STRUCTURE AND MAINTENANCE PROCESS OF STATIONARY SNOWFALL SYSTEM ALONG COAST IN THE HOKURIKU DISTRICT, JAPAN

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1 Introduction

When the outbreaks of winter cold airmass from Siberia occur, various types of snow clouds develop over the Sea of Japan. The snow clouds reach at the Japan Islands in the north-westerly wind and bring a lot of snowfall along the coastal region of the Sea of Japan. When the snow clouds come to the coast, a significant modification and intensification occur. Takeda *et al.* (1982) showed from the echo structures by using RHI radar in the Hokuriku District that most of isolated convective snow clouds had the two stages of variation in their landing. Ishihara *et al.* (1989) also had the observation in the Hokuriku District. They analyzed snow bands which generated between the north-westerly monsoon wind and the south-easterly land breeze on the sea near a coast with single Doppler radar data. The snow clouds generated by land breeze in the outbreaks of cold airmass were also reported in the Ishikari Plain at Hokkaido, Japan (Fujiyoshi *et al.*, 1988; Tsuboki *et al.*, 1989a, b). About microphysical aspect, Harimaya and Sato (1992) showed from observation that riming process is important on coastal region in the growth of snow particles. Besides, Harimaya and Kanemura (1995) showed that the degree of riming increases when the maximum updraft increases and the maximum updraft on coastal region is stronger than that on inland regions. A synthetic observational study of process of significant intensifications and modifications near coasts have not been carried out.

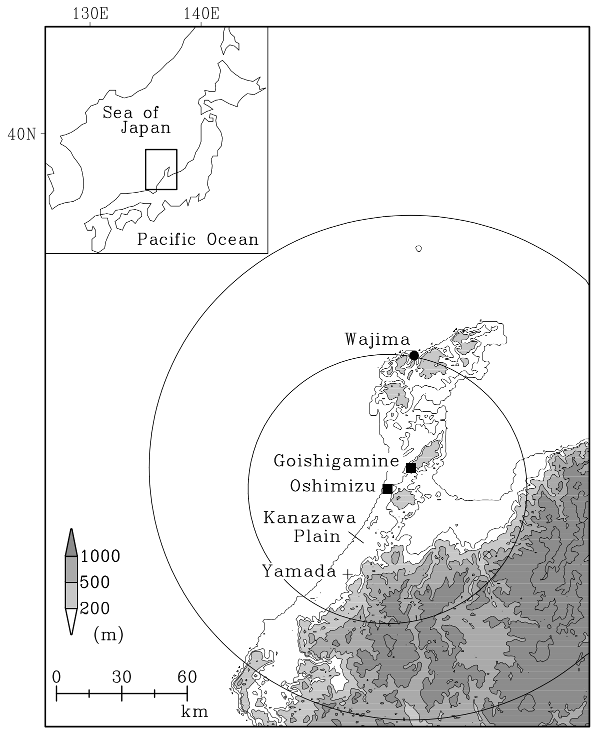

Fig. 1 Locations of each observation. ■, ● and + show the locations of radar (Oshimizu and Goishigamine), upper-air sounding (Wajima) observations and the site which pictures of snow particles were taken, respectively. Circles and show the ranges of each radar. The altitude of topography is shown with contours and shades. The contours are drawn at 100 m, 200 m, 500 m, 1000 m and 2000 m.

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The special observation was carried out using the Doppler radar of Nagoya University placed at Oshimizu, Hokuriku from December 2000 to February 2001 as a part of special observation 'Winter MCSs Observation over the Japan Sea-2001'. In the intense observation period, a snowfall system stayed along the coastal region of the Kanazawa Plain for about 20 hours from 15 to 16 January 2001. The purpose of this study is to clarify the structure and maintenance process of the snowfall system. This would contribute to clarify the process of significant modifications around the coasts.

The data used in this study were Doppler radar data at Oshimizu, dual-polarization radar data at Goishigamine, upper air sounding data at Wajima (Fig. 1), satellite imagery of NOAA and the pictures of snow particles.

2 Synoptic situation

At the middle of January 2001, the outbreak of cold airmass from Siberia occurred and a large amount of snow clouds developed over the Sea of Japan. In the period, the snowfall system developed along a coast. The satellite imagery of the time is shown in Fig. 2. Transverse mode clouds, which had the direction almost pependicular to north-westerly wind predominant at lower levels (Fig. 3), developed over the Sea of Japan. The coastal region of Kanazawa Plain, in which the snowfall system devel-

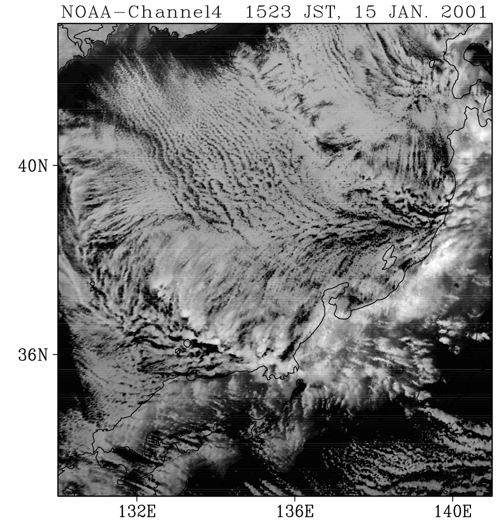

Fig. 2 The satellite imaginary of NOAA-14 channel 4 (thermal-infrared) at 1523 JST, 15 January 2001.

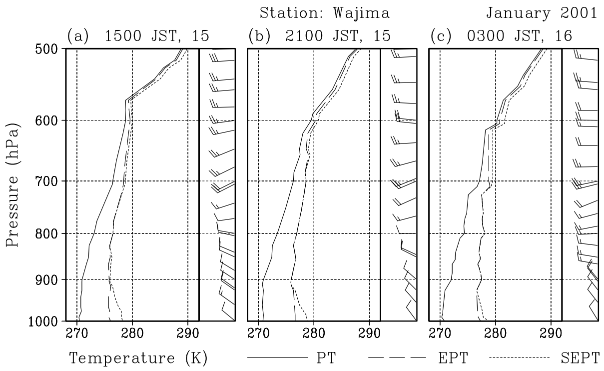

Fig. 3 Vertical profiles of potential temperature (PT), equivalent potential temperature (EPT), saturated equivalent potential temperature (SEPT) and horizontal wind at (a) 1500 JST, 15, (b) 2100 JST, 15, (c) 0300 JST, 16 January 2001 at Wajima. A half barb and a full barb are 2.5 m s^{-1} and 5 m s^{-1}, respectively.

oped, was located in downward side of the transverse mode clouds. At Wajima, which was located in the several tens kilometers to the north of the snowfall system, the convective mixing layer developed below the inversion at about 600 hPa. This convective mixing layer was maintained in during the period of the snowfall.

3 Structure of the snowfall system

3.1 Radar echo structure

The snap shot of horizontal structure of the snowfall system at 1808 JST (Japan Standard Time), 15 January 2001 at a height of 0.75 km is shown in Fig. 4 . The region of the snowfall system with relatively strong reflectivity extended with the width of about 20 km nearly parallel to a coast. The X and Y axes are defined normal and parallel to the snowfall system. The origin is on the Oshimizu radar site. Reflectivities averaged in the Y-direction in the rectangle shown in Fig. 4 at a height of 0.75 km at a time

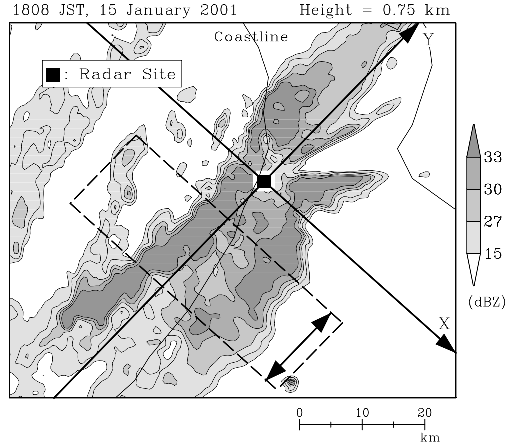

Fig. 4 The horizontal reflectivity pattern at 1808 JST, 15 January 2001 at a height is 0.75 km. The contours is drawn at 15 dBZ, 21 dBZ, 27 dBZ, 30 dBZ and 33 dBZ. The thick contours show coastline. ■ shows the location of the Doppler radar of Nagoya University. The thick lines with an arrow show the X and Y coordinates. The rectangle with broken lines corresponds the averaged area in Figs. 5 and 7.

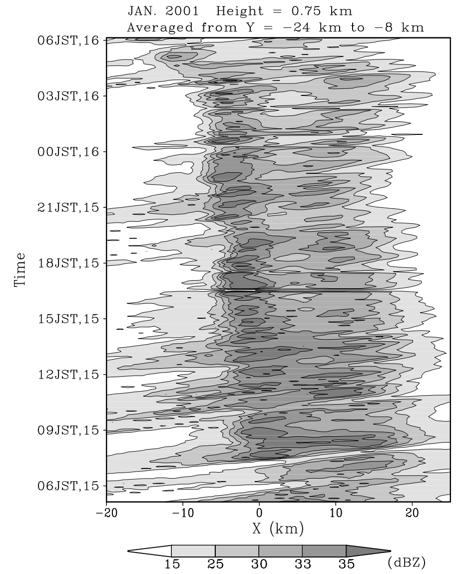

Fig. 5 The time-distance cross section of reflectivity at a height of 0.75 km. The reflectivity in a time is averaged in the rectangle area surrounded by broken lines of Fig. 4 in the Y-direction (from Y = −24 km to Y = −8 km).

give the time-distance cross section (Fig. 5). The snowfall system stayed for over 20 hours from 0730 JST, 15 to 0400 JST, 16 January around X = −10 km ∼ 20 km. The maximum echo region was present at X = −5 km ∼ 0 km. In addition to the region, another maximum echo region with relatively weak reflectivity was present at X = 5 km ∼ 10 km. The two maximum echo regions gradually became clear with time. After this, the period from 1500 JST, 15 to 0400 JST, 16 January will be focused on because the two maximum echo regions were clearly in the period. We call the period "clearly echo-split period". Figure 6 shows the time-averaged reflectivity pattern in the clearly echo-split period at a height of

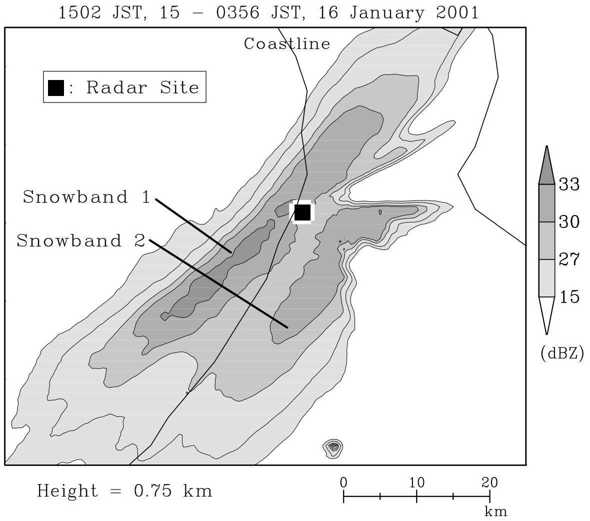

Fig. 6 As in Fig. 4 except for the time-averaged pattern from 1502 JST, 15 to 0356 JST, 16 January 2001.

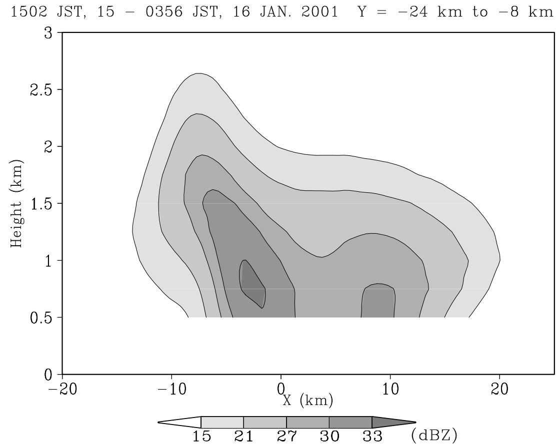

Fig. 7 The vertical cross section of time-averaged reflectivity. The averaged period is from 1502 JST, 15 to 0356 JST, 16 January 2001. The reflectivity is also averaged in the rectangle of Fig. 4 in the Y direction.

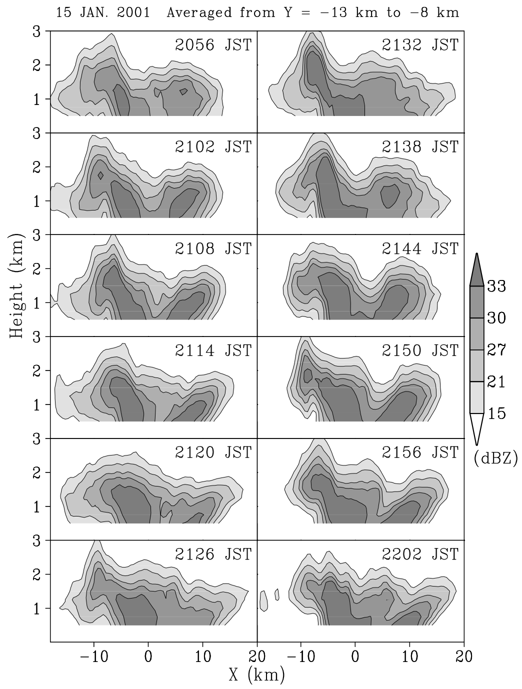

Fig. 8 Time-series of the vertical cross section of reflectivity. Each time intervals are 6 minutes from 2056 JST to 2202 JST. The reflectivity at a time is averaged from −13 km to −8 km.

0.75 km. The snowfall system was composed of two echo maximum bands. One was located over the sea with the strong reflectivity and the other was located over the land with the relatively weak reflectivity. We call the former "Snowband 1" and the latter "Snowband 2". The time-averaged vertical structure is presented in Fig. 7. This figure is also averaged in the Y-direction in the rectangle shown in Fig. 4. Snowband 1 had high echo-top, strong echo and the axis of maximum echo inclined toward the sea (toward left in the figure). On the other hand, Snowband 2 had relatively low echo-top, relatively weak echo and the echo bulged toward the land. The vertical structure every 6 minutes from 2056 JST to 2202 JST, 15 January in the clearly echo-split period is shown in Fig. 8, which is averaged in the Y-direction from Y = −13 km to −8 km. The echo regions of Snowband 1 and Snowband 2 were clear at 2056 JST. At 2102 JST, a new strong echo region developed at a height of 1.75km on the side of the sea of Snowband 1. This echo descended and constituted Snowband 1 (2108 JST ∼ 2144 JST). After the new echo descended, echo-top increased on the side of land of the falling echo from 2126 JST or 2132 JST and another echo developed below the increased echo-top at 2138 JST. This developed echo region corresponds to Snowband 2. The series of the change of echo pattern repeated.

3.2 Airflow around the snowfall system

The airflow around the snowfall system is showed to clarify how the echo structure of the snowfall system with two bands was made. Wind fields derived from single Doppler radar data are presented. The result of VAD analysis gives horizontal wind fields at the Oshimizu radar site (Fig. 9). Arrows and contours show the horizontal wind corresponding to the X and Y coordinates and the wind speed of the X-component, respectively. Though the north-westerly monsoon wind was predominant in the morning at the Oshimizu radar site, land breeze represented by contours with the negative value developed gradually from the lowest levels in the morning and maintained the thickness of about 300 m during the clearly echo-split period.

Figure 10a shows time-averaged reflectivity and time-averaged horizontal wind on the plane derived from RHI scans' data of 300 ° , which is nearly normal to the snowfall system. Over the sea at 40 km from the Oshimizu radar site, wind from the sea to

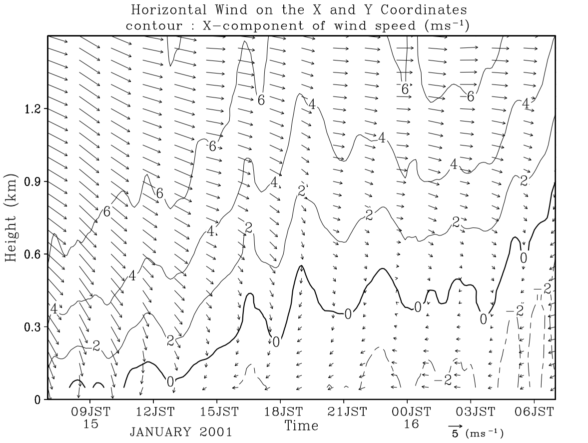

Fig. 9 The time-height cross section of horizontal wind obtained from VAD method over the Oshimizu radar site. Arrows show the horizontal wind on the X and Y coordinates which are shown at Fig. 4. The contours represent the wind speed of the X-component every 2 m s^{-1}. The contours with solid and broken lines show positive and negative velocities, respectively.

the land (monsoon wind) was almost uniform with height. Wind speed from the sea to the land at the upper level largely decreased in approaching to the snowfall system, increased on the side of sea of the snowfall system and decreased gradually on the side of the land again. On the other hand, wind speed didn't largely decreased at the lower level in approaching to the snowfall system and much decreased very close to the snowfall system because of the land breeze. These time-averaged horizontal wind fields give time-averaged horizontal divergence fields (Fig. 10b) under the hypothesis of two-dimensionality. As expected from horizontal wind fields, strong convergence at the lower level between the monsoon wind and the land breeze and strong divergence over the convergence region were present. This result shows that the strong updraft by convection was present. The weak convergence downstream (right) from the strong divergence region was also present. This weak convergence probably generated weak updraft.

3.3 Microphysical structure

The parameter of dual-polarization radar data used in this study is differential reflectivity Z_{DR} which is defined as

$$Z_{DR} = 10 \log_{10} \left(\frac{Z_{HH}}{Z_{VV}} \right) \quad (1)$$

where Z_{HH} and Z_{VV} are the horizontally transmitted/horizontally received and the vertically transmitted/vertically received reflectivity factors, respectively. Therefore dual-polarization radar data reflects shapes of the particles. In this study, particle types in each grid were classified into 12 types with Z and Z_{DR}. As the result of classification, almost grids were classified into 3 particle types (the dry snow, the drizzle and the dense snow). The particle types of the dry snow, the drizzle and the dense snow represent flat particles, spherical particles and vertically-long particles in falling, respectively.

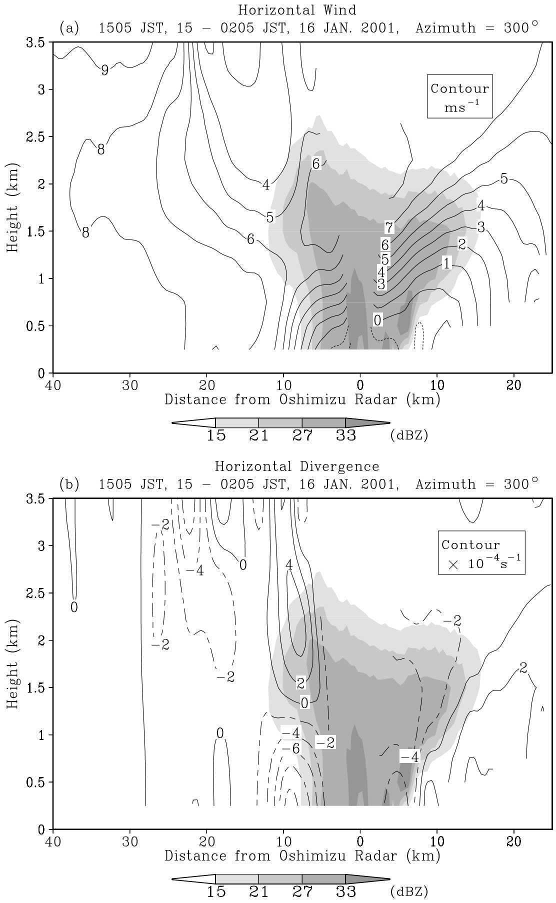

Fig. 10 The vertical cross sections of (a) the horizontal wind and (b) the horizontal divergence on the section and the reflectivity averaged from 1505 JST, 15 to 0205 JST, 16 January 2001 by RHI scans. The azimuth is 300°. The right in the figure shows the side of the land. The averaged reflectivities are shaded. (a) The averaged horizontal wind on the section is shown with the contours which are drawn every 1 m s^{-1}. The contours of positive and negative show wind from the sea to the land and from the land to the sea, respectively. (b) The horizontal divergence drawn every -2×10^{-4} s^{-1} calculated from the horizontal wind on the section. The contours with solid and broken lines show positive and negative values, respectively.

Figures 11b, c and d show the patterns of 3 particle types derived from dual-polarization radar data, which was averaged from Y = −24 km to −8 km and in the clearly echo-split period. Snowband 1 corresponds to the strong echo region at X = −3 km in Fig. 11a. On the other hand, Snowband 2 corresponds to the strong echo region centered at X = 10 km. Snowband 1 had the high probability of the dense snow and Snowband 2 was occupied by mainly the dry snow in its upper part and mainly the drizzle at a height of about 1.25 km.

To discuss more strictly, relationships between Z and Z_{DR} in each volumes in the clearly echo-split period are showed in Fig. 12. The particles which

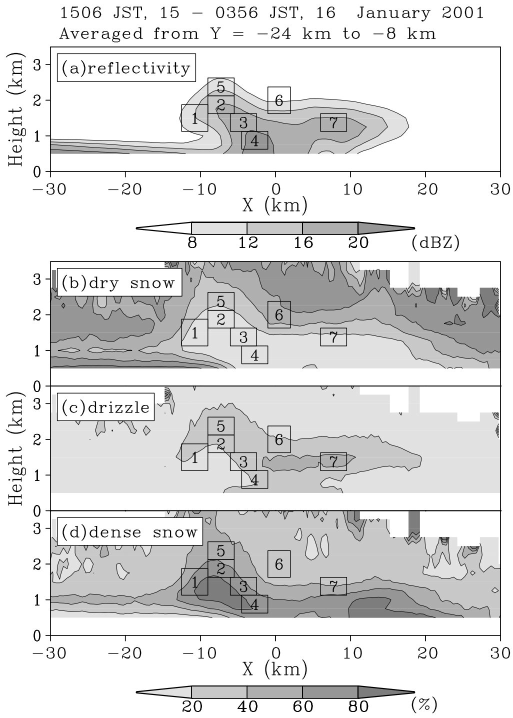

Fig. 11 The vertical cross sections of (a) the averaged reflectivity and distribution of the ratios of (b) the dry snow, (c) the drizzle and (d) the dense snow. The figures are calculated between Y = −24 km and −8 km during the period from 1506 JST, 15 to 0356 JST, 16 January 2001. The ratios are defined as the number of the grids of each particle types which are included in the given area and period. The boxes with numbers are used in Fig. 11.

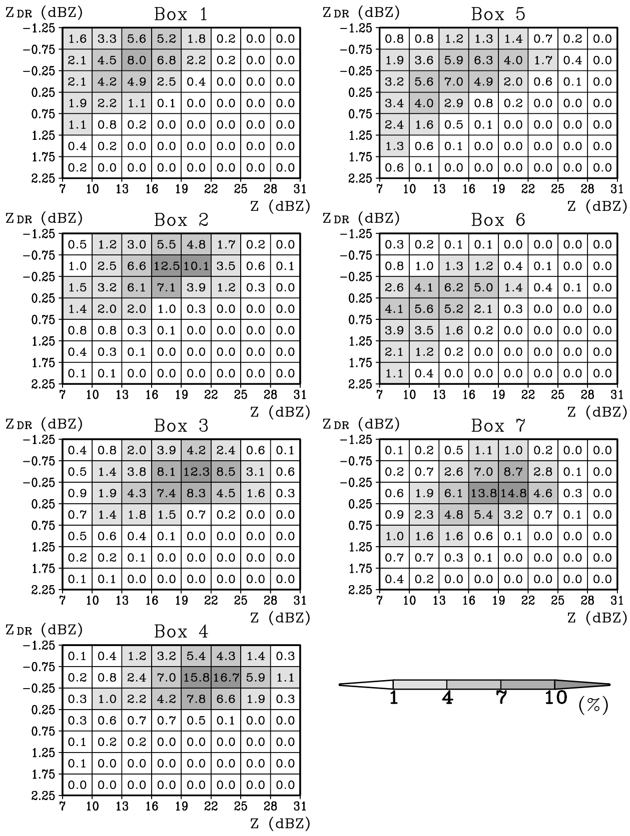

Fig. 12 The Z-Z$_{DR}$ relationships in some volumes showed in Fig. 11 from 1506 JST, 15 to 0356 JST, 16 January 2001. Ratios are defined as the number of grids included in each Z-Z$_{DR}$ regions.

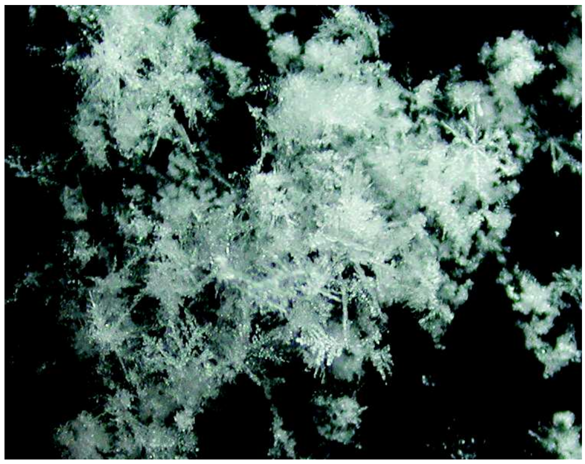

Fig. 13 The picture of the snow particle taken at the Yamada Area at 0309 JST, 16 January 2001.

constitute Snowband 1 were expected to move from the box 1 to box 4 via boxes 2 and 3 in Fig. 11 a from analysis of echoes and airflows. Z increased from box 1 to box 4 and Z$_{DR}$ had the maximum at from −0.75 dBZ to −0.25 dBZ. On the other hand, the particles which constitute Snowband 2 would have grown up in weak updraft. Therefore, particles in box 5, which were not able to grow largely and fall rapidly, probably fell down to box 7 through box 6 in westerly wind. Z$_{DR}$ in boxes 5 or 6 was large value. Z$_{DR}$ in box 7 also shifted toward large value from that of boxes 3 or 4.

81 pictures of snow particles were taken from 2332 JST, 15 to 0343 JST, 16 in the clearly echo-split period at the Yamada Region (136 ° 33' 24"E, 36 ° 27' 11"N), where was located below Snowband 2. All snow particles of these pictures were aggregates. The almost aggregates were composed of many densely rimed snow particles and some aggregates included lightly rimed or unrimed snow crystals. A picture of example is shown in Fig. 13. This picture shows an aggregates which included lightly rimed or unrimed snow crystals.

4 Discussion

Structure and maintenance mechanism of the snowfall system with two snowbands (Snowband 1 and Snowband 2) is schematically shown in Fig. 14. The north-westerly monsoon wind converged with the land breeze with its thickness of about 300 m. In convective mixing layer with almost neutral stratification, a strong convection with strong updraft developed. In strong updraft, riming process is predominant as mentioned in Harimaya and Kanemura (1995). Therefore, many graupels or densely rimed snow crystals probably developed through riming

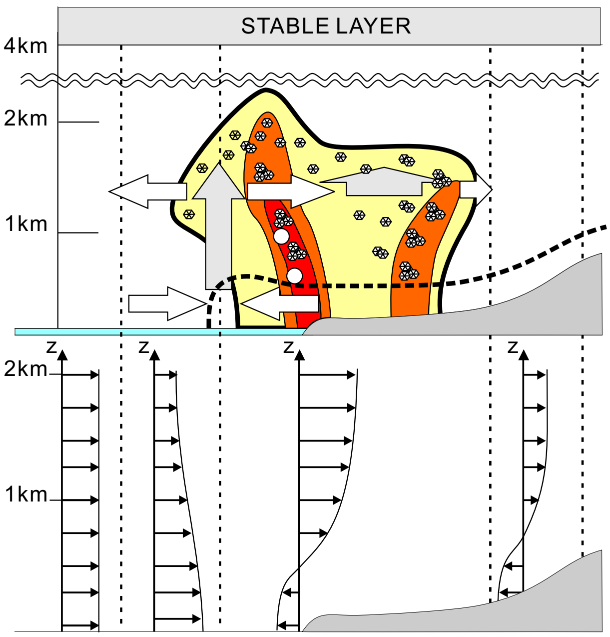

Fig. 14 The schematic figure of structure and maintenance process of the snowfall system.

process. The small values of Z_{DR} are consistent with the presence of these particles. But the sizes of graupel or densely rimed snow particles would not be so large because reflectivity in Snowband 1 was not so strong.

The strong updraft generated by the strong convergence between the monsoon wind and the land breeze diverged at the upper level of Snowband 1. The divergent flow at the upper level made weak convergence on its land side to be resulted in weak updraft. The particles which were not able to grow up enough to fall on grounds fell down in the weak updraft. These particles grew through aggregation process not deposition process in little water vapor because water vapor had been used to form Snowband 1.

5 Summary

We observed a stationary snowfall system along the coast of the Hokuriku District. The snowfall system stayed for about 20 hours and two echo maximum regions were present: Snowband 1 and Snowband 2. The two snowbands had different reflectivity structures composed of different particle types. Maintenance mechanisms of the snowbands were also different. Snowband 1 was maintained by the intense low-level convergence between the south-easterly land breeze and the north-westerly monsoon wind while Snowband 2 was formed by weak dynamic forcing. Riming process was important of the formation of Snowband 1. On the other hand, aggregation process was main process of the formation of Snowband 2.

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