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Direct measurement of air and precipitation particle motion by very high frequency Doppler radar

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Microwave meteorological Doppler radars are the most efficient tool for understanding the dynamical properties of precipitating systems in the troposphere[1]. However, these radars do not directly observe ambient air motion, but rather the velocity of precipitation particles within a particular region. We have recently completed very high frequency (VHF) Doppler radar at Shigaraki, Japan (34.85° N, 136.10° E) which has enabled the three-dimensional motion of both air and precipitation particles to be observed simultaneously. In particular, it enables vertical air motion as well as precipitation fall speed to be directly observed. Doppler broadening of the precipitation echo reveals features which, when above the melting layer, are characteristic of snowflakes and, when below this layer, are characteristic of raindrops. Sensitive VHF (and, most likely, ultrahigh frequency, UHF) Doppler radars equipped with fast-beam steerability open new possibilities for the investigation of the dynamical properties of precipitation particles in close combination with ambient air motion.

MST (mesosphere-stratosphere-troposphere) radars are sensitive, high-power VHF/UHF Doppler radars that can detect clear-air (refractive-index) fluctuations or turbulence in the middle atmosphere (altitude range of 10-100 km[2,3]). Received echoes are Doppler shifted because of radial motion of the clear air turbulence (CAT). The mean Doppler shifts acquired in three different directions provide three-dimensional velocity of CAT. This velocity is shown to be equal to the ambient air motion by comparison with measurements obtained by conventional techniques that use rawinsondes or meteorological rockets[2,4]. MST radars have rarely been used for the observation of tropospheric meteorological phenomena, with the exception of a few short-term studies of frontal zones[5] and thunderstorms[6].

Radar reflectivity of the inertia subrange turbulence in clear-air regions is dependent on the power law of $\lambda^{-1/3}$ (where λ is the radar wavelength). The reflectivity in the VHF band is observed to be within the range of 10^{-18}-10^{-15} cm^{-1} in the troposphere and lower stratosphere[7]. The power law yields a reflectivity of 5×10^{-18}-5×10^{-15} cm^{-1} in the microwave frequency band.

On the other hand, an estimate of the radar reflectivity for raindrops in the VHF band, for example, at 50 MHz, gives 10^{-19}-10^{-16} cm^{-1} for a precipitation rate of 3×10^{-1}-3×10 mm h^{-1}, assuming the Marshall–Palmer drop-size distribution function (T. Yokoyama, personal communication). The reflectivity of the melting layer (or bright band) is ~50 times larger than that of raindrops. Thus, the reflectivity of precipitation particles at 50 MHz is within the range of 10^{-19}-5×10^{-15} cm^{-1}, which is essentially the same range as that of CAT. This value is nine orders in magnitude smaller than that of microwave radars.

Because the reflectivities of both CAT and precipitation particles at 50 MHz are in the same range, sensitive 50-MHz MST radars are expected to detect simultaneously both types of echoes from precipitating air. This contrasts with the situation found in microwave radars, where precipitation echo is much more dominant than CAT echo. This is because the microwave reflectivity of precipitation particles is 4–12 order of magnitude larger than that of CAT.

The middle and upper atmosphere radar (MU radar) located at Shigaraki, Japan is a 46.5-MHz radar using an active-phased array system[8]. It is composed of 475 Yagi antennas and an equivalent number of solid-state power amplifiers (transmitter-receiver (TR) modules)[9]. Each Yagi antenna is driven by a

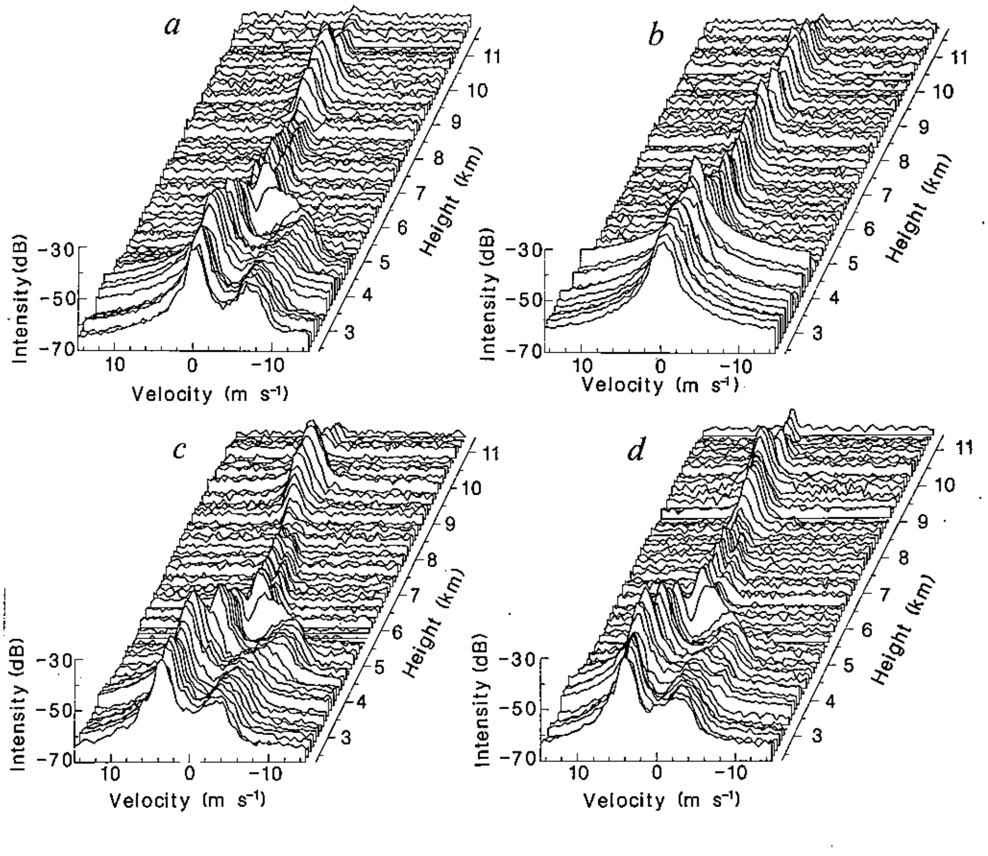

Fig. 1 Doppler velocity spectra plotted against altitude obtained in the vertical direction by the MU radar, Shigaraki, Japan. The observational periods are: *a*, 0845–0851 JST (Japan Standard Time) and *b*, 0750–0756 JST on 22 August 1984. The ordinate is relative power in decibels with an arbitrary reference level. The abscissa is represented in terms of radial (vertical) Doppler velocity (Note that the sign is given in the reverse direction.) The positive and negative speeds correspond to departure from and approach to the MU radar, respectively. This usage is the opposite of the meteorological convention. *c*, *d*, Same as *a*, except *c* is northward and *d* is the eastward beam direction. The spectra are plotted against radial Doppler velocity.

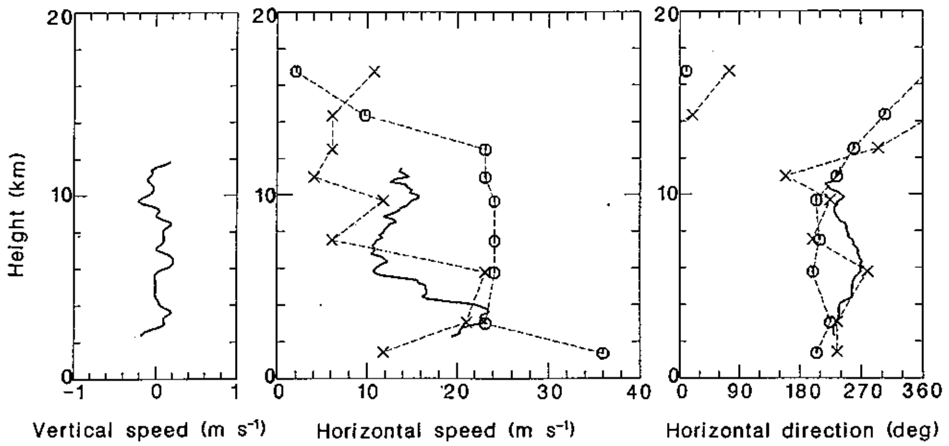

Fig. 2 Altitude variation of vertical and horizontal components of air motion estimated from the major spectral component present in Fig. 1*a*, *c*, *d* (solid line). Positive vertical speed indicates updraft of air. Horizontal velocity is given in terms of wind speed and direction following the meteorological convention. The beams in the northward and eastward directions that are tilted 15° off from the zenith sample echoes at a range 100–300 m lower in altitude than that of the vertical beam. This altitude difference is taken into consideration when determining three-dimensional velocities by interpolating the vertical speed at the corresponding altitudes with a spline function. Comparisons are made with horizontal winds measured by rawinsondes launched from Shionomisaki, 150 km to the south of Shigaraki, and from Wajima, 250 km to the north, indicated by crosses and circles, respectively.

TR-module with peak output power of 2.4 kW. The nominal peak and average radiation powers of the whole system are 1,000 and 50 kW, respectively. This system makes it possible to steer the antenna beam up to 30° from the zenith in each interpulse period.

Recently, we have observed precipitating air in the troposphere, using the fast beam steerability of the MU radar. We present the preliminary results of a short-term study which was successfully conducted on 22 August 1984. The full capabilities of the MU radar system were only partially employed. A nominal beam width of 4.0° and peak transmitted power of 760 kW were selected. Pulse width is 1.0 μs, which corresponds to a range resolution of 150 m. Echoes were sampled above 2.4 km from ground level (375 m above sea level) to obtain the delay required to protect the TR modules. The beam was steered during each interpulse period of 400 μs sequentially to three different directions: zenith and 15° away from the zenith to the north and east. At an altitude of 5 km, the distance separating the off-vertical beams from the vertical beam was 1.3 km.

The bipolar video signal from each beam was sampled at 64 points spaced in the region from 2.4 to ~12 km aloft at 150-m intervals. 128 point complex fast Fourier transforms were calculated in real time to obtain Doppler velocity spectra for each 7.7-s period. The resulting power spectra were averaged for ~1 min before being written on magnetic tape.

Figure 1*a*, *b* shows typical altitude variations of the Doppler velocity spectra obtained in the vertical direction during periods (*a*) with and (*b*) without perceivable precipitation on the surface. Each spectrum is the average of a 6-min period. The surface rainfall rates during these periods were 1 and 0 mm h^{-1}, respectively, as observed by the Japan Meteorological Agency at their facility in Kinose, 6.9 km north of the MU radar. The rainfall is classified as being of the weak stratiform type.

Of the spectral components illustrated in Fig. 1, the minor one with comparably large negative (downward) Doppler shift exists only when precipitation is observed (Fig. 1*a*), whereas the major one with near zero Doppler shift appears persistently irrespective of precipitation.

Figure 1*c*, *d* clearly illustrates the correspondence of these spectral components to those obtained in the northward and eastward beam directions. For the major spectral component, horizontal velocity is calculated by assuming the presence of a uniform velocity field within the region illuminated by the three beams (Fig. 2). The result is compared with the horizontal wind velocity measured by rawinsondes launched from Shionomisaki, ~150 km south of Shigaraki, and from Wajima, 250 km north. The radar-deduced horizontal velocity is consistent with the meteorological wind field, the difference between the three locations is in accord with that usually observed below 12 km (ref. 9). The vertical velocity shown in Fig. 2 is directly measured by the vertical beam.

Below 5 km, the vertical speed of the minor spectral component is ~7 m s^{-1}, whereas it is <2 m s^{-1} above 6 km (Fig. 3). This change in the altitude range of 5–6 km is quite certain, because the minor spectral component clearly separates from the major one $\leq$8.5 km. It merges with the major component $\geq$9 km.

During periods when rainfall was perceived at the surface level, the melting layer was detected at 5.4 km by a dual frequency (C/Ku band) microwave radar located next to the MU radar[10]. Both spectral components of the 46.5-MHz radar echo are also enhanced at this altitude; the enhancement of CAT echo presumably results from a signature in the vertical

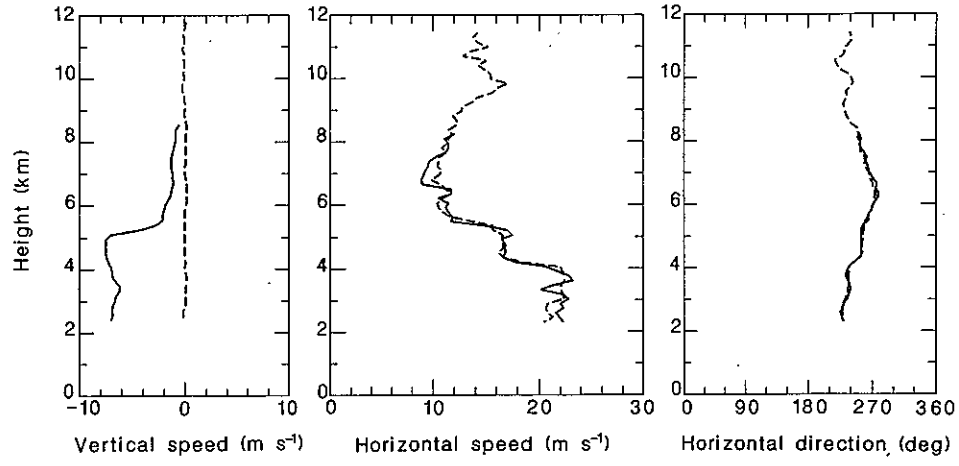

Fig. 3 Mean vertical (fall) speed and horizontal velocity of precipitation particles plotted against altitude estimated from the minor spectral component in Fig. 1*a*, *c*, *d*. Positive vertical speed indicates updraft. The ambient atmospheric wind velocity shown in Fig. 2 is also given by dashed lines for comparison. Precipitation particle motion is not given above 8.69 km, because the spectral component due to precipitation particles merges with that of ambient air origin above this altitude.

temperature gradient in the melting layer.

The spectral width of the minor spectral component varies by more than three times near 5-6 km, ranging from 0.8 m s^{-1} above and 2.7 m s^{-1} below the melting layer. It is roughly constant elsewhere.

The above features concerned with vertical speed and spectral width are consistent with those of precipitation particles observed with meteorological Doppler radars[1,11]. This would indicate that the minor spectral component of the MU radar echo originates from precipitation particles, that is, snowflakes above and raindrops below the melting layer. Note that, by using Doppler velocity spectra obtained by the vertical beam of the MU radar, drop-size distribution functions can be directly determined, obviating the need to make assumptions concerning vertical air motion. By and large, this type of direct measurement is not feasible using conventional meteorological radars.

Mean horizontal speed of precipitation particles is inferred in the same way as that of air (Fig. 3). The precipitation particles of the weak stratiform rain in the present example generally follow the ambient air motion. However, a detailed investigation of the differential motion would certainly be of interest.

In the present observation of a weak stratiform rain, vertical beam and two off-vertical beams with 15° off-zenith angles were used. This assumes that the wind field is uniform over the area containing the three beams, a region ~2 km at an altitude of 5 km. The assumption of wind field uniformity is necessary in monostatic wind vector measurements. However, it may be a source of error in convective storm environments. Depending on spatial scales of meteorological phenomena observed, a combination of three (or more) beams can be arbitrarily selected from the 1,657 directions within 30° off-zenith angle to which the MU radar can steer its beam. To provide significant three-dimensional motion, minimum beam separation can be reduced to beam width, or 350 m at an altitude of 5 km. This spatial resolution is sufficient to enable the observation of precipitating systems of a moderate size and larger.

Although the MU radar is capable of observing a substantial part of the deep and strong updrafts associated with frontal passages or convective storms which generally extend above an altitude of 10 km, it cannot provide the information concerning activities in the planetary boundary layer. Therefore, simultaneous observations with microwave meteorological radar and/or other conventional instruments (such as the rawinsonde) will have an important supporting role in future investigations of the tropospheric meteorological phenomena which employ the MU radar.

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