Vertical profiles of snow and rain in Tokyo, Japan, examined by Micro Rain Radar (MRR)

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Abstract

This study used a Micro Rain Radar (MRR) system installed on the roof of the Institute of Industrial Science at the University of Tokyo to examine precipitation on 31 December 2004. A passing cyclone from the southern coast of Japan had brought snowfall that had then changed to rainfall exceeding 6 mm/hour. The MRR is a low-cost, K-band Doppler radar system that can detect vertical velocities using Doppler radar reflectivity. Typically, MRR has been used to observe rainfall, and there are no previous reports of MRR examinations of snow and rain clouds, especially in an urban area. In this paper, we report on MRR-based determinations of the cloud properties that brought snow cover to Tokyo in late 2004. This study shows that vertical spectral observations by MRR are useful in distinguishing snow and rain.

1. Introduction

Classification of surface precipitation (snow, rain, or a mixture of precipitation types) is important for managing urban transportation. Tokyo had not experienced snow cover on 31 December for 24 years prior to our study. The precipitation began as snow and then changed to rain. Typically, snow falls on Tokyo when a cyclone center passes over the southerner than Hachijyo Island (about 280 km SE of Tokyo). However, the snow observed in this study originated from a cyclone that passed just south of the Japan coast. Rain followed the snow under low-temperature conditions of nearly 0ºC at ground level. The associated precipitation cloud was thus difficult to classify according only to surface conditions.

Several instruments can assist in classifying precipitation. Ralph et al. (1995), for example, used an ultrahigh-frequency (UHF), vertical-pointing radar (a wind profiler), but wind profilers are too large to operate in urban areas. Another option is the Precipitation Occurrence Sensor System (POSS; Sheppard and Joe, 2000), which is a low-cost, simple Doppler radar. The POSS focuses on precipitation at the surface and does not determine a vertical profile. Thus, only precipitation near the POSS installation point can be classified. However, if we can infer the vertical position of the melting layer, it is then not difficult to draw the boundaries between snow, rain, and a snow/rain mixture based on data taken at the ground surface.

Since August 2003, our study team has investigated precipitation clouds using a Micro Rain Radar (MRR; METEK GmbH, Elmshorn, Germany) system installed on the roof of the Institute of Industrial Science at the University of Tokyo, located in Meguro Ward of southwestern Tokyo. A MRR is a small, low-cost instrument that can detect the radar reflectivity of each Doppler spectrum (Loffler-Mang et al., 1999). Raindrop-size distributions can then be calculated at each vertical level using the equation by Gunn and Kinzer (1949).

In Europe, MRR is mainly used to investigate rain, and various results have been reported. Peters et al. (2002), for example, compared MRR observations with rain gauge data to characterize a high-frequency observation period, and reported sample data that included those from the bright band. Wagner et al. (2004) described vertical profiles of raindrop-size distributions using both MRR and calibrated C-band weather radar data.

However, no previous reports have discussed the use of MRR for simultaneous observations of rain and snow. This study used MRR to examine the vertical structure of the precipitation clouds that brought snow, rain, and a snow/rain mixture under low-temperature conditions to Tokyo on 31 December 2004. This application of MRR was useful in detecting the melting layer and improving the precipitation classification algorithm.

2. Synoptic situation and Data

The MRR is a vertical-looking, frequency-modulated continuous-wave (FMCW) Doppler radar with a K-band wavelength of 1.2 cm. The MRR can detect radar reflectivity from falling precipitation particles in 29 bin steps up to 6000 m. We observed the precipitation for these 29 levels at 100-m intervals up to a height of 2900 m, which corresponds to the low-cloud top in winter. The data sampling interval was 1 min.

Double-cyclone systems were located over Japan's main island of Honshu on 31 December 2004. The southern cyclone, which was located near Shikoku Island at 09:00 JST, was moving faster than the northern cyclone; the cyclones crossed paths at 12:00 JST. At that time, the southern cyclone was located just above Tokyo according to the weather map provided by the Japan Meteorological Agency (JMA). Heavy rainfall is expected from such kind of double-cyclone systems that the southern move faster than the northern; the maximum precipitation was recorded in the Ootemachi area of central Tokyo (6.5 mm/hour at 15:00 JST)

The MRR radar reflectivity observations showed the snow and rain in this situation well, although when snow accumulated on the antenna, signals from snow were attenuated. Overall, based on strong characteristic reflectivity in the time–height cross sections, two precipitation periods were revealed by the MRR observations:

1) The snow period from 12:30 to 13:30 JST
2) The rain period from 15:15 to 16:00 JST

3. Snow Cloud Observations

3.1. Spectral reflectivity of snow clouds

Figure 1 shows the radar reflectivity index for the Doppler spectrum at each height averaged over the snow period. The vertical axis of Figure 1 represents the density amplitude of the radar reflectivity index (Z), corresponding to the Doppler velocity. During snowfall, characteristic changes in the Doppler spectra allowed

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us to define three layers in the snow cloud. The thick solid lines in Figure 1 indicate the boundaries between these layers. Layer S1 ranged from 2900 to 2000 m in height. The peak of the Doppler spectrum gradually increased downward, and the distribution of the Doppler velocity remained generally steady. At the peak, the Doppler velocity was approximately 1 m/s. Layer S2 was between 2000 and 1200 m in height. This layer had the largest increase in downward radar reflectivity, and data indicated particle generation and growth. The peak of the Doppler spectrum increased in a downward direction, and the distribution of Doppler velocity became broader. Doppler velocity corresponding to the peak gradually shifted from 1 m/s at a height of 2000 m to 2 m/s at 1200 m. Layer S3 was between the surface and 1200 m. The peak of the Doppler spectrum decreased quickly, and the distribution of the Doppler velocity remained as broad as that found at 1200 m.

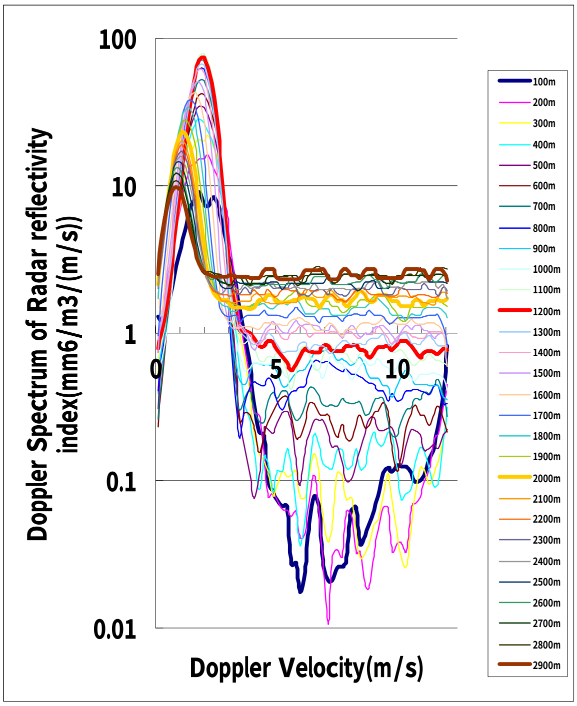

Fig. 1. Doppler spectrum of the radar reflectivity index at each observation level, averaged over the snow period (12:30-13:30JST, 31 December 2004). Bold lines indicate the boundaries of each layer.

3.2 Comparison of the snow cloud and meteorological elements

Figure 2 shows the vertical profiles of temperature and relative humidity estimated by a mesoscale model (MSM; JMA) for 12:00 JST, 31 December 2004 (initial time 09:00 JST) at the grid (35.66ºN, 139.7ºE) nearest the MRR observation site. The black line denotes the air temperature, and the red line indicates the relative humidity. We consider these data reliable for discussion purposes because the location of the southern cyclone by the above model and as indicated by the JMA weather bulletin map coincided at this time.

Figure 2 also suggests a frontal zone from 850 to 900 hPa and nearly saturated conditions from 700 to 850 hPa. Murakami et al. (1992) noted the existence of a rapid depositional growth layer with water saturation just above a frontal zone. Therefore, in layers S1 and S2, snow particles likely grew by ice deposition.

Precipitation increased more in layer S2 than in layer S1. The temperature in layer S2 ranged from –4 to –1ºC. Hobbs et al. (1974) reported that temperatures near 0ºC are favorable for the aggregation of ice particles. Thus, the proposal that deposition dominated in layer S1 and aggregation dominated in layer S2 is consistent with the results of previous studies.

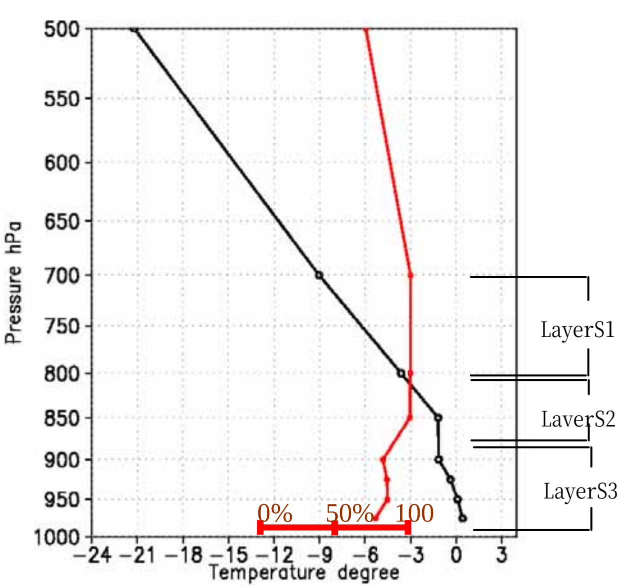

Fig. 2. Vertical profile of temperature and relative humidity from MSM prognosis to 12:00 JST (initial time, 09:00JST, 31 December 2004) at the 35.66N and 139.7E grid. The black line denotes temperature and the red line denotes relative humidity.

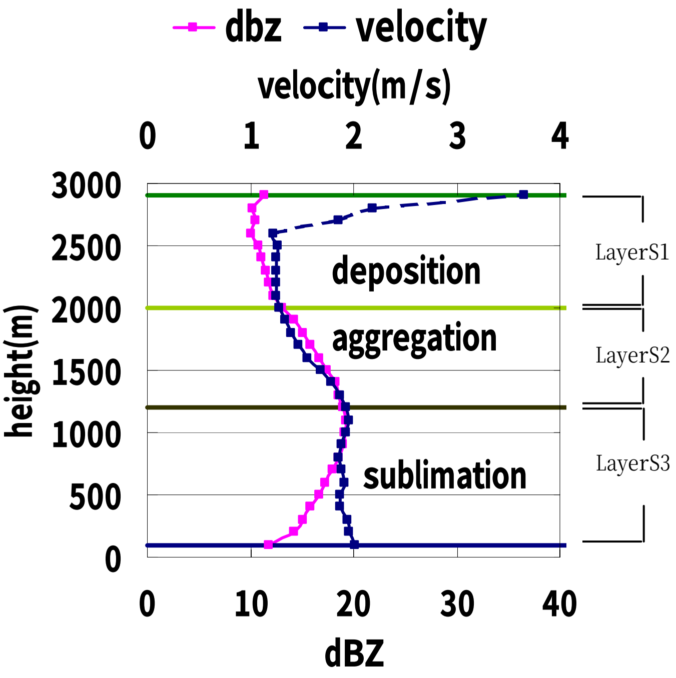

Fig. 3. Doppler spectrum of the radar reflectivity index at each observation level, averaged over the snow Period(12:30-13:30 JST 31 December 2004).

As mentioned previously, below 1200 m, the spectrum peak decreased downward. Figure 2 suggests that the layer between 900 hPa and the surface was quite dry. Many snow particles may have sublimated in this dry area of layer S3. Figure 3 summarizes the vertical profiles of the radar reflectivity index and the Doppler speed averaged over the snow period for the inferred precipitation process. Those values were calculated from the radar reflectivity spectra shown in Figure 1. An area of large Doppler velocity from 2700 to 2900 m was identified near the MRR observation limit.

These large values may include noise associated with the large Doppler velocity. Radar reflectivity was weaker during the snow period; the maximum value was 20 dBZ at a height of 1200 m, where snow particles grew rapidly. From 1200 m to the surface, Doppler velocity remained unchanged (about 2 m/s). However, the radar reflectivity index decreased gradually toward the surface. A Doppler velocity of less than 2 m/s is consistent with the typical falling-snow velocity observed by Ralph et al. (1995) using a UHF-band wind profiler, and we can thus infer that precipitation above the ground surface was snow.

4. Rain Cloud Observations

4.1 Spectral reflectivity of rain clouds

Figure 4 shows the same properties as Figure 1 but for the rain period. We averaged each value by shifting 100 m (the bin-range minimum) each 7 min until the end of the period (16:00 JST) because the height of the strong echo level ascended by 700 m over 45 min, as shown in the time–height cross section of radar reflectivity (Supplement 2). As a result, the echo top was at almost the same level throughout the averaged period. The heights shown in Figure 4 are those for 16:00 JST. We were unable to clearly define the bright-band structure during the observation period. Clouds during this period were considered convective.

We were able to define four typical layers using the Doppler profiles in Figure 4. Layer R2 showed the greatest increase in radar reflectivity, which suggests the generation of high precipitation. Layer R1 extend from 2900 to 1900 m; the Doppler spectrum peak increased gradually in a downward direction, and the distribution of the Doppler velocity broadened slightly. Layer R2 was from 1900 to 1500 m; the Doppler spectrum peak increased, and the Doppler velocity distributions were broader than those in layer R1. Layer R3 was from 1500 to 1000 m; the peak of the Doppler spectrum remained large, and the corresponding Doppler velocity shifted from 4 to 8 m/s. Layer R4 extended from 1000 m to the surface; its Doppler spectrum peak remained large, and velocity distributions showed little change.

4.2 Comparison of the rain clouds to meteorological elements

Figure 5 shows the vertical profiles of temperature and relative humidity from the MSM with initial conditions at 15:00 JST on 31 December 2004. As shown in the figure, the 0° level was at 850 hPa; below this level, the layer above the surface was stable. The boundary of this stable layer, 850 hPa, corresponded to the upper boundary of layer R3, which was determined using MRR data to be the melting layer.

In layer R1, a small peak in reflectivity appeared at approximately 1–2 m/s and resembled a composite of layers S1 and S2. The precipitation particles in this layer were snow. Increased radar reflectivity appeared to correspond to not only the emergence but also the growth of snow particles. In layer R2, a major spectrum appeared around the area where Doppler velocity exceeded 2m/s (the typical velocity of snow) below 1900 m. The peak in the Doppler spectrum increased downward from 1900 m. Characteristically, the distribution of the spectrum became broad.

Ralph et al. (1995) set threshold values for hydrometers based on UHF-band wind profiler observations; according to their analyses, 3 m/s was the lower boundary for rain. Therefore, most of the precipitation in layer R2 appears to have been snow, a conclusion consistent with the temperature profile. However, there were also particles falling faster than 3 m/s, suggesting that some of the snow was starting to melt at this height. The increased radar reflectivity and Doppler velocity indicates that snowflakes aggregated at the 0° level and that partially melted snow particles fell faster and became larger with accretion from the surrounding snowflakes or cloud drops.

Layer R3 had increased Doppler velocity but little change in the radar reflectivity index. The peak value of the spectrum shifted from 4 m/s at 1500 m to 8 m/s at 1000 m, as shown in Figure 4. However, the magnitude of the spectrum changed little. Drummond et al. (1996) mentioned that reflectivity was the same above and below the melting layer if there was no breakup, aggregation, or growth of precipitation particles during melting. The increased Doppler velocity found by the present study suggests that precipitation particles were melting in layer R3. The spectrum changed little in layer R4. The properties of the rain drops seemed to retain the same characteristics as those observed at the bottom of layer R3.

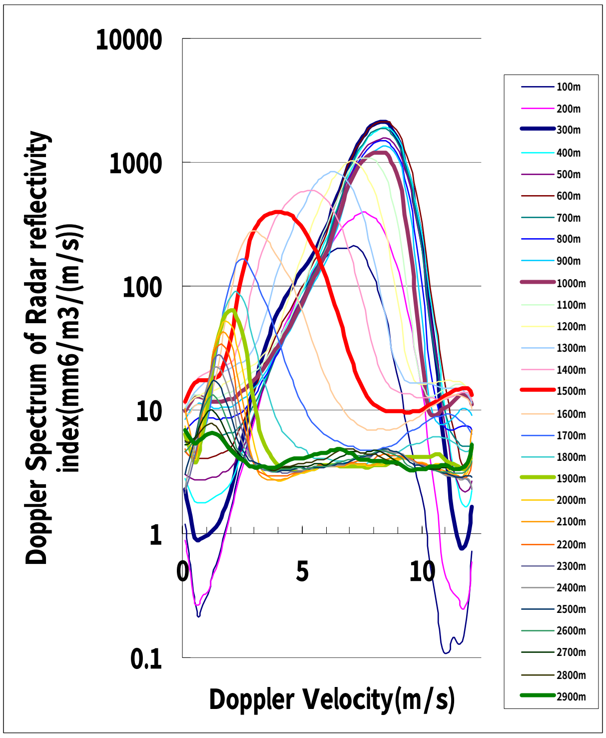

Fig.4. Same properties as Figure 1, but for the rain period (15:15-16:00 31 December 2004). The height was referred to 16:00.

Figure 6 shows the same properties as those in Figure 3, but for the rain period. A large Doppler velocity was evident in the high layer from 2900 to 2200 m. To calculate vertical velocity, the observed wind range was set from 0 to 12.1 m/s. We may have overestimated the Doppler velocity during this period, by including large Doppler velocity as well as a Nyquist velocity of negative value (upward velocity).

Using the MRR-observed radar reflectivity spectra, we investigated the change from snow to rain during the observed precipitation event. These data also suggested a melting layer. In this case study, layer R3 and part of layer R2 were indicated as melting layers. However, delineating a clear boundary between liquid water and ice water contents proved difficult. Ralph et al. (1995) set 3 m/s as the lower velocity boundary for rain. In this study, there were likely raindrops with a falling velocity of 3 m/s. Raindrops with diameters of approximately 0.7 mm were falling at the same velocity, as determined by Gunn and Kinzer's equation (1949).

However, graupel often has a falling speed that exceeds 3 m/s. Future research should devise an algorithm that can detect a boundary between rain and snow using drop-size distributions observed by MRR and determine the ratio between rain (liquid water) and snow (ice water).

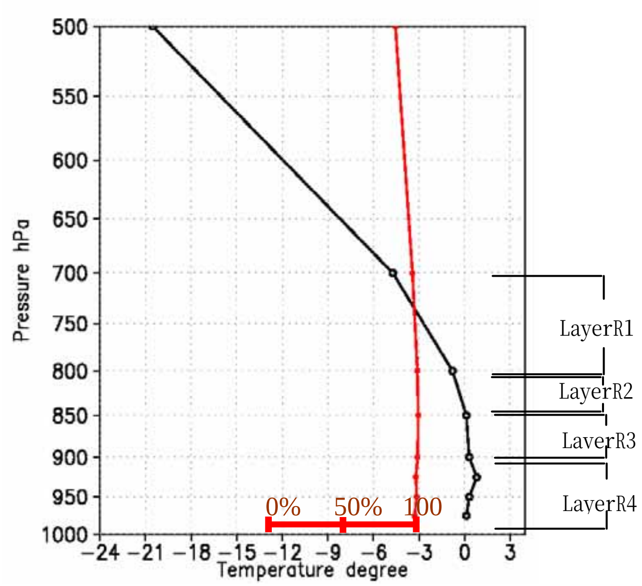

Fig. 5. Same properties as Figure 2, but for MSM data taken at 15:00 JST 31 December 2004.

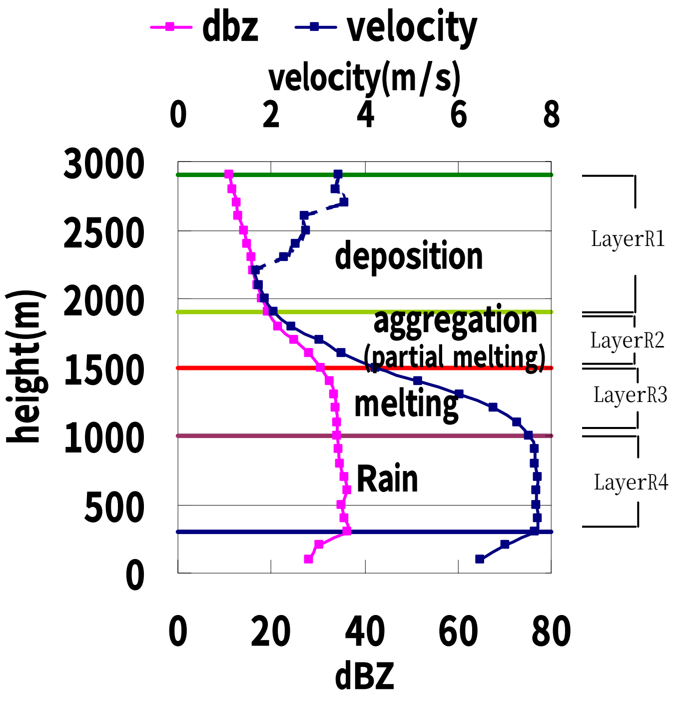

Fig.6. Same properties as Figure 3, but for the rain period (15:15-16:00 JST 31 December 2004). The vertical axis represents the relative height corresponding to the 3000m determined at 16:00 JST.

5. Summary

A precipitation cloud that was over Tokyo on 31 December 2004 was analyzed using MRR observations of the Doppler spectrum. Snow turned to rain during the observed precipitation event. The JMA had forecasted precipitation types using air temperature and relative humidity at the surface and in the upper atmosphere. Matsuo et al. (1981) reported that errors can occur if an inversion exists at the surface. The MRR can detect the melting layer in such an inversion, as shown in the rain period results of this study. Furthermore, snow-particle growth was well represented by the low Doppler velocity observed by the MRR during the snow period. Therefore, vertical observations using low-cost MRR may be useful in classifying precipitation. By using several sets of MRRs placed in different locations, we should be able to detect the spatial distribution of snow/rain areas.

Acknowledgements

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Comments and supplements

1. MRR observations on the roof of the Institute of Industrial Science at the University of Tokyo (Supplement 1).
2. The Japan Meteorological Agency Weather Bulletin map at 15:00 JST, 31 December 2004 (Supplement 2).
3. Time–height cross section the radar reflectivity index and vertical Doppler velocity on 31 December 2004 (Supplement 3).

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