Vertical profiles of winter precipitation in Tokyo, Japan, examined using Micro Rain Radar

Tomoki Koshida[1], Shin Miyazaki[2], Taikan Oki[3], Shinjiro Kanae[3] and Kei Yoshimura[3]

[1] *IDEA consultants Inc., Yokohama, Japan*
[2] *Center for Global Environmental Research, National Institute for Environmental Studies, Ibaraki, Japan*
[3] *Institute of Industrial Science, The University of Tokyo, Tokyo, Japan*

Abstract

The process of melting of precipitation particles is important to determine the type of precipitation (rain, snow, or a mixture) on the ground. We used a Micro Rain Radar (MRR) system to examine precipitation in Tokyo on 31 December 2004 in focusing to the melting of particles. The precipitation was brought by a passing cyclone from the southern coast of Japan as snowfall that subsequently changed to rainfall. The MRR is an inexpensive K-band Doppler radar system that can detect vertical velocity using the Doppler spectrum.

The observed Doppler velocities and variance of the Doppler spectrum were appropriate indicators of precipitation type. In a comparison of the variance at melting conditions near the surface to that in the bright band, the former was smaller than the latter. The difference seemed reflect of strength of local vertical mixing condition. Then upward transportation of large melting particle from the bottom seemed important contribution magnified radar reflectivity in bright band, while the change of dielectric constant during melting have been considered as the most significant contribution.

1. Introduction

The study of melting particles is useful in the classification of surface precipitation types. If one wishes to know the locations where snow is falling to the ground, the use of surface temperature and relative humidity is an easy approach (Matsuo *et al*. 1981). However, a classification according to surface conditions alone is problematic because the transformation from snow to rain may occur in the thick isothermal layer at temperatures near 0ºC.

Melting particles have been studied in relation to the radar bright band (hereafter BB). Fabry and Zawadski (1995) observed precipitation clouds using X-band vertical pointing radar (hereafter VPR) with a Wind Profiler (here after WPR) in Montreal, Canada. They determined the property of bright bands and the quantitative calculation of radar reflectivity factors around a melting layer and pointed out the importance of processed other than typical BB explanation; effects associated with the shape and density of melting snowflakes. Their X-band VPR had no Doppler spectrum, so a WPR used even it is 60km apart from VPR. Ralph et al. (1995) reported the classification of a precipitation threshold in the study of precipitation observed using a WPR. They detected the melting layer using Doppler velocity and the variance of Doppler velocity. Large variance is characteristic of the melting layer in a MCS (mesoscale convective system).

Without remote sensing techniques, in situ observation via airplane is almost the only method to detect melting particles and air conditions. Stewart et al. (1984) suggested the ice particle multipication suspected near -5℃ and they pointed high-concentrate particles were necessary to make large particles for the BB in stratiform rain cloud comparing with C-band radar. Willis and Heymsfield (1989) studied the transformation from solid water to liquid water by going through the cloud of MCS. They mentioned the isothermal layer was made by diabatic cooling of melted small ice particles and the large melting particles surviving below the isothermal layer were accounted for BB.

The MRR (METEK GmbH, Elmshorn, Germany) used in this study was a small, inexpensive instrument that can detect the radar reflectivity of each Doppler spectrum. It has the same VPR that was developed in the 1960s to calculate raindrop size distributions at different vertical levels. MRR is frequency-modulated continuous-wave (FMCW) radar and uses a K-band wavelength of 1.2 cm. So far, MRR has mainly been used to investigate rain. For example, Peters *et al*. (2005) compared MRR observations with rain gauge data to characterize the vertical profile of rain below the BB.

We show the result of the MRR examination of the vertical structure of the precipitation clouds at temperatures near 0°C.

2. Synoptic Situation and Data

The precipitation that we observed began as snow and then changed rapidly to rain. This is one of the typical snowfall situations for Tokyo, when a cyclone center passes just south of the Japan coast. A double-cyclone system was located over the main Japanese island of Honshu on 31 December 2004. The southern cyclone, which was located near Shikoku Island at 0900JST, was moving faster than the northern cyclone. That cyclone caught up with the latter at 1200JST, and overtook at 1500JST, and located close to Tokyo (Fig. 1). By the surface observation, at 1120JST the snow was observed , Ootemachi, Tokyo where is about 7km away from MRR. And the maximum precipitation there during this event was recorded 6.5 mm/h. This precipitation seemed to be brought by stratiform cloud located just north of the cyclone, not by the cold front which has often strong convection, judging by GOES-9 IR picture 1500JST.

The MRR detects the radar reflectivity factor (hereafter Ze) from falling precipitation particles. We observed the precipitation for 29 levels at 100-m intervals up to a height of 2900 m, to observe a low melting layer in winter. The data sampling interval was 1 min.

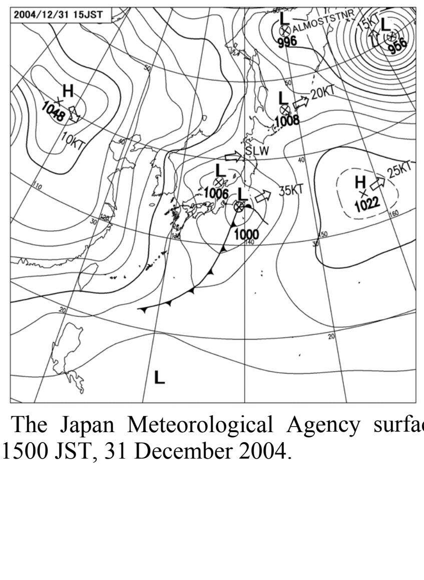


Fig. 1. The Japan Meteorological Agency surface weather map at 1500 JST, 31 December 2004.

Corresponding author: Tomoki Koshida, IDEA Consultants Hayabuchi 2-2-2, Tsuzuki, Yokohama, Kanagawa Prefecture, Japan 224-0025
E-mail: koshida@ideacon.co.jp

In this precipitation event, Ze observed by the MRR clearly showed the characteristics of snow and rain, except when snow accumulated on the antenna and temporarily attenuated the signal. The two precipitation regimes, just after removing the snow from the antenna, were selected from the MRR observations as cases for analysis.

A) The snow regime from 1340 to 1350 JST, and
B) The rain regime from 1515 to 1525 JST.

3. Snow Observations

3.1 Spectral reflectivity of snow clouds

Figure 2 shows the vertical profile of the mean velocity, the variance of the Doppler spectrum, and averaged Ze over the snow regime. We can identify three layers in Fig. 2 based on their characteristics. Layer S1 was at heights from 2900 to 1200 m. The mean Doppler velocity and mean radar reflectivity increased gradually downward. In Layer S2, from 1200 to 600 m, the Doppler velocity still increased, but this layer had almost no increase in reflectivity.

In Layer S3, the profiles began to increase rapidly from 600 m to the surface, and the radar reflectivity decreased below 400m in Layer S3.

Below 400 m in Layer S3, the radar reflectivity decreased downward. The structure resembles the lower boundary of a BB, but the Doppler velocity did not increase and the variance of the spectra did not change. When particles complete melting, the Doppler velocity and its variance should be larger than above layer in the typical melting layer. Therefore, we considered that the particle in this layer might be snow or partially melting snow and that the intensity of Ze here should be large. So the layer from 400m to the ground had some error, for example, by receiver saturation.

3.2 Comparison with the meteorological elements

Figure 3 shows the vertical profiles of temperature and relative humidity estimated using a mesoscale model (MSM; JMA) for 1200 JST on 31 December 2004 (initial time 0900 JST) at the grid (35.66ºN, 139.7ºE) nearest the MRR observation site (35º39'38"N, 139º41'6"E); 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 locations of the southern cyclone according to the above model and that indicated by the JMA weather bulletin map coincided at this time.

Figure 3 suggests a frontal zone from 850 to 900 hPa and nearly saturated conditions from 700 to 850 hPa. The high humidity in Layer S1 favors the growth of ice deposition.

The greatest increase in the radar reflectivity was in the upper part of Layer S3. The temperature in the upper of Layer S3 ranged from –1 to –0ºC. This area, corresponding to the dominance of aggregation in Layer S3 at the upper boundary of the bright band, is consistent with the typical bright band explanation. The Doppler velocity of less than 2 m/s and variance of $0.1 m^2/s^2$ are consistent with the typical falling-snow velocity observed by Ralph *et al*. (1995) using a UHF-band WPR. For this reason, we can infer that the precipitation was snow in the upper of Layer S3. And we may deduce the precipitation was snow or partially melting snow above the ground surface.

4. Rain Observations

4.1 Attenuation correction

MRR uses a K-band frequency, and so the attenuation problem becomes serious in the case of heavy rainfall. Therefore, in this study, we tried to correct the attenuation by raindrops to the rain regime under Rayleigh approximation.

The method to calculate the attenuation coefficient and used equations were referred those written in Section 6.3 of Fukao and Hamatsu (2005). Special technique in this study is to use the "observed" value to calculate the amount of attenuation. Generally the corrected rain is used to calculate the amount of attenuation in the next range bin, but it often gives unrealistic values at the far range of the radar antenna. It is a merit of our simple method that it never gives infinite values, while it is a demerit that it tends to underestimate amount of attenuation.

4.2 Spectral reflectivity of rain clouds

Figure 4 shows the spectrum of Ze for the Doppler velocity at each height averaged over the rain regime. The vertical axis of Fig.4 represents height and density amplitude of Ze corresponding to the Doppler velocity. Figure 5 show the same properties as Figs.2, except for the rain regime. There seemed some signals above 2500m, but they were too small to be extracted as the spectrum. Figure 5 shows Ze after the attenuation correction. We can clearly see the BB structure in the rain regime around the height of 1000 m after the attenuation correction.

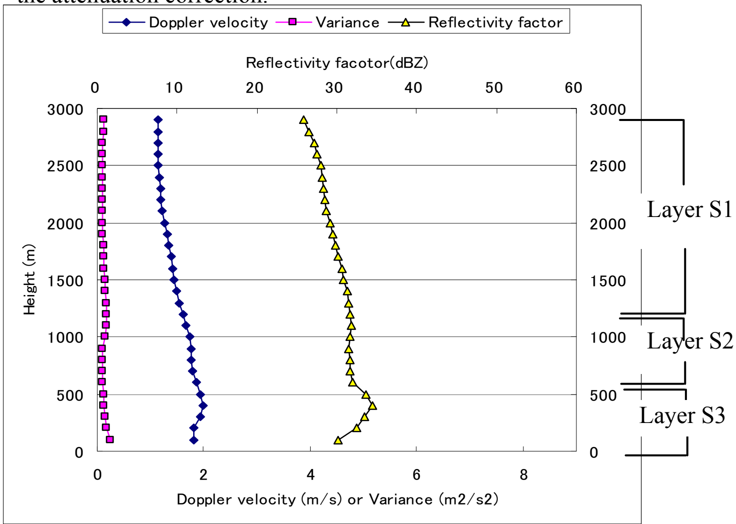


Fig. 2 Vertical profile of the radar reflectivity factor at each observation level averaged over the snow regime (1340–1350 JST on 31 December 2004).

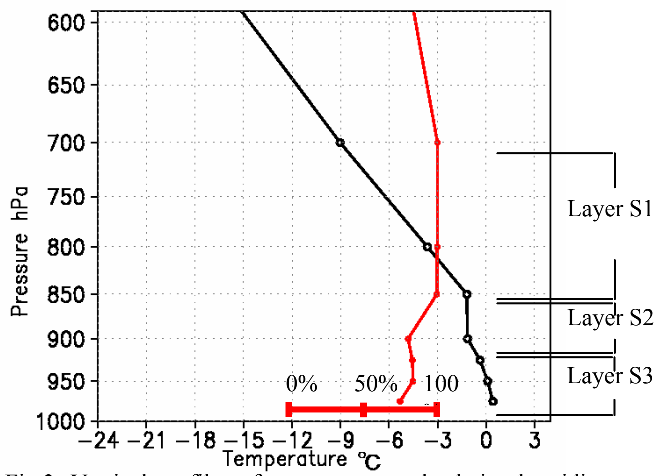


Fig.3. Vertical profiles of temperature and relative humidity from the MSM prognosis at 1200_JST (initial time, 0900 JST on 31 December 2004) for the grid at 35.66°N, 139.7°E. The black line indicates temperature and the red line denotes relative humidity.

We were able to define three typical layers using the profiles in Fig.5. Layer R1, which extended from 2500 to 1500 m, showed the significant increase in radar reflectivity, which suggests the generation of large amounts of precipitation. Throughout Layer R1, the Doppler spectrum peak increased gradually in a downward direction, and the distribution of the Doppler velocity broadened slightly in Fig. 4. Layer R2 extended from 1500 to 500 m; the Doppler spectrum peak increased, and shifted from 2 to 8 m/s. The Doppler velocity distributions were much broader than those in layers R1 and R3 (Fig. 4). Large variance in the Doppler spectra is also appeared in Fig. 5, which suggests the mixing of solid, liquid, and melting precipitation particles. Such large variance is reported in the melting of MCS that Ralph et al. (1995) observed by WPR. Layer R3 extended from 500 m to the surface; its Doppler spectrum peak remained large, and the velocity distributions changed little.

4.3 Comparison with the meteorological elements

Figure 6 shows the same properties as Fig. 3, but it is from the MSM with the initial conditions at 1500 JST on 31 December 2004. The 0ºC level was at 850 hPa; the layer below this level was stable. The boundary of this stable layer, i.e., 850 hPa, corresponded to the upper boundary of Layer R2, which was determined using MRR data to represent the BB.

In Layer R1, a peak in reflectivity appeared at approximately 1–2 m/s and resembled a composite of Layers S1 and S2 (not shown). The increased radar reflectivity corresponds to the emergence and growth of snow particles under almost saturated conditions. In Layer R2, the distribution of the spectrum characteristically became broad. The peak value of the spectrum shifted from 2 m/s at 1500 m to 8 m/s at 500 m, as shown in Fig. 4. The increasing Doppler velocity suggests that the precipitation particles were melting in Layer R2, which is consistent with temperatures slightly warmer than 0ºC in Fig. 6. In Layer R3, the precipitation appeared to be rain under near 0ºC conditions.

Overall, the MRR clearly observed the Doppler spectrum of a precipitation event in which snow turned to rain rapidly at near 0ºC.

5. Discussion

In order to improve classification algorithm, Figure 7 shows the comparison of the precipitation types and MRR observation values every 10 min during the precipitation event with meteorological elements observed at MRR site.

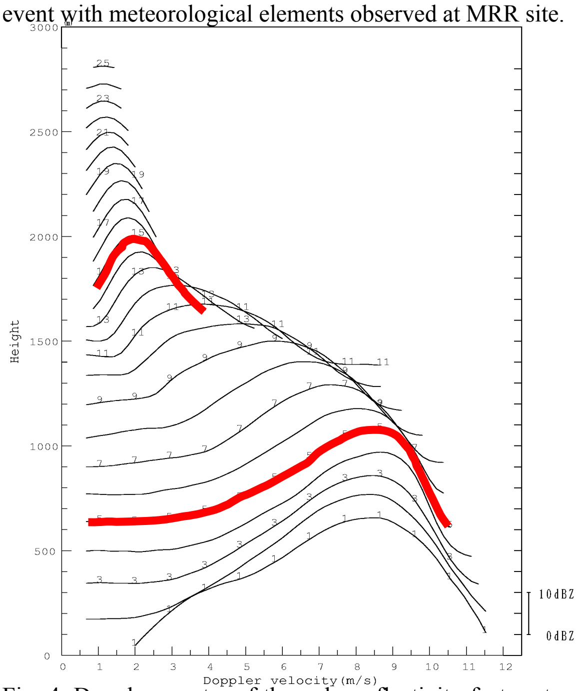


Fig. 4. Doppler spectra of the radar reflectivity factor at each observation level averaged over the rain regime (1515–1525JST on 31 December 2004). The small numbers on the curves indicate the height divided by 100m. The scale on the right side is for the spectra at a height of 100 m. The red line indicates the boundary of the bright band.

The precipitation type was based on the JMA observation reports at Ootemachi and the MRR observation at 400 m was used as the surface. The reason that we selected a height of 400m was to avoid error contamination from lower altitudes as mentioned in 3.1. The distance between the Ootemachi site and the MRR site accounted for a 10-min difference at the most, based on the cyclone speed. Thus, taking 10-min averages is useful method to overcome gap in distance. At the two sites, the temporal changes in temperature and relative humidity were almost the same and differences in absolute values were quite small in the two sites. Thus, the comparison provides us significant information for classifying precipitation.

The major change in MRR values occurred between 1440 and 1520JST. Doppler velocity, variance, and Ze increased quickly with transformation of precipitation type from sleet to rain. Before the transformation, under sleet situation, Ze was equally large to Ze under rain situation. Doppler velocity and variance increased gradually from small value 2.0m/s and $0.15 m^2/s^2$ at the end of snow situation until abrupt change at 1440JST. As far as melting process was concerned, Ze increased suddenly from snow to sleet. So sleet observation period and the BB situation appeared to be the same situation as melting process. The fact confirms that the melting of particles is a main contribution to BB. But variance didn't show the maximum value under sleet situation. There is possibility that maximum occurred in no data period, though. Before sleet situation temperature decreased and relative humidity increased after snow felled again suggesting sublimation cooling.

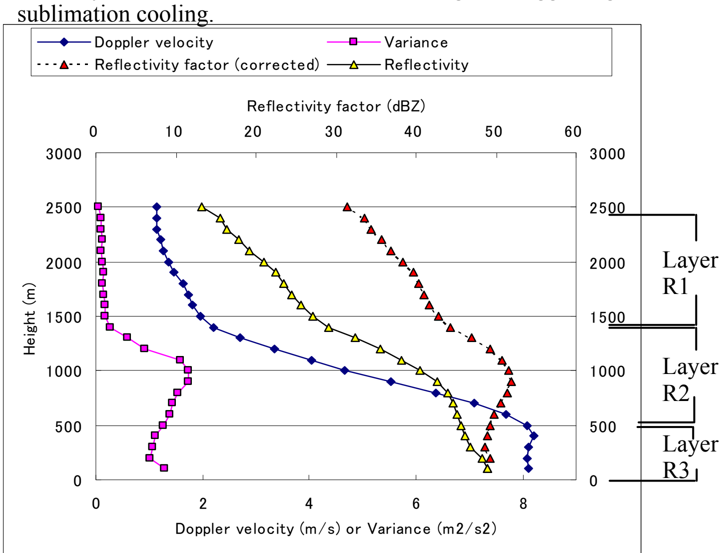


Fig. 5. The same as Fig. 2. Except for the rain regime (1515–1525JST on 31 December 2004).

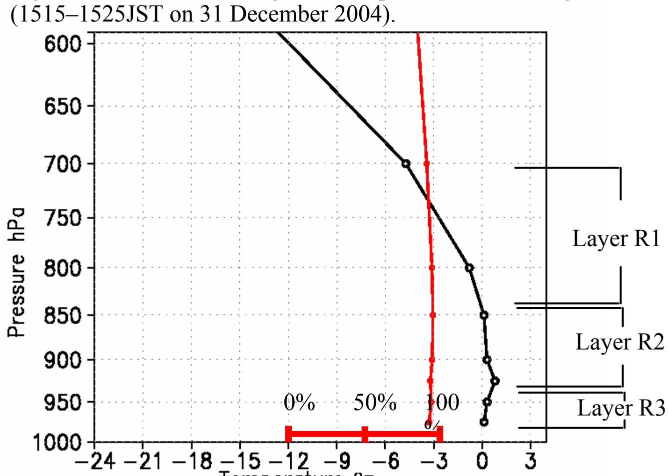


Fig. 6. The same as Fig. 3, except for the MSM data obtained at 1500JST on 31 December 2004

We may say that Ze under sleet situation was not so large comparing under rain situation which is equivalent to under the BB and variance under sleet situation was intermediate between the value of snow and that of rain observed near the surface. This change of variance is favorable to build up the threshold of classification into rain or sleet. But there are dispatches of previous study Ralph et al. (1995) or the profile of this study in rain regime. Their variance showed the maximum in the BB showed in Fig5. One possible explanation is that the BB aloft has a wide area to vertical mixing but the surface has a "boundary" of mixing.

Matsuo et al. (1985) suggested the existence of vertical mixing was derived by the unstable layer under BB which might be created by cooling of melting snowflakes. Such a vertical mixing should transport the melting large particles upward. On the other hand there was no space at the ground even if the cooling of melting occurs. Thus, the difference in the two variances seemed to be reflected in the difference of the local vertical mixing between the air and the ground.

If precipitation type is classified using MRR observations, it is good to set an intermediate value between snow and rain as sleet (or mixture) conditions. It would be possible from observations using MRR to classify precipitation and to detect the transition layer from snow to rain aloft.

6. Conclusions

The analysis of melting layer using MRR resulted in the following findings.

1) Attenuation correction is necessary to find the BB in the MRR wavelength.
2) Doppler velocity and variance increased gradually with transformation from snow to rain in a way of sleet.
3) The timing of an increase of Ze near the surface coincides with that of transformation from snow to sleet. Melting is still the important factor producing the BB.

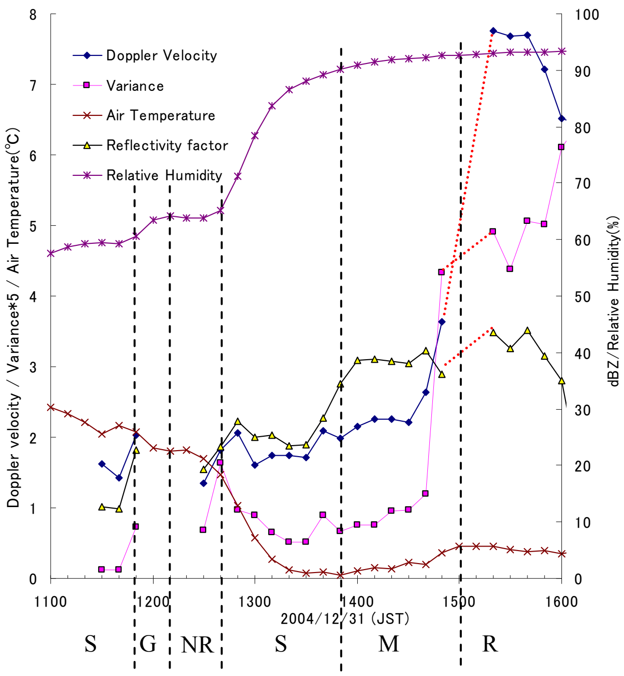


Fig. 7. Comparison of MRR observations and surface air conditions with the precipitation type. Letters indicate the precipitation type(S: snow, G: graupel, NR: no precipitation, M: sleet, R: rain). Variance is plotted five times the actual value because the absolute value small. The red dotted line indicates interpolation between periods lacking MRR data.

4) The variance of the Doppler spectrum of BB attains a maximum value through the observation height range from 100 to 2900m, whereas the time series of variance at 400m height level did not show a significant peak above the MRR site. This may results from the restriction of local vertical mixing in company with transportation of large particles induced by instability under the bottom of BB.
5) There is a decrease in Ze before the beginning of melting with an increase in relative humidity and a decrease in temperature. The sublimation of snow particles appears to be significant in the cooling and moistening of the environment air.
6) The Ze of sleet was not so large that of rain at the surface. That might be lack of large particle transported by vertical mixing from lower of melting layer.

Comparing MRR observations to ground observations provides much information on the melting layer. The typical BB calculation tends to underestimate the intensity of radar reflectivity. The effect of vertical mixing with transportation of large particles may bury the difference.

Acknowledgments

The MSM data were acquired from the GPV Archive Site (http://www.tkl.iis.u-tokyo.ac.jp:8080/GPV/) managed by the Kitsuregawa Lab and Oki/Kanae Lab of the Institute of Industrial Science, the University of Tokyo. The deduction program was constructed by Dr. Wakatsuki of Nagoya University. Dr. Murakami of the Meteorological Research Institute provided valuable comments and suggestions for the analysis. Parts of this study were supported by the Core Research for Evolutional Science and Technology (CREST), the Japan Science and Technology Agency (JST), and the Research Institute for Humanity and Nature (RIHN).

Comments and supplements

1. MRR observations made on the roof of the Institute of Industrial Science at the University of Tokyo (Supplement 1).
2. Time-height cross-section of the radar reflectivity index and vertical Doppler velocity on 31 December 2004 (Supplement 2).

References

Fukao, S and K. Hamatsu, 2005: Radar System Studies for Atmospheric Remote Sensing. Kyoto Univ. Press. 491pp. (In Japanese)

Matsuo, T., Y. Sasyo, and Y. Sato, 1981: Relationship between types of precipitation on the ground and surface meteorological elements. J. Meteorol. Soc. Jpn. **59**, 462–476.

Matsuo, T., H. Sakakibara, J. Aoyagi and K. Matsuura, 1985: Atmospheric Cooling Around the Melting Layer in Continuous Rain. J. Meteorol. Soc. Jpn. **59**, 462–476.

Peters, G., B. Fischer, H. Munster, M. Clemens and A. Wagner, 2005: Profiles of Raindrop Size Distributions as Retrieved by Microrain Radars. J. App. Meteorol. **44**, 1930–1949.

Ralph, F.M., P.J. Neiman, D.W. van de Kamp, and D.C. Law, 1995: Using spectral moment data from NOAA's 404-MHz radar wind profilers to observe precipitation. Bull. Am. Meteorol. Soc. **76**, 1717–1739.

Stewart, R E., J.D. Marwitz, and J.C. Pace, 1984: Characteristics through the Melting Layer of Stratiform Clouds. J. Atmos. Sci. **41**, 3227–3237

Willis, P. T. and A. J. Heymsfield, 1989: Structure of the Melting Layer in Mesoscale Convective System Stratiform Precipitation. J. Atmos. Sci. **46**, 2008–2025

Fabry, F. and I. Zawadzki, 1995: Long-Term Radar Observations of the Melting Layer of Precipitation and Their Interpretation. J. Atmos. Sci. **52**, 838–851

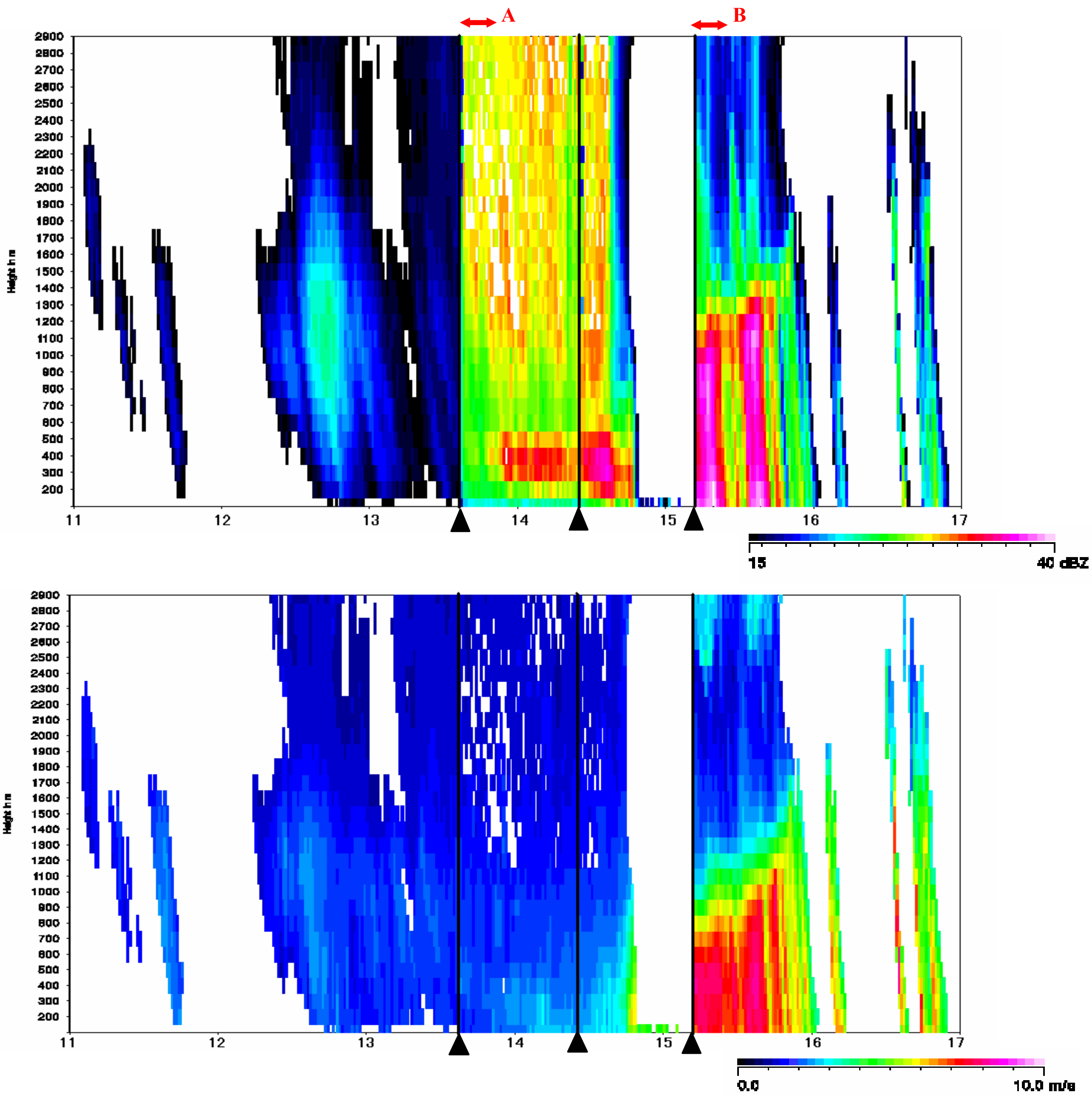
(Manuscript rejected on 16 January 2008)

Supplement 1

MRR observation equipment on the roof of the Institute of Industrial Science
at The University of Tokyo.
More information is available at the Web site:
http://hydro.iis.u-tokyo.ac.jp/MRR/

Koshida *et al*. Vertical profiles of winter precipitation in Tokyo, Japan, examined using micro rain radar (MRR)

Supplement 2



Time-height cross-section of the radar reflectivity factor (above) and vertical Doppler velocity (below) from 1100 to 1700 JST on 31 December 2004. Triangles denote times of snow removal from the antenna.
Broad red arrows denote the averaging period in the text.
A and B represent the snow regime and the rain regime respectively.