteristics of aspect sensitivity between the troposphere and the stratosphere suggests the importance of the atmospheric stability in determining the reflection or scattering mechanism of VHF radar echoes [*Gage and Green*, 1978].

3.4. *Thickness and gradient of scattering layers*

In order to investigate the relation between the aspect sensitivity and the structure of the scattering

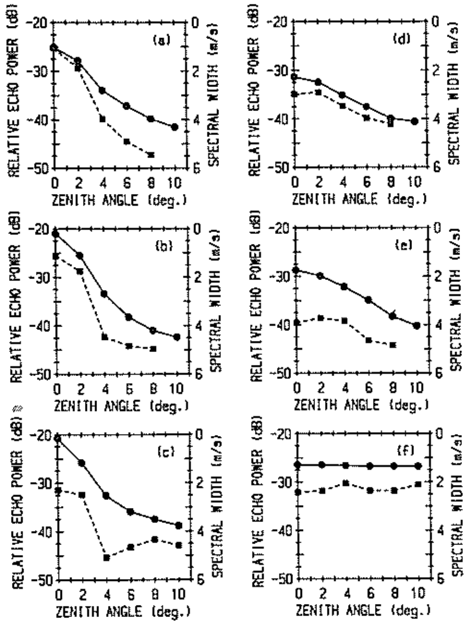

Fig. 12. Zenith angle dependence of P_x (a circle) and a 3-dB spectral width (a square) of the Doppler spectra shown in Figure 11.

layers, we have calculated mean height h, time derivative of the mean height dh/dt, and thickness Δh of the layer, where the thickness is defined as 3-dB height difference of P_0. Figures 9 and 10 show results for layers in the troposphere and the stratosphere observed on February 5–6, 1985, respectively.

P_0/P_8 in Figure 9 ranges from 0 to 15 dB with a large time variation. In the troposphere dh/dt is generally larger than in the stratosphere, but Δh is smaller. P_0/P_8 exceeding 10 dB in the troposphere coincides with the condition that the corresponding dh/dt approaches zero, and Δh becomes smaller than 150 m, the range resolution, except for the peak at around 0530 LT. It is suggested that the abrupt increase of aspect sensitivity in the troposphere occurs when the layer becomes horizontal enough to give rise to the Fresnel reflection.

In Figure 10, P_0/P_8 is larger than 10 dB in the whole observation period, but it is not so sensitive to the fluctuation of dh/dz, as it was in the troposphere. The layer thickness is about 250 m on the average, and is generally larger than that in Figure 9. This suggests that stratospheric echoes with large aspect sensitivity could not be attributed to the contribution from a single isolated reflection surface caused by an abrupt vertical change in the refractive index, but to contributions from many reflecting layers that fill the whole stratosphere.

It seems that the stratosphere is filled with many reflecting layers, so that the received echo power, which is an incoherent sum of each reflection, does not have a large vertical variation. On the other hand, the condition for a specular reflection is less frequently satisfied in the troposphere than in stratosphere, therefore, the layer thickness deduced from the height structure of tropospheric P_0 becomes smaller than stratospheric one.

4. ECHO POWER SPECTRA

Figure 11 shows variation of the echo power spectra versus zenith angle at several altitudes. Figures 11*a*, 11*b* and 11*c* show the power spectra observed at altitudes where intense stratospheric echoes with large aspect sensitivity are detected. The vertical echo power spectra have smaller spectral widths than those at large zenith angles. At 2° zenith angle the echo power spectra are asymmetric, which suggests that an intense specular reflection dominates in the vertical direction. When the zenith angle becomes larger than 4°, that is, when the antenna beam has only small gain in the vertical direction, the echo power spectra become symmetric, with a large spectral width. The stratospheric echoes shown in Figures 11*d* and 11*e* have rather symmetric distribution, but they also decrease in echo power and increase in spectral width versus zenith angle.

Figure 11*f* exhibits the non–aspect sensitive echo detected in the troposphere, which seems to be caused by isotropic turbulent scattering. There seems a slight variation in the echo power and the spectral width versus zenith angle.

It is useful to investigate the spectral width of

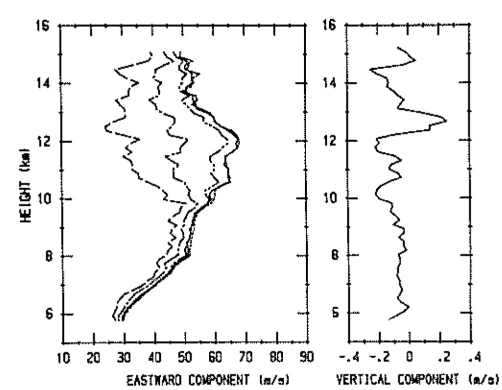

Fig. 13. Mean profiles of (right) the vertical and (left) the eastward wind velocities observed on December 20–21. A broken, chained, doubly chained, dotted and solid lines correspond to the observations at zenith angles of 2°, 4°, 6°, 8° and 10°, respectively.

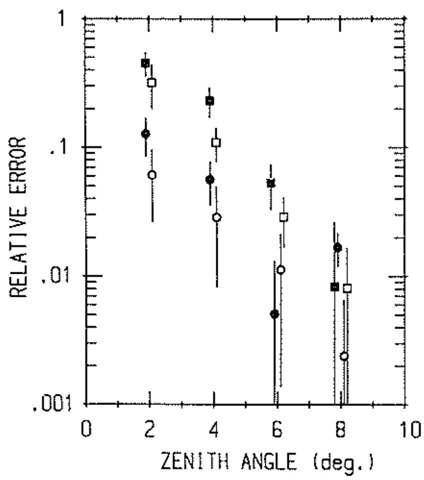

Fig. 14. Zenith angle dependence of a relative error in the measurements of the eastward wind velocity. A circle and a square indicate the results in the troposphere and the stratosphere. Open and solid symbols correspond to the observations on December 20–21 and February 5–6, respectively.

Doppler power spectra in discriminating Fresnel reflection from isotropic turbulent scattering, because specular reflection has a longer correlation time than turbulent scattering, and therefore has a smaller spectral width. Figure 12 shows variations of echo power and spectral width as functions of the zenith angle for the echoes shown in Figure 11. Note that the vertical axis for the spectral width is plotted in the reverse direction. It is clear that large aspect sensitivity is accompanied by a rapid increase of the spectral width versus zenith angle. Among these, the echoes shown in Figures 12*a* and 12*b* have especially small spectral widths at zenith angles of 0 and 2°, suggesting that these are intense specular reflections from stable layers with long correlation times. Figure 12*f* is from the troposphere and shows only a slight dependence of echo power and spectral width on the zenith angle.

5. ERROR IN WIND MEASUREMENTS

A Doppler beam swinging method can derive the horizontal wind velocity from simultaneous vertical and oblique radial wind velocity measurements, by assuming that the antenna bore sight determines the direction of the measured radial wind velocity. This section is devoted to clarify the effect of aspect sensitive echoes on radial wind velocity measurements. Figure 13 shows mean profiles of the vertical and eastward winds observed on December 20–21, 1984. Because the oblique observations are done simultaneously at five different zenith angles of 2°, 4°, 6°, 8°, and 10°, five profiles of the horizontal wind velocity are estimated. Obviously, the observations with small zenith angles do not correctly delineate the eastward wind velocity in the stratosphere. Furthermore, there is systematic discrepancy in the tropospheric wind velocity measured at zenith angles of 2° and 4° relative to the other observations. The aspect sensitivity of the echo power causes a discrepancy between the bore sight beam direction and the effective one determined by the convolution of the antenna gain pattern and the zenith angle dependence of the reflectivity [*Röttger*, 1981].

Assuming that the horizontal wind velocity is correctly estimated from measurements at 10° zenith angle, the error of the horizontal wind velocities at other smaller zenith angles is shown in Figure 14 for both stratospheric and tropospheric observations. Since the tropospheric observations contain smaller errors in the horizontal wind measurements than the stratospheric ones because large aspect sensitivity is infrequent, measurements at zenith angles less than 4° should be avoided. The discrepancy in the horizontal wind velocity measurement at 8° zenith angle seems to be within the statistical error. The effective antenna direction for measurements with the antenna bore sight pointing at 2°, 4° and 6° zenith angle can be estimated by comparing the apparent amplitude of the horizontal wind velocity with that observed at 10° zenith angle. The results are 1.38°, 3.25° and 5.70° on December 20–21, and 1.52°, 3.61° and 5.83° on February 5–6, respectively.

6. CONCLUSIONS

We have studied the aspect sensitivity of the backscattered echo power in the troposphere and lower stratosphere using the MU radar. The enhancement of the vertical echo power and the aspect sensitivity seem to be due to the reflections from stratified layers which are very frequent in the stratosphere.

1. Aspect sensitivity occurs throughout the stratosphere, while, in the troposphere it occurs only in relatively small height ranges for short periods. Enhancement of the aspect sensitivity usually occurs near the tropopause [*Rastogi and Röttger*, 1982], but it does not necessarily occur at the altitude of the meteorologically defined tropopause.

2. In the stratosphere P_0 vs. altitude is enhanced above the nearly constant level of P_8, which seems to be due to the vertical variation of aspect sensitivity.

3. Large values of P_0/P_8 are usually detected from thin layers with small temporal gradients. Be-

cause the condition for a stratified layer to give specular reflection is less frequently satisfied in the troposphere, contributions to the tropospheric echo come from fewer reflecting layers than in the stratosphere. Therefore, the vertical variation of echo power is more abrupt than in the stratosphere, and the reflecting layers for the tropospheric echoes with large aspect sensitivity sometimes appear thinner than those in the stratosphere.

4. Intense specular reflections sometimes give Doppler spectra with fairly narrow spectral widths in the vertical direction, and asymmetric Doppler spectra in directions near the vertical.

5. The aspect sensitivity of echo power is clearly correlated with the increase of the spectral width of the Doppler spectra versus zenith angle. Spectral widths of tropospheric echoes with a small aspect sensitivity do not depend on the zenith angle.

6. Characteristics of the aspect sensitivity in the troposphere is different between the two observations done in December and February in that large aspect sensitivity is more frequently detected in the latter period. It might be attributed to the different meteorological conditions such as the passage of a cyclone.

7. To estimate the horizontal wind velocity correctly in the stratosphere, the zenith angle of the MU radar, with the 3-dB beam width of 3.6°, should be larger than 8°. Even in the troposphere, abrupt increases of the aspect sensitivity could give errors in short duration wind measurements at small zenith angles.

If there were a single specular reflecting layer in the volume illuminated by the radar beam, the received echo power would decrease as rapidly as the two way antenna gain pattern. The observed aspect sensitivity is, however, usually more gradual than the antenna beam pattern. It can be inferred that this is due to interference among incoherent reflections with similar intensity.

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