Simultaneous observation of precipitating atmosphere by VHF band and C/Ku band radars

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Multifrequency meteorological radar observations provide more detailed information on precipitation than single-frequency observations. However, these observations have been generally limited to the microwave range. This paper describes a simultaneous observation of precipitating atmosphere by using the VHF band radar and the microwave C/Ku band radar. The frequency difference makes it possible to discriminate atmospheric scattering from precipitation scattering. The preliminary result shows that (1) VHF echoes stronger than those expected from the clear atmosphere condition are received from precipitating atmosphere and (2) the intensity of VHF scattering strongly depends on precipitation structures.

1. INTRODUCTION

Microwave meteorological radars have been standard tools for the study of precipitating atmosphere. Since the precipitation reflectivity is deduced from the received echo power, a multifrequency observation obviously provides more detailed information on precipitation than a single-frequency observation. Besides reflectivity, atmospheric motions are estimated by using meteorological Doppler radars [e.g., *Rogers*, 1984; *Doviak and Zrnić*, 1984]. The estimates, however, may not be completely identical to the atmospheric motions, because the echo with microwave radars returns from precipitation, but not from the atmosphere itself.

The mesosphere-stratosphere-troposphere (MST) radars are sensitive VHF/UHF band Doppler radars. This type of radar is a powerful tool for the study of atmospheric motions such as wind, waves, and turbulence, because the echoes return from the atmospheric (refractive index) fluctuation [e.g., *Balsley and Gage*, 1980; *Harper and Gordon*, 1980]. Echoes mainly originate from the temperature fluctuation in the stratosphere and the troposphere. The fluctuation

due to the presence of gaseous water vapor is also important even for the clear atmosphere condition in the troposphere. *Green et al.* [1978] reported cloud observations by the VHF band radar at Sunset, Colorado, and a coherent scatter of radio waves from clouds was discussed by *Gossard* [1979].

Simultaneous observations by using these two kinds of radars, i.e., a meteorological radar and an MST radar, are expected to provide more detailed information on the role of water in generating VHF echoes and on interactions between the precipitation and the atmospheric turbulence. This paper discusses a multifrequency observation of precipitating atmosphere by using microwave C/Ku band radar and the VHF band middle and upper atmosphere (MU) radar at Shigaraki, Shiga, Japan (34.85°N, 136.10°E). The radar systems are briefly described in the next section, and then a preliminary result obtained in summer 1983 is presented.

2. RADAR SYSTEM

MU radar system

The MU radar is a monostatic radar of an active phased-array system; it is composed of 475 crossed three-element yagi antennas and the same number of solid-state transmitter-receiver (TR) modules [*Fukao et al.*, 1980; *Kato et al.*, 1984]. All yagis and modules are grouped into 25 subarrays (i.e., 19 yagis and TR modules constitute one subarray). The basic parameters of the MU radar are shown in Table 1. The main features of the MU radar are as follows. (1) A flexible operation is feasible because each TR module is inde-

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TABLE 1. Basic Parameters of the MU Radar (Final System) and the C/Ku Band Radar

	MU Radar	C Band	Ku Band
Frequency, MHz	46.5	5.265×10^3	13.85×10^3
Antenna			
Type	yagi array (circular)	parabolic	Cassegrain
Diameter, m	103	3	2
Gain, dB	34.0	40.1	45.7
Beam width, deg	3.6	1.0	0.6
Transmitter			
Peak power, kW	1.0×10^3	40	40
Pulse width, μs	1.0–512	1.1	1.1
Pulse repetition frequency, Hz	$\leq 2.5 \times 10^3$	163	163
Receiver			
Noise figure, dB	5	10	10
Minimum level, dBm	-120	-93	-93

pendently and promptly controlled by a sophisticated software of the radar controller (HP9835A). This makes it possible to scan the antenna beam rapidly, i.e., more than 1000 directions every second up to 30° from the zenith. Moreover, it is possible to excite only a portion of the antenna and receive the echo by other portions and/or to steer multiple beams at different directions. (2) A large number of data (up to 1024 altitude samples) can be processed in real time. A superminicomputer (VAX-11/750) and an array processor (MAP-300) with a 2-Mbyte random access memory (RAM) are installed for this purpose. Before being processed by the computer, the echo signals are decoded for pulse compression and then coherently integrated for data compression by special purpose hardware. (3) High reliability of the system is achieved by a network of 25 microprocessors which automatically monitors the TR modules. The radar controller, which supervises the overall operation of the MU radar system, is linked with these microprocessors for interchanging data.

C/Ku band radar system

The C and Ku band dual-frequency radar system was once used extensively for studying rain attenuation characteristics on the earth-space communication paths [*Yamada et al.*, 1978]. We have reconstructed and installed this system at the MU radar site. The basic parameters of the C/Ku band system are also included in Table 1. Two separate antennas (3 m and 2 m in diameter, respectively) are fixed pointing vertically for measuring the vertical structure of precipitation. Each antenna is excited by a magnetron. The received signals are converted to an

intermediate frequency of 45 MHz. Detected signals are analogue-to-digital converted every 2 μs (corresponding to the altitude interval of 300 m) and then averaged over 1.6 s. This radar system is controlled and monitored by an 8-bit microcomputer, and the standard interfacing system GP-IB is used for transferring data.

3. OBSERVATIONAL RESULTS

The multifrequency radar observation started in summer 1983, when the MU radar was still under construction. Since the MU radar was partly in operation, we used only three subarrays composed of 57 yagi antennas in fixed beam directions. The nominal beam width was 9°, and the transmitted power was 120 kW. The installation had been completed for the C/Ku band radar at that time. The following is the result of two preliminary precipitation observations made in August and September 1983. The time and range (altitude) resolutions of these observations are 1 min and 150 m, respectively, for the MU radar, and 1 min and 300 m, respectively, for the C/Ku band radar.

Doppler velocity spectra are obtained with the MU radar, while only echo power is estimated by the C/Ku band radar. The spectra generally have a single enhanced peak over the wide-band white noise, corresponding to the atmospheric echoes. The zeroth moment of the peak gives echo power, while the first moment yields the line-of-sight component of atmospheric motion. During the present observation the MU radar was not so sensitive, and the system adjustment was yet incomplete, but it was observed, though not so clearly, that the spectra bifurcated

below about an altitude of 4 km, when the precipitation echo was obtained with the C/Ku band radar. Two spectral components differ by approximately 15 dB in magnitude at 3 km. The major spectral component which exists both above and below 4 km should be of atmospheric origin. However, the minor one is presumably due to precipitation particles or raindrops, considering that its Doppler velocity seems to be 6–8 m s^{-1} downward [e.g., Lhermitte and Atlas, 1963]. However, since the beam width was comparably large and the two-way side lobe attenuation was only 20 dB for the present partial system, the possibility that the minor spectral component may have been generated by the side lobe echoes is also not absolutely excluded. Therefore, in what follows, only the major spectral component is investigated, and the minor one will be studied in the near future with a more sensitive system of the MU radar.

One observation was performed on September 27, 1983, when a front was generated by typhoon 10 (T8310). Figure 1 shows a vertical cross section observed with the C/Ku band radar. A remarkable agreement can be noticed between the C and Ku band echoes, although the Ku band radar, with its thinner beam width, features more detailed structure than the C band radar. The cloud top is estimated to be at an altitude of 6–8 km, while strong rain cells and their vertical structures are observed below 4.0 km. The enhanced echo, which is almost continuously observed at an altitude of 3.6 km, is considered to be a bright band where falling particles pass through the melting (0°C) layer. Radar echoes are enhanced there by the change in precipitation state from ice to liquid water and by the aggregation of ice crystals [e.g., Battan, 1973].

Figure 2 shows the averaged echo power profiles for the C band (left) and the MU (right) radars. The antenna beam of the MU radar was pointing 30° off from the zenith toward east. The MU radar echo profile shows a peak at the altitude where there is a remarkable peak in the C band echo corresponding to the melting layer. This coincidence suggests that the MU radar echo may have been directly scattered by precipitating particles. If it were from the precipitation, the wind profile by the MU radar should indicate a considerable change at the same altitude because the precipitation fall speed should increase to about 6–8 m s^{-1} below the melting layer [e.g., Lhermitte and Atlas, 1963]. The dotted curve (right) in the figure shows the zonal wind estimated from the radial Doppler shift of the MU radar echoes. This

wind profile shows, however, no abrupt change at that altitude but rather exhibits a constant wind shear with magnitude of 1.1 m s^{-1} km^{-1} over the 2.5- to 8.0-km altitude region. This result indicates that the MU radar echo does not originate from the precipitation, but rather from the atmospheric refractive index fluctuation.

The MU radar antenna beam was then pointed to the zenith for measuring the vertical motion of the atmosphere. Figure 3 shows a 2-hour average of the vertical wind profile. Upward motion is continuously observed. The vertical speed varies from about 0.2 m s^{-1} above the 5- to 6-km region to 0.6 m s^{-1} below it. This altitude region is a little lower than the cloud top observed by the C band radar (Figure 1), but the upward wind dominates beyond the precipitating region, and no significant change is noticed at the bright-band altitude. These results also imply that the MU echo and the C band echo independently return from the atmospheric fluctuation and the precipitation particles, respectively.

The other observation is a 36-hour observation of typhoon T8305. The observation started at midnight on August 16, 1983, when the typhoon was located 500 km south from the MU radar site. The pressure at the eye of the typhoon was 955 mbar. The typhoon was moving northeastward and approached the MU radar site most closely before dawn on August 17. The site was in the rainstorm zone from the evening of August 16. The antenna beam of the MU radar was fixed 30° from the zenith toward east to measure the zonal wind [Kato et al., 1984]. Since we used a 16-element complementary code (total pulse length of 16 μs) for pulse compression, the present observation was limited above the altitude of about 5 km.

The C band time-altitude section of precipitation in the top panel of Figure 4 shows several intermittent echoes during the daytime on August 16 and almost continuous echoes corresponding to the rainstorm from the evening of the same day. This figure features a part of a vertical section of typhoon T8305 because the typhoon was close to the MU radar site.

In the typhoons (and hurricanes) the precipitation is generally concentrated in an eye wall rainband surrounding the center of the typhoon and in several outer spiral rainbands; strong convective motions dominate in the rainbands [e.g., Houze, 1981]. The echoes around 0500, 0800, 1000, and 1300 LT on August 16 in the figure are characterized by a heavy rainfall in a short period of time and by a relatively
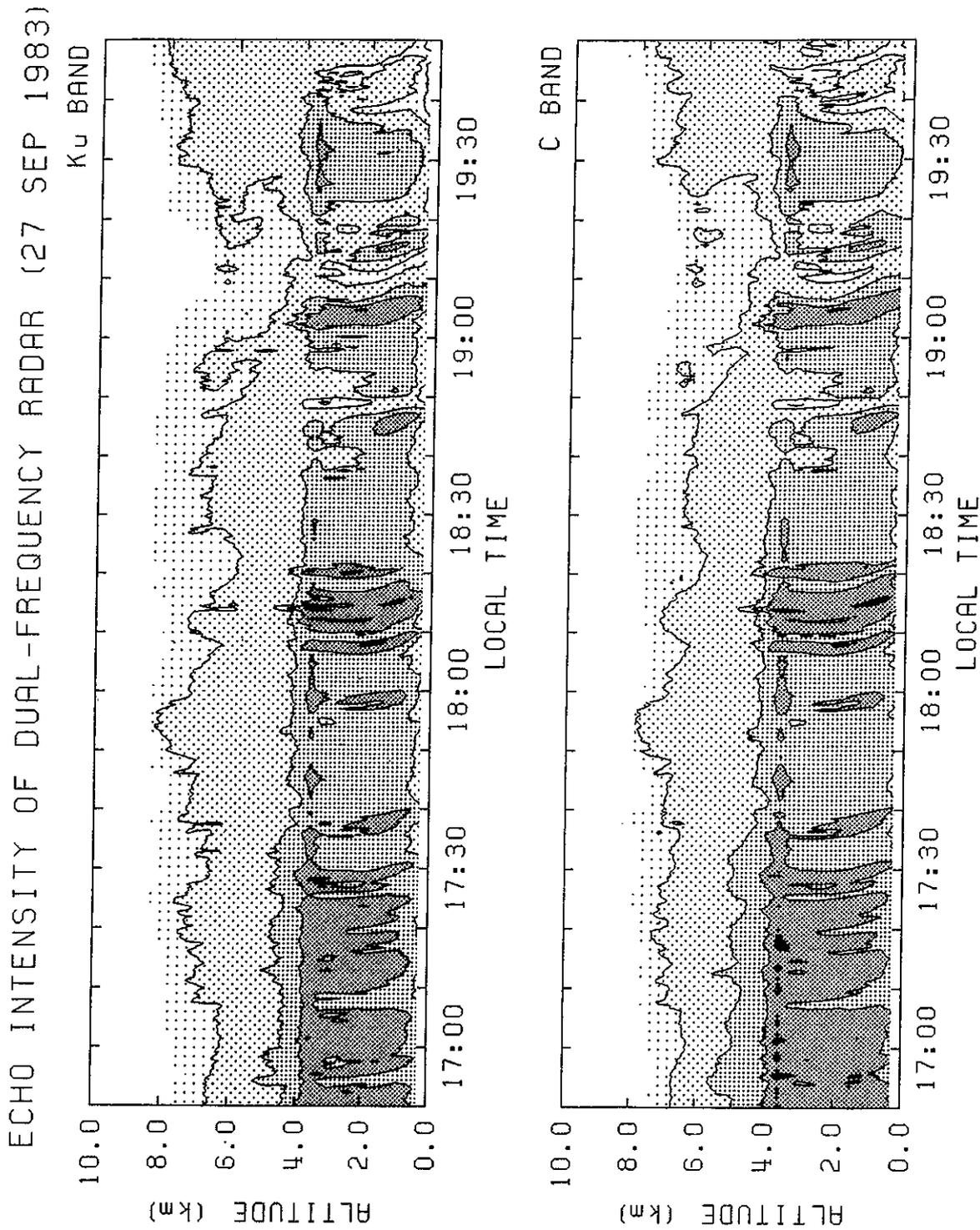
Fig. 1. Time-altitude section of precipitation observed at 1650–1950 LT (Japan standard time) on September 27, 1983, with the dual-frequency radar operating at Ku band (2.2 cm; top) and C band (5.7 cm; bottom). The echo power is the equivalent reflectivity factor Z_e in decibels.

high echo top which reaches an altitude of 6–8 km. Therefore these intermittent echoes are considered to correspond to the outer rainbands of the typhoon.

The passage of the rainbands is also confirmed with the Miyama meteorological radar located 70 km west from the MU radar site (H. Kasai, personal communication, 1983). An example of the rainband echo observed by the Miyama radar is illustrated in Figure 5.

The bottom panel of Figure 4 shows the corresponding section observed by the MU radar. The dynamic range is relatively small for the atmospheric echo in contrast to the precipitation echo. However, there is a remarkable correlation between these echoes in the intermittent rainband periods. The enhanced atmospheric echoes reach up to an altitude of 12 km, where no precipitation echo is detected by the C/Ku band radar. The radial wind speed within the rainbands deviates by several meters per second from the mean speed observed outside the rainbands. The C band intermittent echoes are most likely precipitation cells supported by updrafts, and the buoyancy and shear between updrafts and environment produce an increase in turbulent intensity, resulting in the observed correlated variation of both echoes. Nevertheless, no significant correlation is detected for
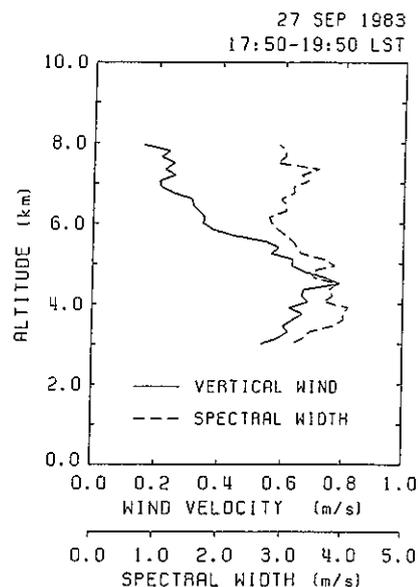

Fig. 3. Two-hour averaged profile of the vertical wind (solid curve) and the spectral width (dashed curve) observed by the MU radar.

the echoes during the rainstorm period, especially at altitudes below 8 km.

Finally, we discuss a simultaneous use of the C and Ku band echoes. The C band echo variation is generally the same as that of the Ku band echo. However, the scattering and the attenuating properties of these wavelengths are not completely identical [e.g., *Ulaby et al.*, 1981]. The dotted curve in Figure 2 (left) shows a ratio of the Ku to C band reflectivities. Although the absolute value has an error of 2–3 dB due to the difficulty in measuring both sensitivity and loss of the system, a dip is clearly detected at the altitude corresponding to the C band peak. Since the path length is relatively short, the effect of differential attenuation is negligibly small for this case. Therefore it is inferred that the dip is due to the difference in the C and Ku band reflectivities originating from the Rayleigh and non-Rayleigh scattering by large hydrometeors in the melting layer. Therefore this ratio can be used as a measure of precipitation structure.

Figure 6 shows the C band echo profile and the Z_e ratio of Ku to C band echoes for typhoon T8310. Z_e is the equivalent reflectivity factor (in $mm^6 \ m^{-3}$). When the typhoon is still far from the MU radar site, the melting layer is easily identified at an altitude of 4.2 km by the echo peak and/or by a remarkable dip of the ratio in the left panel of Figure 6. While it is rather difficult to identify the melting layer by the echo peak alone during the rainstorm period in the
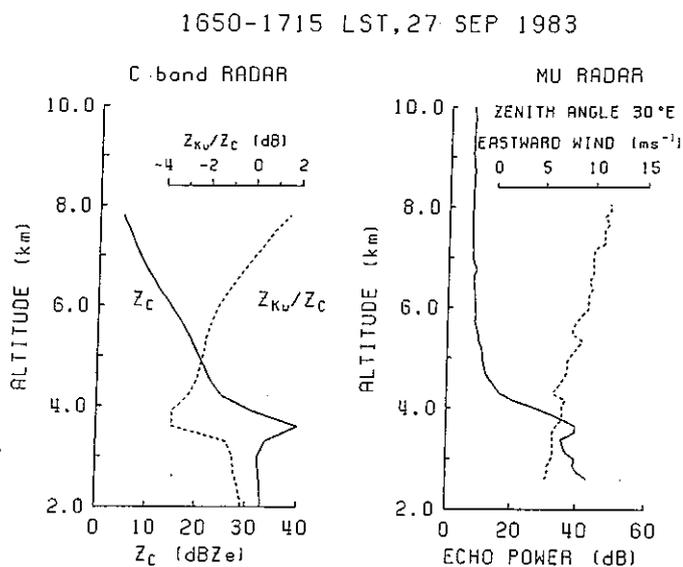

Fig. 2. Echo power profiles (solid curves) observed with the C band radar (left) and the MU radar (right). The echo powers are expressed by the equivalent reflectivity factor and a relative unit in decibels, respectively. The dotted curves are the ratio of the Ku band to the C band reflectivity factors (left), and the zonal wind speed obtained with the MU radar (right) by assuming that the vertical wind velocity is negligibly small in comparison with the horizontal wind velocity.
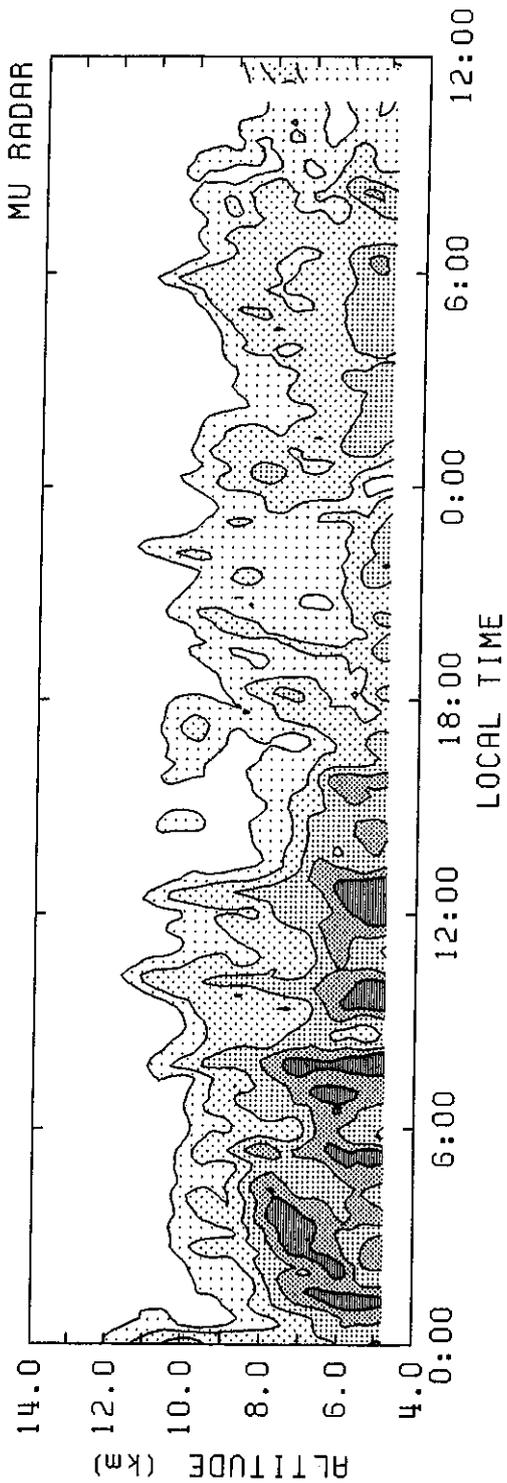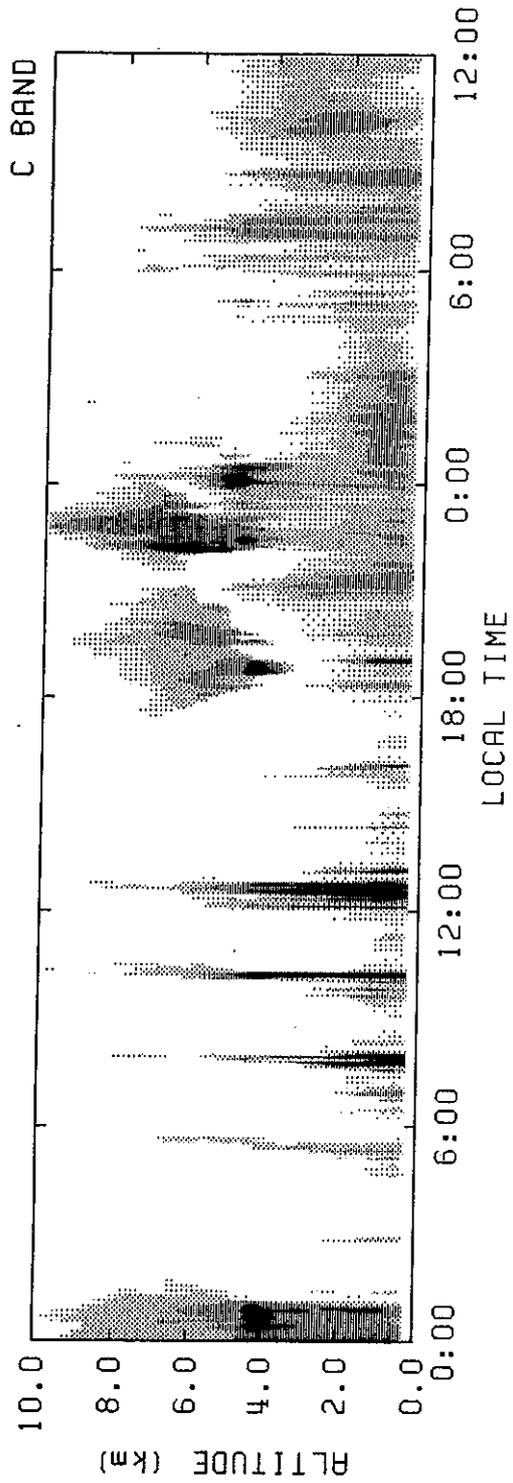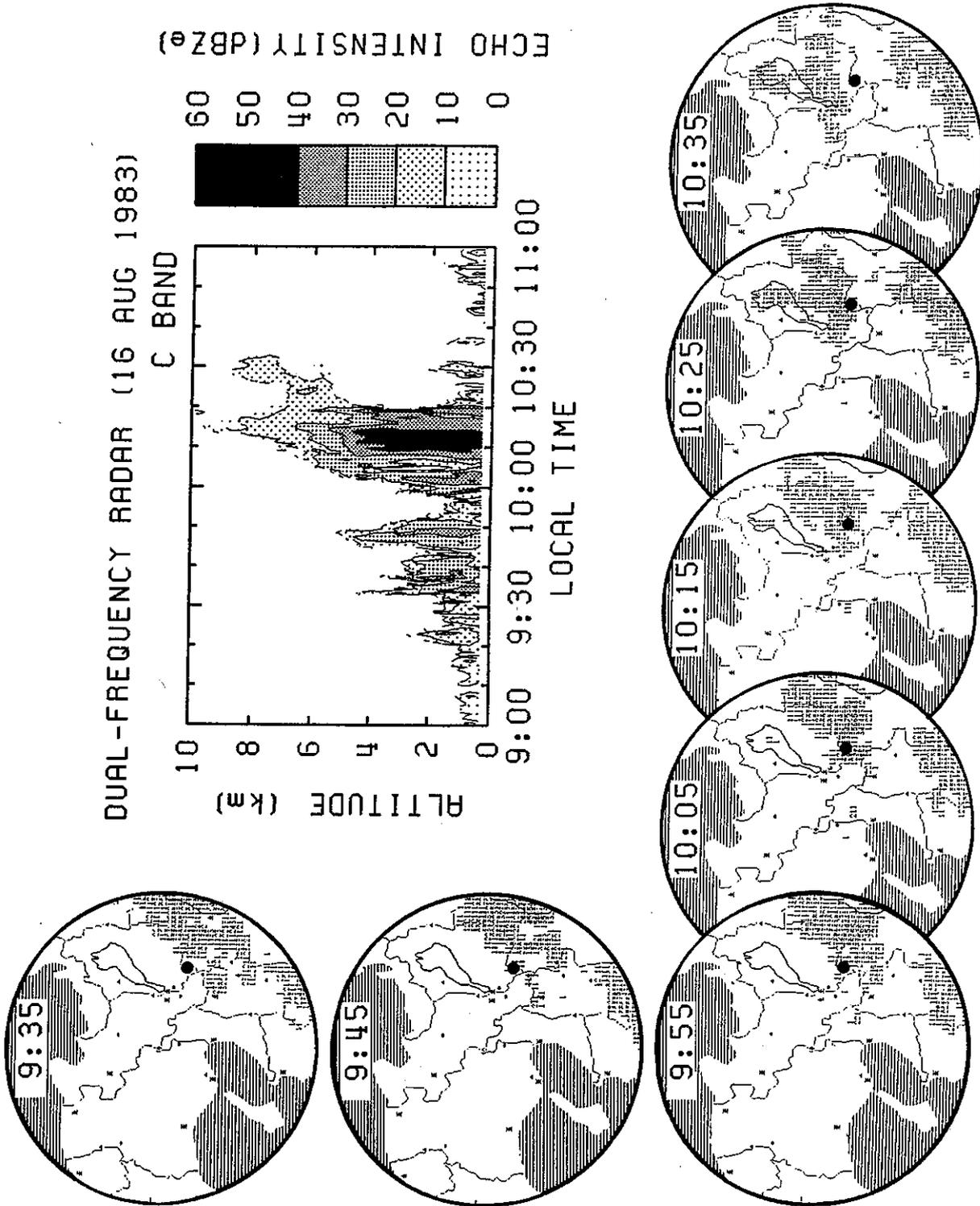
Fig. 5. Passage of a rainband observed by the C band radar at Shigaraki and the Miyama meteorological radar around 1000 LT on August 16, 1983. The time-altitude section of the C band radar (right top) is expressed by the equivalent reflectivity factor Z_e in decibels. The plan position indicator (PPI) scans obtained by the Miyama radar display a temporal variation of rainfall area every 5 min. The dot in each PPI circle shows the location of the MU radar site, while the circle center is the location of the Miyama radar. The distance between the two radars is about 70 km. The shaded area that changes with time corresponds to the rainfall over 1 mm/h (about 20 dBZ$_e$).
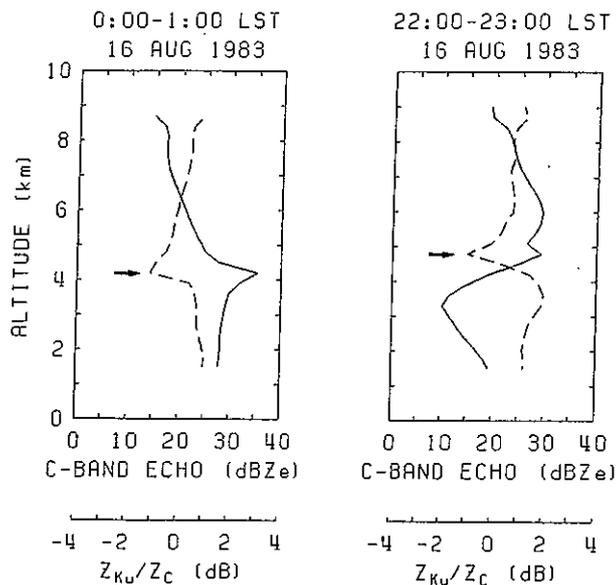
Fig. 6. Profiles of the C band echo (solid curves) and the ratio of the Ku band to the C band reflectivity factors (dashed curves) observed on August 16, 1983.

right panel of Figure 6, a sharp dip is still detectable from the ratio at an altitude of 4.8 km. These results imply that the Z_e ratio is a reliable measure for detecting the melting layer height. It is also notable that the height of the melting layer was raised by 600 m when the typhoon most nearly approached the MU radar site. This value corresponds to an increase of the atmospheric temperature by 3°–4°C at altitudes of 4–5 km during the rainstorm period. Our result coincides well with the rawinsonde observation of typhoons which shows that the temperature increases, in general, by several to ten degrees in the center of typhoons [Yamasaki, 1981].

4. DISCUSSIONS AND CONCLUDING REMARKS

We have reported a multifrequency observation of the precipitating atmosphere by using the VHF band MU radar and the microwave C/Ku band radar. It features an enhanced VHF echo, and its intensity variation depends on precipitation structures. Since the MU radar was under construction and the system adjustment was yet incomplete during the present observation, it was difficult to assess precisely the absolute intensity of turbulence from this preliminary result. Thus only a very rough estimate of the turbulence intensity is made below.

The echo power with the MU radar is estimated by the radar equations for turbulent scatter [Van-

Zandt et al., 1978] and for precipitation scatter [Probert-Jones, 1962] as follows:

Turbulent scatter

$$P = 131.0 + 10 \log C_n^2 - 20 \log R \quad \text{dBm} \qquad (1)$$

Precipitation scatter

$$P = -51.4 + 10 \log Z_e - 20 \log R \quad \text{dBm} \qquad (2)$$

where C_n^2 is the turbulent structure constant (in $\text{m}^{-2/3}$), and R is the altitude of observation (in meters).

From Figure 2 the C band equivalent reflectivity factor is approximately 33 dBZ_e below the melting layer. Supposing the same value of Z_e valid in the VHF band, (2) gives a precipitation echo of -88 dBm for the MU radar. If the minor spectral component mentioned in section 3 is recognized to be due to precipitation particles, the turbulent scatter echo at a 3-km altitude, which is some 15 dB stronger than the precipitation echo, is estimated to be -73 dBm. Accordingly, a C_n^2 value of $5 \times 10^{-14} \text{ m}^{-2/3}$ is given at that altitude by (1). From the echo power profile for the MU radar in Figure 2, the C_n^2 value decreases to $10^{-16} \text{ m}^{-2/3}$ at 5 km. These values are consistent with those reported by Crane [1981] in the altitude range considered. Also, the same order of C_n^2 values are estimated from the signal-to-noise ratio of the turbulence scatter echo [VanZandt et al., 1978]. The C_n^2 value seems to exceed $10^{-13} \text{ m}^{-2/3}$ in the rainband periods.

The origin of enhanced echoes for the MU radar could be attributed to two factors: (1) an increase of atmospheric turbulence intensity in and around convective cells and (2) an increase of reflectivity fluctuation due to the presence of gaseous water vapor. Within the intermittent rainbands where strong convective motions exist, the MU radar echoes reach up to an altitude of 12 km as shown in Figure 4. Since no significantly strong echo is observed by the MU radar corresponding to the C/Ku band radar echo during the rainstorm period, we attribute the enhanced echoes in the rainbands to the increase of atmospheric turbulence intensity. The role of gaseous water vapor is no doubt important for the MU radar echoes, but it is difficult to understand its contribution quantitatively from the present observation. In regard to long-wavelength scattering observed by such as VHF band radars, Gossard [1979] concludes

that the gaseous water vapor fluctuation is about 30 times as important as fluctuations in cloud liquid water.

Another remarkable result is the enhanced echo peak observed by the MU radar around the altitude corresponding to the melting layer in Figure 2. The dashed curve in Figure 3 shows a spectral-width profile of MU radar echoes. Since the spectral broadening due to the background wind shear and the finite beam width is less than 1 m s^{-1} in the present observation, the observed spectral width is considered as a good measure of turbulent intensity [e.g., *Cunnold*, 1975]. However, it shows no significant change in the melting layer. Since the ice particles release their latent heat at the melting layer, the temperature fluctuation is expected to be large there. Thus the peak observed by the MU radar is attributed to an increase of refractive index fluctuation enhanced by the temperature fluctuation rather than to that of the turbulent intensity. Above the melting layer, however, ice particles can produce reflectivities comparable to those of the liquid water below, though the turbulent intensity should be lower. Ice particle contamination therefore may be present in the MU radar echoes. Since the fall velocity of ice particles ranges from 1 to 2 m s^{-1}, the contamination may bias the vertical velocity values shown in Figure 3 and may cause the relatively large spectral width evident in the same figure.

Our preliminary observations show a possibility of studying the atmospheric and precipitation echoes separately by using the VHF radar and the microwave radar. The observational results suggest a potential importance of the multifrequency observation of the troposphere for the study of the scattering mechanism and the detailed structure of precipitating atmosphere. Clearly, more quantitative discussions based on the radar observations of various weather conditions are desirable in the near future.

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