Jour. Fac. Sci., Hokkaido Univ., Ser. VII (Geophysics), Vol. 9, No. 5, 445-462, 1995.

Aircraft Observations of Precipitation Particles in the Winter Monsoon Clouds over the Japan Sea

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(Received November 17, 1994)

Abstract

An aircraft observation of off-shore clouds was carried out over Wakasa Bay, Japan, on February 17, 1991, in the outbreak of the winter monsoon season. The observed cloud was organized in a band structure which was parallel to the prevailing wind direction. Snow trails were recognized under the cloud base. The aircraft traversed the band cloud at the heights of 1.1 (near the cloud base), 1.3, 1.6 and 1.9 km a.s.l.. The temperatures at each height were −6.5, −7.6, −9.8 and −11.9°C, respectively. The cloud top height was 2.7 km a.s.l.. Particle images in this cloud were examined using a 2D-P probe.

As a result, it was found that a number of small supercooled droplets existed in the lower part of the cloud with diameters of a few hundred micrometers. Furthermore, graupel particles coexisted with these droplets. Graupel particles were dominantly found in the middle and lower parts of cloud. It was suggested therefore that graupel particles grew rapidly through the collection of these supercooled droplets. It was surmised that the falling of graupel particles from the cloud base was recognized as snow trails. Densely rimed dendrites were also observed apart from the graupel particle region. Two turrets developed around the center of the cloud. Large rimed particles were observed along the circumference of the turrets and small particles were observed in the center. It was concluded therefore that graupel particles grew rapidly in the relatively lower part of the band cloud. It is considered, therefore, that this fact is important in understanding the mechanisms of the local heavy snowfalls along the west coast of northern Japan.

1. Introduction

It is well known that there are many snowfalls in the coastal regions facing the Japan Sea during the winter monsoon seasons. The cold air masses, which burst out from the Siberian Continent, obtain a large amount of moisture and heat while crossing over the relatively warm Japan Sea surface. A humid, warm and unstable mixing boundary layer is formed in the lower atmosphere of the air mass and a number of heavy convective snow clouds are generated in it. When the air mass arrives at Japan Island, a large amount of snowfall is brought to the seashore regions. Sometimes the snowfall seriously impairs human activity, and causes damage.

By the satellite pictures and radar observations, it is known that snow clouds are often organized in a band-shaped, parallel and tangential with the prevailing wind direction depending on the vertical wind shear. The band-shaped clouds often accompany a heavy snowfall when the clouds enter over the seashore and inland areas. This is one of the reasons for the localization of the heavy snowfall in a limited area. There are a number of studies on the band clouds over the Japan Sea up to the present (for example, Higuchi, 1963; Tsuchiya and Fujita, 1967; Kuettner, 1971; Magono, 1971; Muramatsu, 1979; Miura, 1986; Sakakibara et al., 1988; Tsuboki et al., 1989; Fujiyoshi et al., 1992). Recently, Sakakibara et al. (1988) and Tsuboki et al. (1989) observed the band clouds by means of the Doppler radar. And they reported that there was a strong relationship between the cloud formation and the lower level cold outflow from the inland (the land-breeze). Fujiyoshi et al. (1992) reported about the kinematic structure of the band clouds which were formed on the lee side of a mountain. Murakami et al. (1992) reported on the microphysical and thermodynamical structures by means of their special videosondes (HYVIS). However, the observed area by the balloon launched HYVIS is restricted to the vertical direction and it is difficult to obtain the horizontal distributions of the precipitation particles in the target clouds. Thus, the relation between the organization and internal structure of snow clouds is not sufficiently understood, due to a lack of in-situ observations on the band-shaped snow cloud.

Graupel particles and densely rimed snow particles are precipitated from these band-shaped snow clouds. Harimaya and Sato (1992) measured the riming property (grade of riming) of each precipitation particle under the clouds in the coastal area. Mizuno (1992) estimated that the graupel particle is at least 1/4 to 1/3 of the monthly precipitation amount. Thus, it is important to observe the distribution of precipitation particles and to understand the formation mechanisms of precipitation particles, especially, graupel particles in the snow clouds.

The purpose of this paper is to describe the particle distributions and to discuss the formation of the graupel particles in a band cloud over the Japan Sea by means of aircraft in-situ observations. These observations were carried out as a part of the Western North-Pacific Cloud Radiation Experiment in connection with the WCRP (World Climate Research Program) in Japan.

2. Observations

The aircraft observation was carried out on February 17, 1991 at off-shore Wakasa Bay over the Japan Sea during the winter monsoon situation. A strong low (960 hPa) existed off-shore Sanriku, the northern part of Japan. The synoptic situation around Japan Sea was of a typical outbreak situation of the winter monsoon. According to the radio sonde sounding at Wajima, which is located 250 km northeast of the observation area, the mixing boundary layer was well developed in the lower atmosphere and a convective unstable layer existed below 2.7 km a.s.l. (about 700 hPa). A number of band clouds were recognized over the Japan Sea by satellite.

Precipitation particles were observed by means of 2D-P probe (Particle Measuring System Inc., OAP-2D-GB2 GREY PROBE) fixed on a Cessna 404 (TITAN) aircraft. Other observed elements on board, which pertained to this

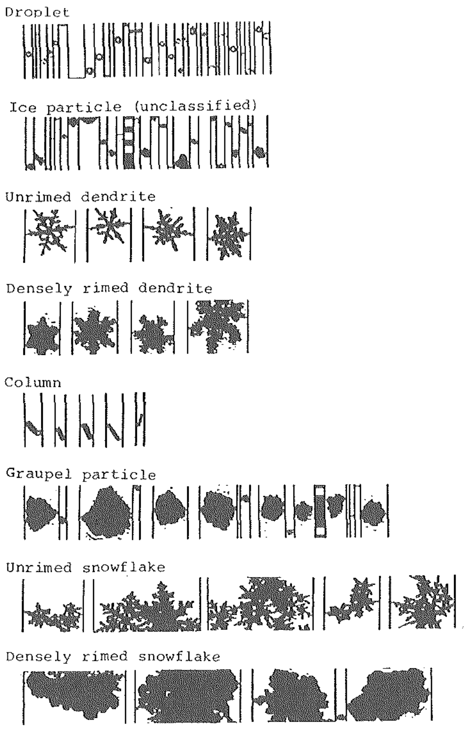


Fig. 1. Typical images of precipitation particles observed by the 2D-P probe. Each particle is divided by the vertical bar. The length of vertical bar indicates 3.2 mm.

analysis, were temperature, dewpoint temperature, pressure, air speed, and cloud views which were recorded by an 8 mm video camera. The 2D-P probe has a resolution of 50 μm. As the 2D-P probe has 64 photodiodes in an array, it can measure directly 50 μm to 3.2 mm. The procedure of analysis was as follows; firstly, error images were omitted from the obtained images. Secondly, the analyzed images were restricted to those which were larger than 100 μm in diameter. If the observed images of precipitation particles were out of view of the 2D-P, their sizes were estimated by the method of Heymsfield and Parish (1978). Thirdly, the images were classified into 8 categories, that is, supercooled droplets, small ice particles (unclassified snow particles), unrimed dendrites, densely rimed dendrites, columns, graupel particles, unrimed snowflakes and densely rimed snowflakes, respectively. Typical examples of those particles are shown in Fig. 1. In the figure, each particle is divided with a vertical bar. The length of vertical bar indicates 3.2 mm in scale. Images of supercooled droplets were identified by their ring. Furthermore, small particles with solid interiors were identified as small ice particles.

We analyzed data of observations from 12:40 to 13:06 JST February 17, 1991 in detail. The observation area is shown in Fig. 2. It was about 100 km off-shore Wakasa Bay. According to the weather radar observations made routinely by Fukui Local Meteorological Observatory, band-shaped radar

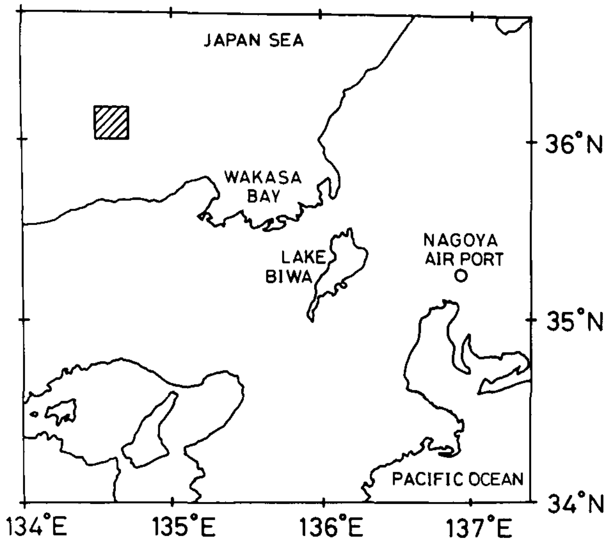


Fig. 2. Map around the observation area (hatched).

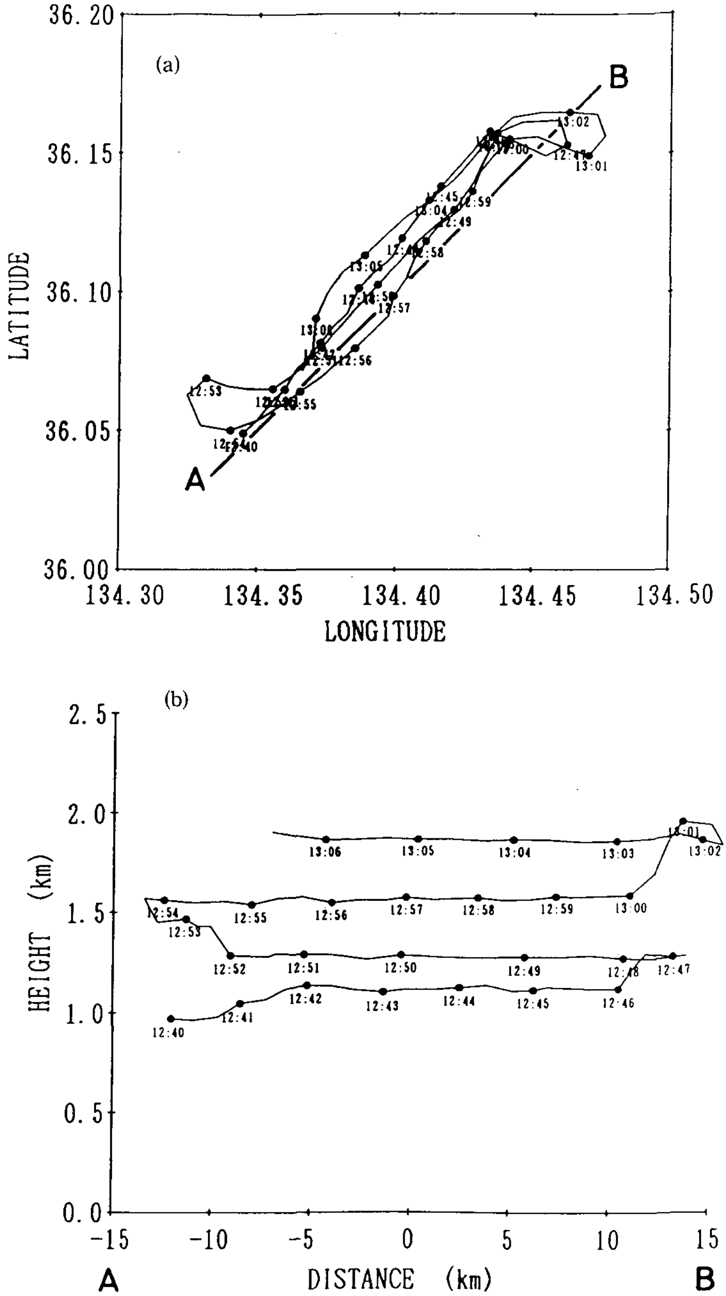


Fig. 3. Flight tracks of the observation aircraft. (a) Horizontal and (b) Vertical tracks. The origin of the abscissa in (b) shows the center of the flight leg.

echoes, which were enlarged from north to south at the observation area, existed. The direction of the band-shaped echoes was parallel to the prevailing wind direction. Band-shaped cumulus clouds corresponding to the band-shaped echoes were observed in the area and snow trails were recognized below these cloud bases. Furthermore, pilots of the observation aircraft reported that the cloud top height was about 2.7 km (8,000 ft) and the cloud base height was 1.2 km (3,700 ft) a.s.l., respectively. The cloud top height was in consistency with the height of the mixing boundary layer. The flight track is shown in Fig. 3. The origin of the abscissas was adopted at the center of horizontal flight leg, as shown in the upper panel. The aircraft passed horizontally across one of the band clouds from southwest to northeast (along the A-B line in the figure) at the height of 1.1 km (near the cloud base), 1.3 km, 1.6 km and 1.9 km a.s.l. as shown in the lower panel, respectively. Average temperatures at each height were -6.5°C (1.1 km a.s.l.), -7.6°C (1.3 km a.s.l.), -9.8°C (1.6 km a.s.l.) and -11.9°C (1.9 km a.s.l.), respectively. According to the aerological data at Wajima Weather Station, the wind direction and speed was 350 degrees and 18 ms^{-1} at 850 hPa. Thus the observed cloud moved from the right to the left along the vertical cross section in Fig. 3(b), at the speed of about 10 ms^{-1}.

3. Results

The number concentration of all precipitation particles which was observed by the 2D-P probe in the vertical cross section across the band cloud is shown in Fig. 4. As the cloud top height was 2.7 km a.s.l., this figure represents the distribution of the precipitation particles of the middle and lower levels of the cloud. Snow trails were recognized from the aircraft below the cloud base at nearly 5 km in the abscissa. A high number concentration of the precipitation particles were found near the cloud base. The maximum value found here was 2.6 particles l^{-1} at 1.3 km a.s.l.. The typical number concentration at each horizontal flight leg was 1-2 particles l^{-1} at 1.9 and 1.6 km and 2-2.5 particles l^{-1} at 1.3 and 1.1 km a.s.l., respectively. Two vertical extended regions, at more than 1 particle l^{-1}, were recognized in the concentration, that is, two cloud turrets existed in the interior of the cloud.

Figure 5(a) to (e) shows the distributions of the concentration of the particles classified by the precipitation types, that is, (a) supercooled droplets, (b) graupel particles, (c) densely rimed dendrites, (d) unrimed and rimed snowflakes, and (e) unrimed dendrites. As the air temperature at the cloud base was below the freezing temperature, all the droplets which were observed

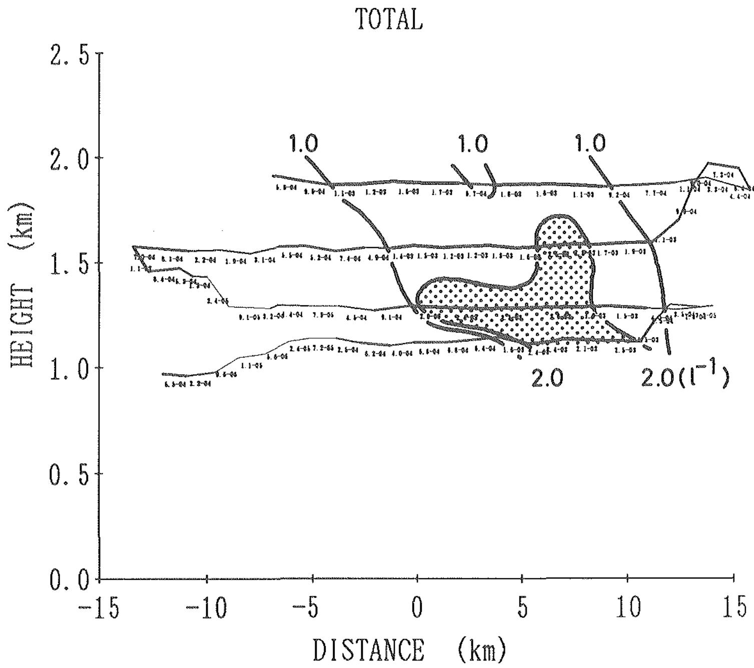
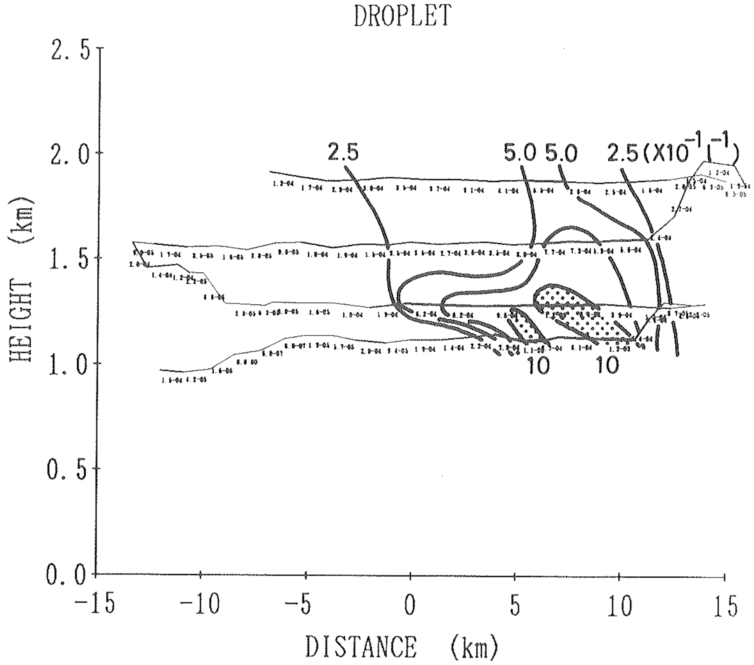
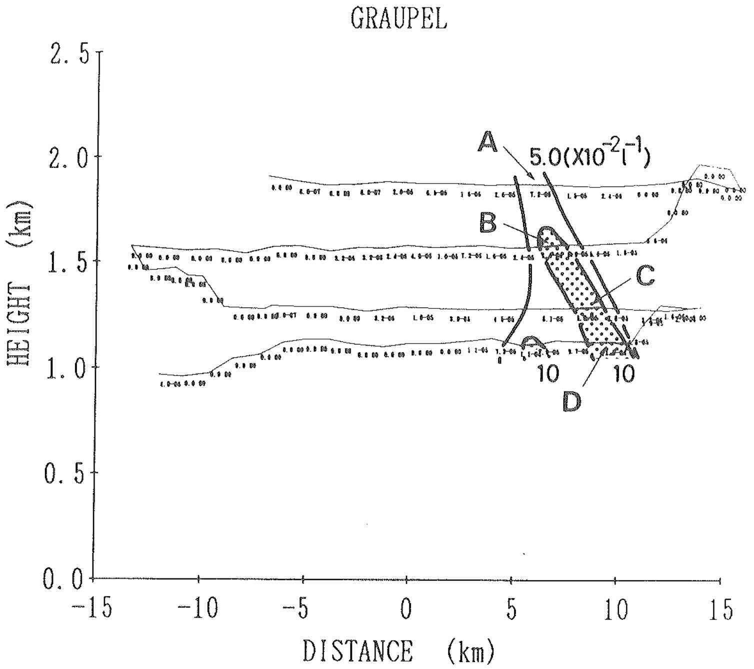


Fig. 4. Concentration distribution of the precipitation particles observed by the 2D-P probe. Shaded area indicates a region larger than 2 l^{-1} in concentration.

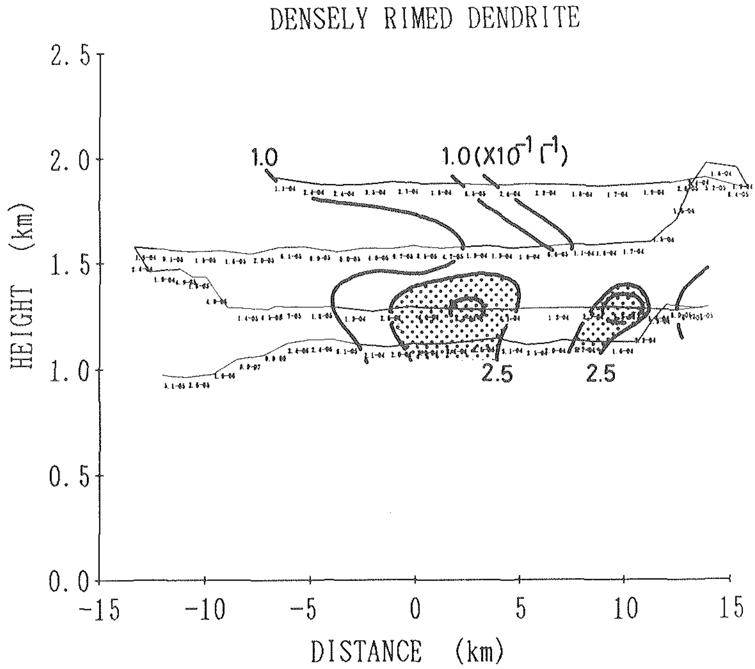
by the 2D-P probe were supercooled droplets. Quite a large number of droplets were observed in the cloud. In spite of the fact that the particles smaller than 100 μm in diameter were excluded from the analysis, a large number of droplets observed were 300–400 μm in diameter as a typical size. As compared to Fig. 4, supercooled droplets occupied a high percentage of particle images obtained. About half of the precipitation particles, therefore, were supercooled droplets near the cloud base. Most of the droplets concentrated at a turret near the cloud base and two maxima were found. One of the remarkable features of the droplet distribution was that a high concentration region of more than 0.5 l^{-1} extended to the higher level vertically. This is surmised to be evidence of the existence of an updraft in this region. Graupel particles were observed in the horizontally narrow region which extended vertically from near the cloud base to a higher level of the cloud. A higher concentration region of more than 0.1 l^{-1} existed in the lower level below 1.6 km a.s.l.. Two maxima were found near the cloud base. These maximal regions corresponded to those of the supercooled droplets described previously. Figure 6 shows the particle images and


DROPLET
2.5
5.0 5.0
2.5(X10^{-1} l^{-1})
10 10
HEIGHT (km)
2.5
2.0
1.5
1.0
0.5
0.0
-15 -10 -5 0 5 10 15
DISTANCE (km)

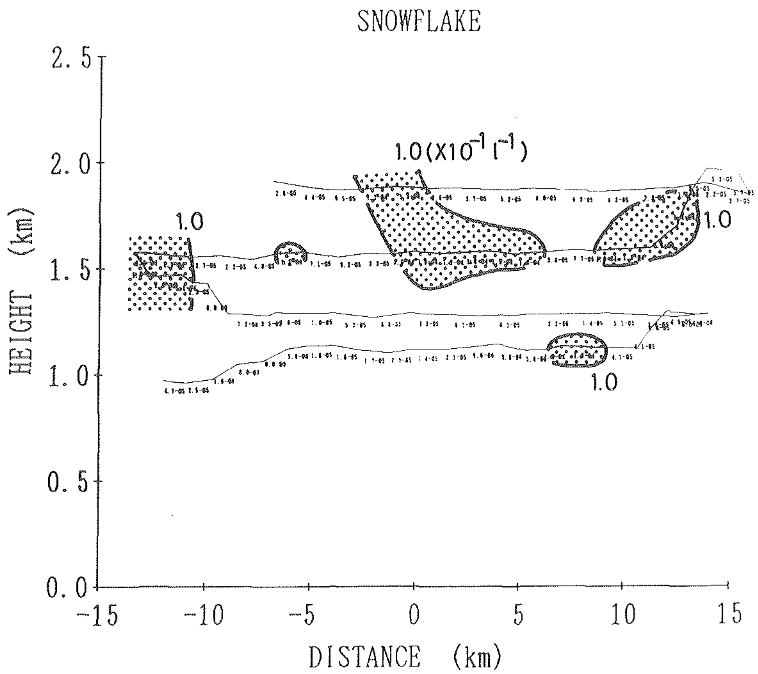
(a)


GRAUPEL
A
5.0(X10^{-2} l^{-1})
B
C
10 10
D
HEIGHT (km)
2.5
2.0
1.5
1.0
0.5
0.0
-15 -10 -5 0 5 10 15
DISTANCE (km)

(b)


DENSELY RIMED DENDRITE
1.0
1.0(X10^{-1} l^{-1})
2.5
2.5
HEIGHT (km)
DISTANCE (km)
2.5
2.0
1.5
1.0
0.5
0.0
-15
-10
-5
0
5
10
15

(c)


SNOWFLAKE
1.0(X10^{-1} l^{-1})
1.0
1.0
1.0
HEIGHT (km)
DISTANCE (km)
2.5
2.0
1.5
1.0
0.5
0.0
-15
-10
-5
0
5
10
15

(d)

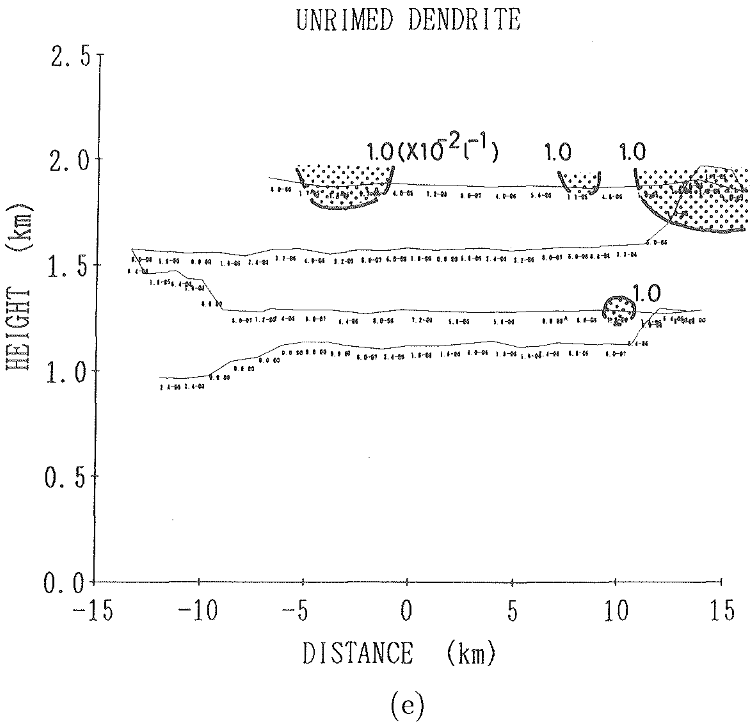
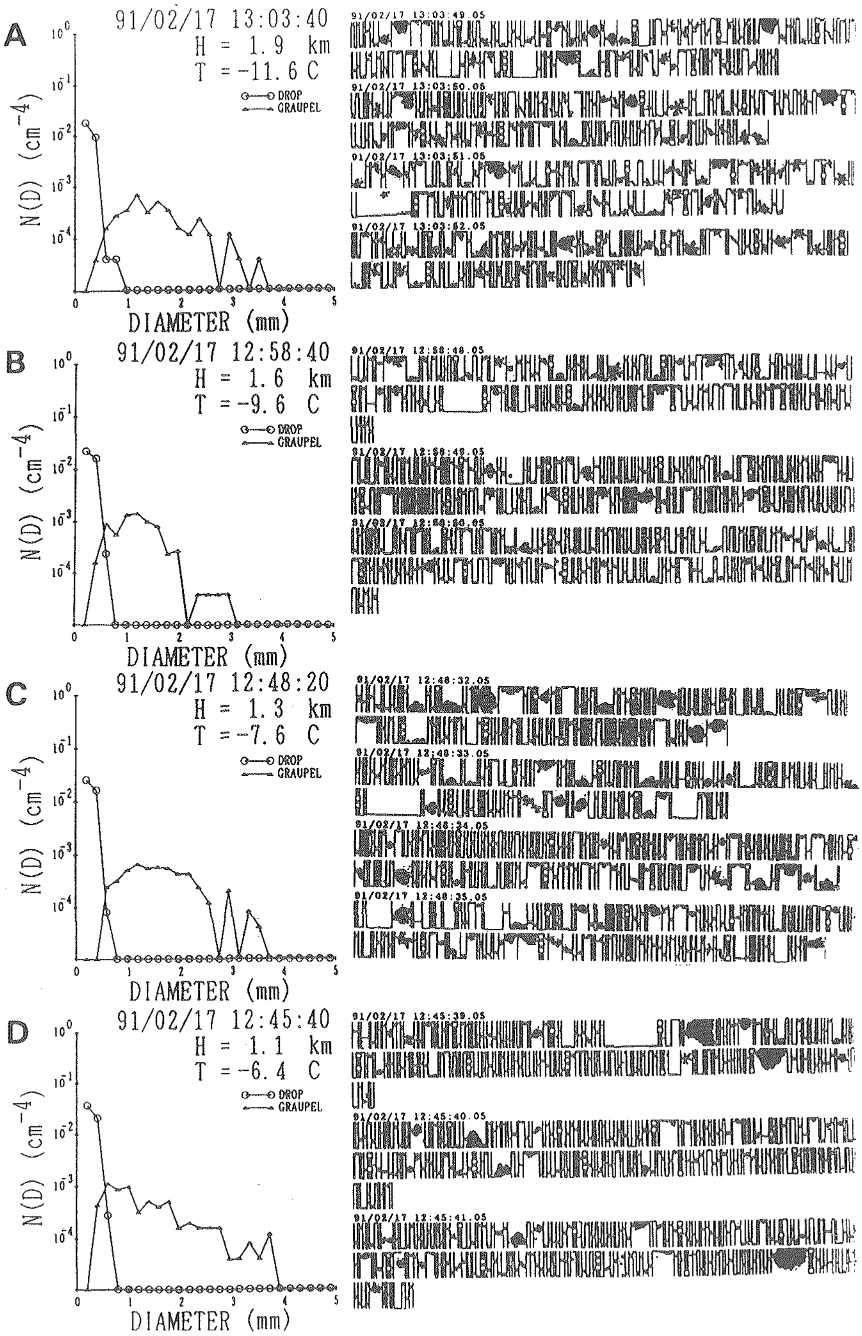


Fig. 5. Vertical dstributions of the concentration of particles classified by the precipitation types, (a) supercooled droplets, (b) graupel particles, (c) densely rimed dendrites, (d) unrimed and rimed snowflakes and (e) unrimed dendrites.

size distributions of the droplets and the graupel particles, at the maximum concentrations of each level, which was indicated by 'A', 'B', 'C', and 'D', respectively, in Fig. 5(b). In the left figure, the open circles, and solid triangles connected with solid lines represent the droplets and graupel particles, respectively. It was found that a large number of small supercooled droplets and large graupel particles coexisted. The concentration of graupel particles was lower than that of droplets, but relatively large graupel particles were observed at 1.1 (level D) and 1.3 km (level C) a.s.l., near the cloud base. It was surmised that the large graupel particles induced the downdraft because of their high fall

Fig. 6. Particle images (right hand side part) and size distribution (left hand side part) of supercooled droplets and graupel particles at the maximum concentrations of each level, which is indicated by 'A', 'B', 'C' and 'D' in Fig. 5(b). In the left figures, the open circles and solid triangles connected with solid lines represent supercooled droplets and grauple particles, respectively.


A
91/02/17 13:03:40
H = 1.9 km
T = -11.6 C
DROP
GRAUPEL
N(D) (cm⁻⁴)
DIAMETER (mm)
91/02/17 13:03:49.05
91/02/17 13:03:50.05
91/02/17 13:03:51.05
91/02/17 13:03:52.05
B
91/02/17 12:58:40
H = 1.6 km
T = -9.6 C
DROP
GRAUPEL
N(D) (cm⁻⁴)
DIAMETER (mm)
91/02/17 12:58:48.05
91/02/17 12:58:49.05
91/02/17 12:58:50.05
C
91/02/17 12:48:20
H = 1.3 km
T = -7.6 C
DROP
GRAUPEL
N(D) (cm⁻⁴)
DIAMETER (mm)
91/02/17 12:48:32.05
91/02/17 12:48:33.05
91/02/17 12:48:34.05
91/02/17 12:48:35.05
D
91/02/17 12:45:40
H = 1.1 km
T = -6.4 C
DROP
GRAUPEL
N(D) (cm⁻⁴)
DIAMETER (mm)
91/02/17 12:45:39.05
91/02/17 12:45:40.05
91/02/17 12:45:41.05

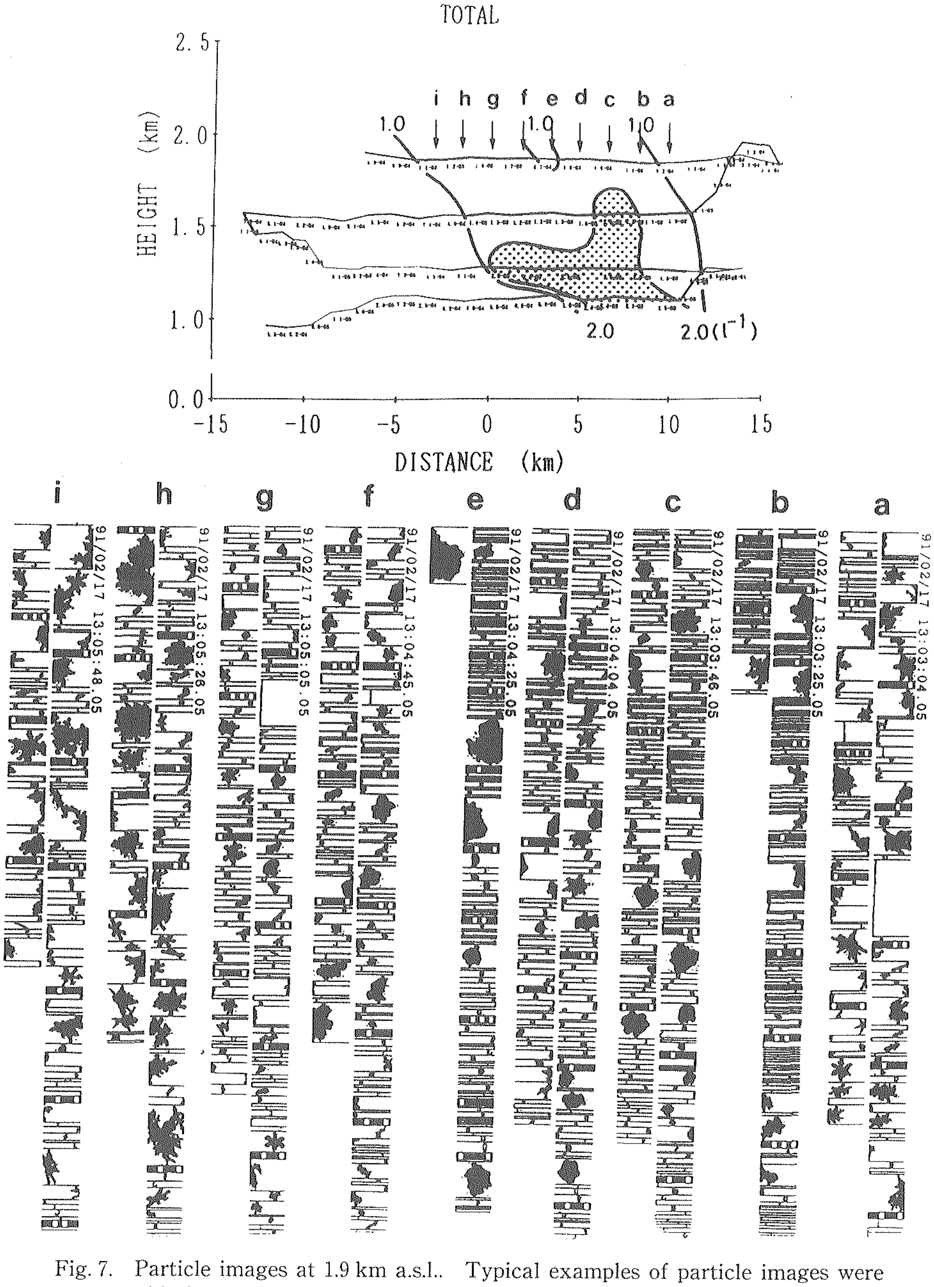


Fig. 7. Particle images at 1.9 km a.s.l.. Typical examples of particle images were put side by side for 20 seconds intervals. Each sampling time from (a) to (i) column of particle images is 1 second. Sampling locations are indicated by downward arrows in the upper vertical cross section of the flight track.

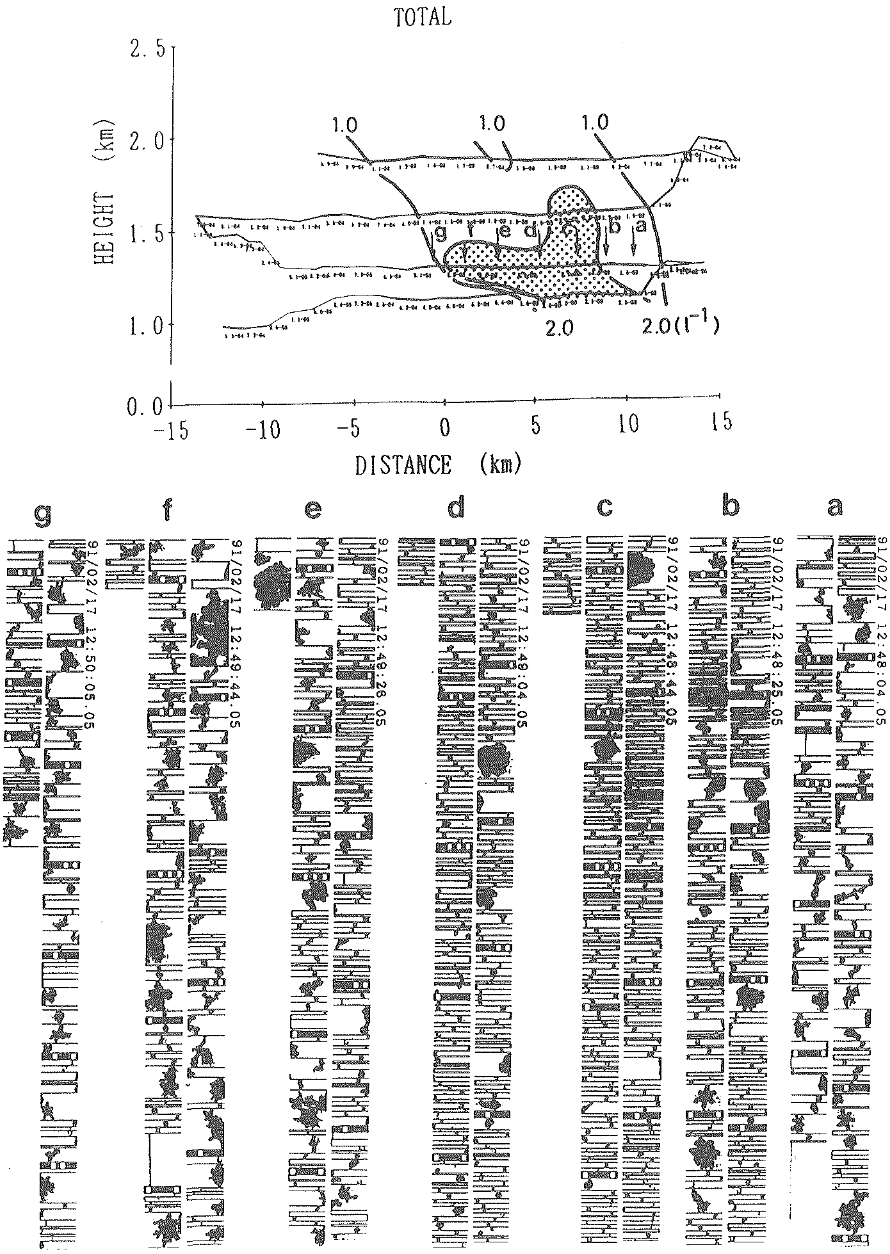


Fig. 8. Same as Fig. 7, but for 1.3 km a.s.l..

velocity and drag force, and they fell below the cloud base with droplets. They were recognized as snow trails from the observation aircraft. At the level of 1.6 (level B) and 1.9 km (level A) a.s.l., small ice particles, small sized graupel particles, and densely rimed dendrites were found. The concentration of droplets was also high at 1.6 km a.s.l., but it became low and several unrimed small dendrites were recognized at 1.9 km a.s.l.. It could not identified which particles worked as embryos of graupel particles. But it was surmised however that graupel particles grew up rapidly in the lower region of the cloud (below 1.6 km a.s.l.) by collecting an abundance of supercooled droplets. The densely rimed dendrites dominated the lower regions of cloud, except for the highly concentrated regions of graupel particles (in Fig. 5(c)). These regions corresponded to that of the air temperature, being warmer than -8°C, while the droplet concentration was 0.5-1.0 l^{-1}. Snowflakes or aggregates of dendritic crystals were concentrated above 1.6 km a.s.l. and the temperature was colder than about -10°C. Unrimed dendrites were observed at the edge of the cloud at 1.9 km a.s.l., at the temperature of about -12°C.

Figures 7 and 8 show the particle images at 1.9 and 1.3 km a.s.l., respectively. Typical examples of particle images were put side by side for 20 second intervals. Each sampling time from (a) to (i) column of the particle images is 1 second (the sampling distance is 75 m) and their sampling location is indicated by downward arrows in the upper vertical cross section of the flight track. In Fig. 7 (1.9 km a.s.l.), it was recognized that densely rimed large particles, which were lower in concentration, and droplets were observed at the center of the turret as shown in Fig. 7(c), and small and highly concentrated particles were observed adjacent to regions in the center, as shown in Fig. 7(d) and (g). Low concentration and large rimed particles were observed between the turrets as shown in Fig. 7(e) and (f). Unrimed dendrites and their aggregates were found at the edge of the clouds. In Fig. 8 (1.3 km a.s.l.), a large number of droplets and large graupel particles coexisted at the center of the turret as shown in Fig. 8(c) and (d). Rimed dendrites and their aggregates were also observed in the edge of cloud.

4. Considerations

Figure 9 represents a schematic illustration which simplified the results observed by the 2D-P probe. Plenty of supercooled droplets were observed in a relatively lower region of the cloud and graupel particles also dominantly were observed in the same region. The fact that graupel particles and small super-

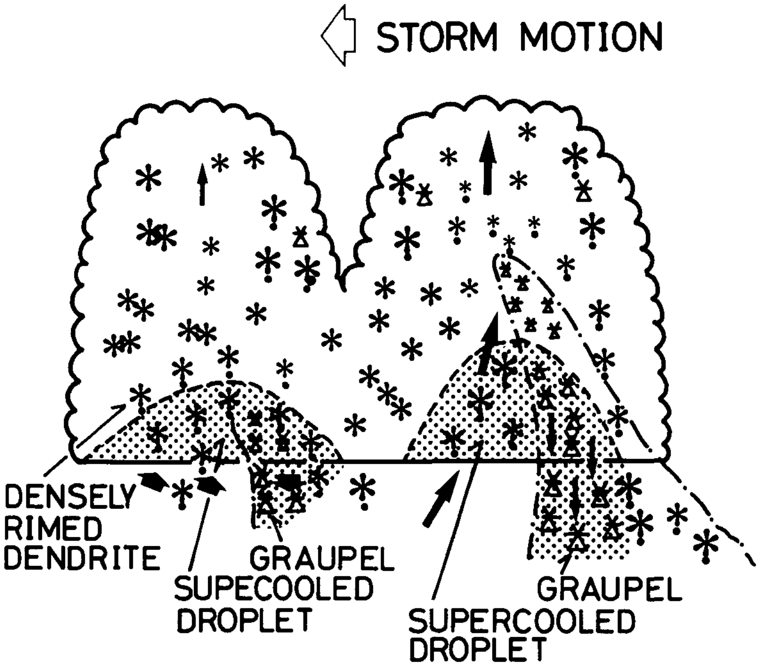


Fig. 9. A schematic illustration of observed cloud. Each symbol •, ✱, ✱, ∗ and ✱✱ indicates supercooled droplets, graupel particles, rimed dendrites, unrimed dendrites and snowflakes, respectively.

cooled droplets coexisted in the lower region in the cloud, allows surmise that the graupel particles grew rapidly by collecting an abundance of supercooled droplets. Small snow particles were observed in the center of the middle level of the cloud, about 2 km high, and a low concentration of large snow particles were present around the edges of the cloud. In the figure, solid arrows indicate the air flows which were inferred by the precipitation particles presented. An updraft which was presumed to be at the center of the turret extended from the cloud base to the higher level of the cloud. It would be surmised that a high number of supercooled cloud droplets would be produced there and they would grow to a size of 300-400 μm in diameter through the collision and coalescence processes. Graupel particles grew rapidly in the lower level of the cloud. A downdraft was induced by the large fall velocity and drag force owing to the large graupel particles. The downdraft, which was identified as a snow trail, then spread out on the sea surface. It was speculated that the updraft, which was located in front of the snow trail, was emphasized accompanying with the storm motion.

Blyth and Latham (1993) reported on the microphysical properties of summer cumulus clouds in New Mexico by aircraft observations. They suggested that the ice phase was formed firstly when the cloud attained a temperature of -10 to -12°C, and large drops were observed just before the formation of ice. They proposed the following scenario for the developing of the precipitation particles. Ice particles, which begin to form in the turret near a temperature of -10 to -12°C, will be transported to the lower levels of the cloud where they are incorporated into an updraft which is formed newly or existed already, or they linger around the cloud top until the arrival of a fresh turret. These ice particles act as graupel embryos and they grow quite quickly if the updraft or a fresh turret contains substantial liquid water. This scenario could be applicable to our observations. As described previously, the air temperature of the middle and lower levels of the cloud was between -6 and -12°C. A high number of supercooled droplets were observed there and the rapid growth of the graupel particles through riming was observed. The following similar points were also found ; (1) The larger graupel particles or larger particles were found in the regions where a low concentration of ice particles was observed. The smaller particles were found in a larger concentration. This result suggests the sorting of the particles in the updraft. (2) Aggregated crystals were observed near the temperature of about -10°C with low liquid water content. In our observations, we could not measure the velocities of the up and downdrafts. Thus in Fig. 9, the speculated vertical velocity has been drafted. And we could not identify the graupel embryos from the images obtained because of their smaller sizes. More detailed observations should be made over the Japan Sea, particularly, in winter monsoon seasons.

5. Concluding remarks

Aircraft observations were carried out off-shore Wakasa Bay over the Japan Sea on February 17, 1991. The aircraft passed across the precipitating band-shaped clouds which were often observed in the winter monsoon condition. Graupel particles and a number of supercooled cloud droplets coexisted near the cloud base. It was surmised therefore that the graupel particles grew rapidly near the cloud base by collecting the small supercooled cloud droplets. It is important to clarify the microphysical and dynamical properties in the band-shaped clouds in order to understand the mechanisms of the localized heavy snowfalls brought by graupel particles and densely rimed snow crystals, or snowflakes, along the west coast of northern Japan.

Acknowledgments

We would like to express our appreciation to Prof. M. Tanaka and Dr. T. Hayasaka, Tohoku University, and Prof. T. Takeda and Dr. T. Ishizaka, Nagoya University for their support of this observation. And also we would like to express our appreciation to the crew members of the Nakanihon Air Service Co. Ltd., Nagoya. This work was done by a special fund from "The World Climate Research Programme (WCRP)" in Japan, supported by the Ministry of Education, Science, and Culture of Japan.

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