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VERTICAL STRUCTURE IN CONVECTIVE CLOUDS PRODUCING GRAUPELS AND SNOWFLAKE AGGREGATES

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Abstract: This paper describes the vertical air motion and evolution of snow particles in snow clouds that bring heavy snowfall to the north-east coast of the Sea of Japan in winter. The vertical winds are investigated in detail by single Doppler radar and by simultaneous measurement of particle diameter and fall velocity at the radar site.

Graupels were formed near the cloud top where updraft was prevailing; they fell in the downdraft region below the cloud base. The downdraft was probably produced by drag force of falling graupels. On the other hand, aggregates grew slowly in comparatively weak updrafts between the cloud top and the ground. When the cloud top was high and the number concentration of the particles was large, the ratio of large aggregates increased because particles aggregate themselves while falling a long distance.

1. Introduction

On the Sea of Japan coast heavy snowfalls from convective clouds are frequently brought by the prevailing north-west wind in winter. In Sapporo, which is located near the north-east coast of the Sea of Japan, the type of snow particles falling on these days is almost always graupel or snowflake aggregate, and it often changes from graupel to aggregate and sometimes from aggregate to graupel at intervals of about 10 min during snowfall. Though the clouds bring high snowfall intensity and the convective activity is large, the clouds are shallow. The highest cloud top is usually about 3–4 km and the cloud base is 1 km.

The present paper describes the vertical structure in the clouds using a Doppler radar comparing with the change of precipitating particles observed at the radar site. The differences in the clouds between the mature stage producing graupel particles and the decay stage producing snowflake aggregates are investigated in detail. The vertical evolution of these particles is also considered.

2. Observation

Observation of snow particles of winter convective clouds were carried out at

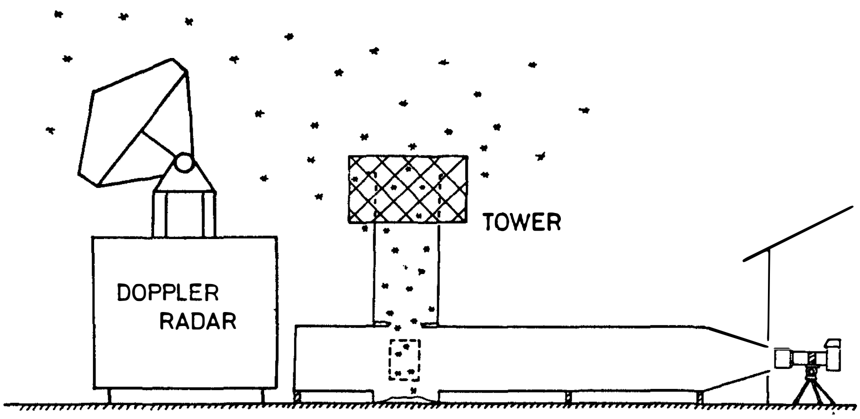

Fig. 1. Section of observation tower and Doppler radar.

the Institute of Low Temperature Science in Sapporo in 1986. A 3-dimensional-scan Doppler radar (wavelength 3.2 cm) and an observation tower to measure the diameter and fall velocity of snow particles continuously were installed on the roof of the main building (Fig. 1). The radar provided the reflectivity factor and mean Doppler velocity of the precipitation particles at 62.5 m intervals up to 10 km altitude. The lower threshold of reflectivity was 10 dBZ and the Doppler velocity resoultion was 12.5 cm/s.

The size of the tower was 3 m (in height) $\times$ 0.9 m $\times$ 0.6 m and trajectories of snow particles falling into the tower were photographed three times per minute illuminated by a stroboscopic light. The diameter, the fall velocity and the number concentration of observed particles were obtained from analyzing photographs.

3. Results

Snow particles were observed in the winter of 1986. The cases mentioned later are typical for change of the snow particle type during a snowfall. The relationship between the average diameter and the fall velocity of particles during a snowfall is shown in Fig. 2, which was measured on February 25, 1986. An open circle in this figure shows the relation between the diameter and the fall velocity of particles averaged in a minute. This averaged relation is similar to that in previous works for individual snow particles (*e.g.*, LOCATELLI and HOBBS, 1974; KAJIKAWA, 1974). This snowfall lasted for about 40 min. In this figure, the region of graupels is separated from that of aggregates; the fall velocity of graupels became larger in proportion to the size and, on the other hand, the fall velocity of aggregates was almost constant for the size range between 1 mm and 3 mm in average diameter. Two types of particle, graupels and aggregates, were rarely observed to fall at the same time on the ground. From the time sequence during a snowfall (not shown here), the fall velocity of graupels was large at first and gradually decreased. However, the fall velocity and the diameter of aggregates were almost constant throughout the snowfall. Similar change of velocity in a snowfall was found in other cases.

The time-height cross section of radar reflectivity and the change of snowfall rate at the ground on this day are shown in Fig. 3. The snowfall rate was high at first when graupels were falling, and it gradually decreased with the the decrease of height

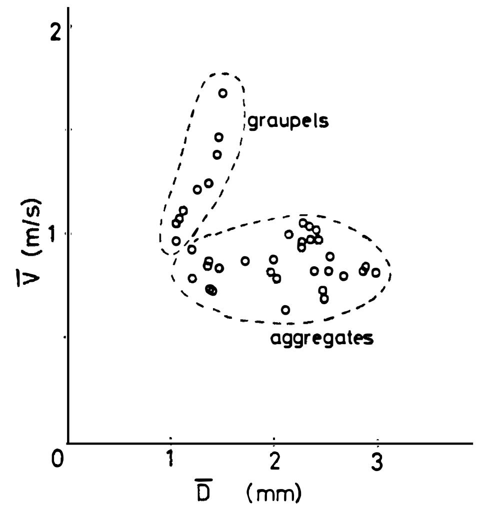

Fig. 2. The relationship between averaged diameter and fall velocity of particles.

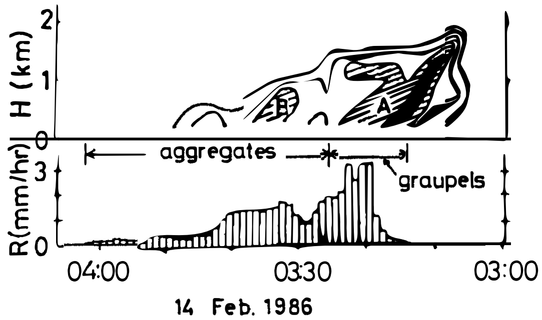

Fig. 3. Time-height cross section and snowfall rate during snowfall. Contour lines of radar echo are 15, 20, 25 and 30 dBZ (Feb. 14, 1986).

of the echo top. The type of snow particles changed at 0325 from graupels to aggregates at the radar site. Comparing the cross section of reflectivity with the snowfall rate, the hatched region A and the hatched region B were inferred to consist of graupels and aggregates, respectively. Though the height of the echo top in region A was low (2 km), the convective activity might be large because snow particles brought by the cloud were graupels. According to radar echoes on the PPI, the horizontal scale of the graupel region was about 10 km and the center of the region passed over the observation point.

Next, the vertical Doppler velocity was compared with snow particle fall velocity to derive the vertical air motion in the cloud. Figure 4 shows the correlation between the averaged fall velocity of the particles on the ground and the Doppler velocity at a height of 250 m, which was the lowest altitude measured by the radar, in two cases of snowfall including the above case. The vertical Doppler velocity in the sum of the

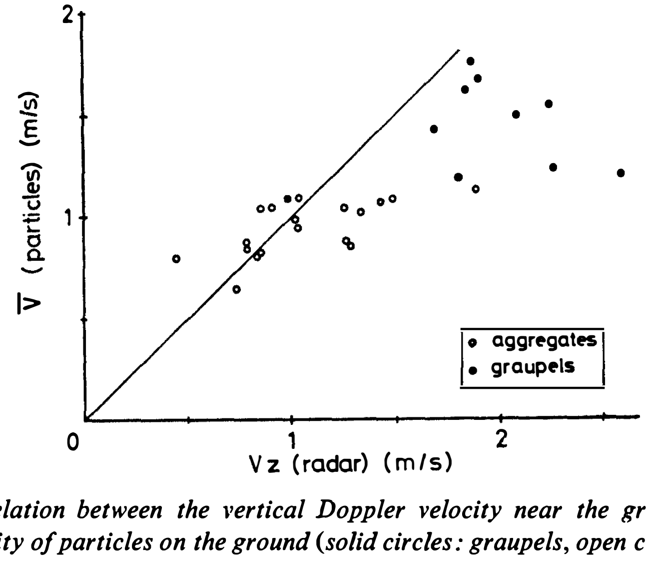

Fig. 4. Correlation between the vertical Doppler velocity near the ground and averaged fall velocity of particles on the ground (solid circles: graupels, open circles: aggregates).

vertical air speed and fall velocity of snow particles. Assuming that near the ground, particles do not grow and the fall velocity of particles does not change, the difference between the two velocities indicates the vertical air motions near the ground. For aggregates (open circles), the difference of the two velocities is usually smaller than 50 cm/s, so the vertical air motion is considered to be small. On the other hand, for graupels (solid circles), the Doppler velocity is nearly 1 m/s larger than the particle velocity. It is concluded that graupels fall into the downdraft region at about 1m/s, however, aggregates fall into air with almost no vertical motion near the ground.

To compare the vertical velocity in the upper air for the cases in Fig. 4, the vari-

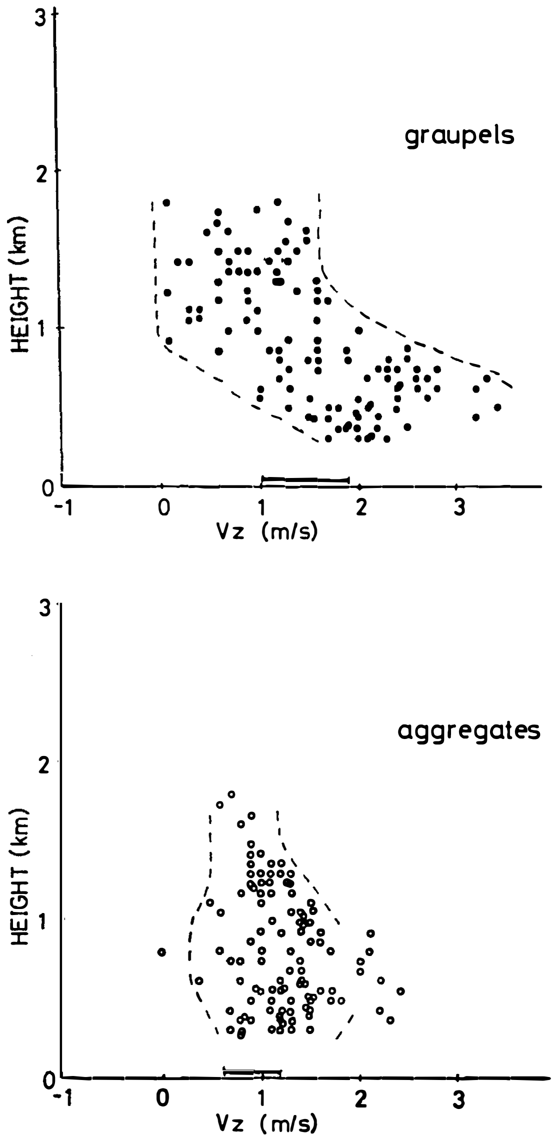

Fig. 5. Vertical distributions of vertical Doppler velocities for high reflectivity (>25 dBZ) graupels (upper figure) and aggregates (lower figure). Solid lines at 0 km indicate the range of the fall velocity of these particles observed at the ground.

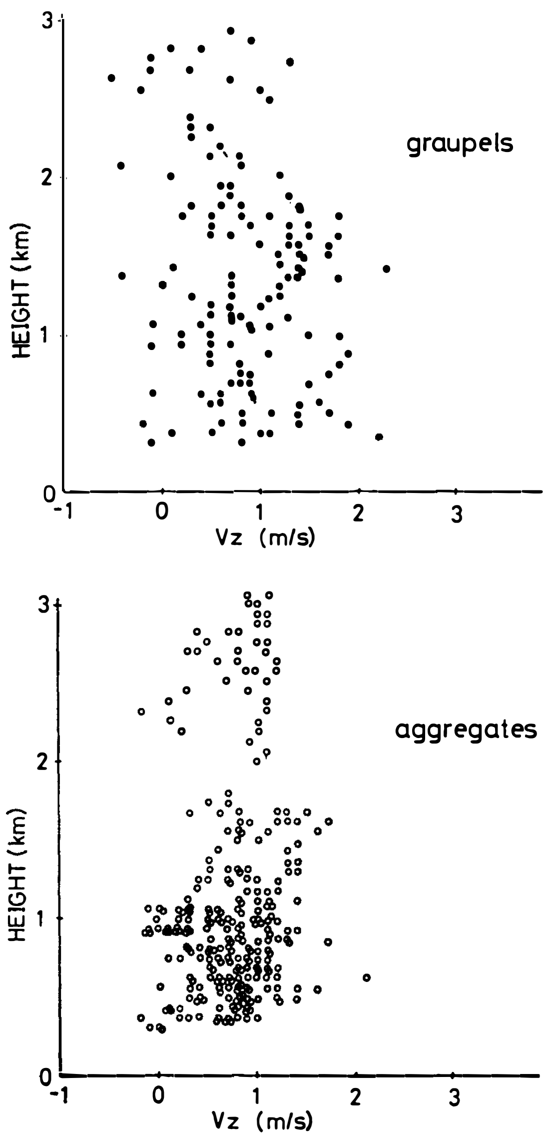

Fig. 6. Same as Fig. 5 but for low reflectivity region (<20 dBZ).

ation of vertical Doppler velocity with height for graupels and aggregates, is shown in Figs. 5 and 6. Figures 5 and 6 correspond to high (>25 dBZ) and low (<20 dBZ) reflectivity regions, respectively. In the graupel region with high reflectivity, the Doppler velocity was small (about 1 m/s) inside the clouds and large (>2.5 m/s) at the level just below the cloud base as compared with the fall velocity of particles at the ground. The height of the visible cloud base was about 1 km in winter for convective clouds, sounding data near the radar site also indicated that the base was at 1 km. On the other hand, for aggregates, the averaged vertical velocity was about 1 m/s, almost constant between the cloud top and the ground for any reflectivity.

In the low reflectivity region (Fig. 6) including the clound top and cloud edge, convection was active in the graupel region because the velocity fluctuated broadly from −0.5 m/s to 2.3 m/s at every height. The remarkable difference of velocity between high and low reflectivity regions is seen below the clouds. Below the clouds, the downdraft became large as the graupels, were falling from the cloud base.

Figure 7 shows four cases of variation of reflectivities and vertical Doppler velocities in the echo core region from the echo top to the ground. Corresponding size spectra

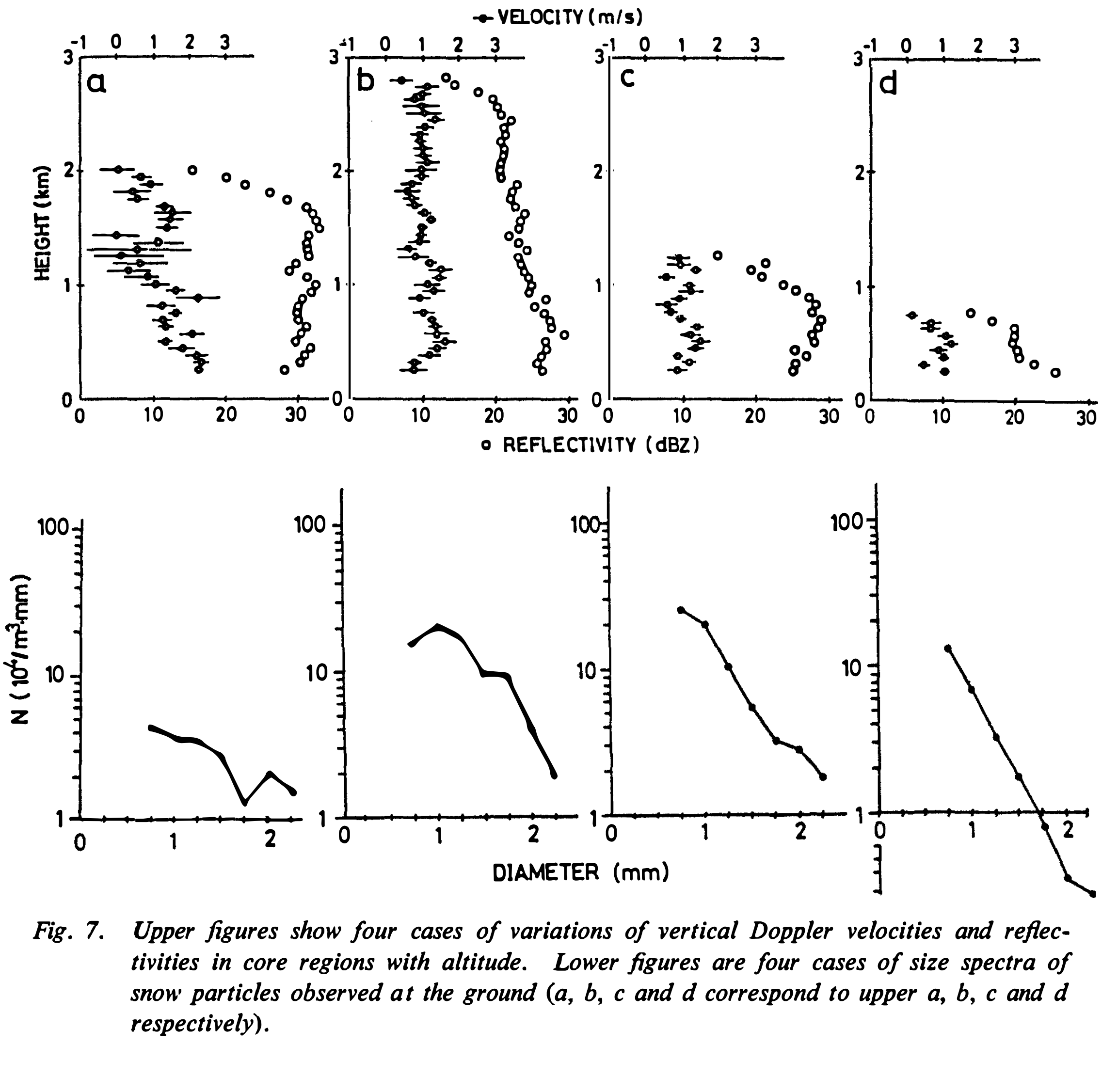

Fig. 7. Upper figures show four cases of variations of vertical Doppler velocities and reflectivities in core regions with altitude. Lower figures are four cases of size spectra of snow particles observed at the ground (a, b, c and d correspond to upper a, b, c and d respectively).

of snow particles at the ground with the radar echoes are also shown in this figure. For graupels (case a) the vertical Doppler velocity gradually increased from the cloud base to the ground, although the reflectivity showed no clear difference between the echo top and the ground. Inside the cloud, convective activity was inferred to be larger than below the cloud, because the ranges of Doppler velocity shown by bars were larger. The updraft is probably large because high reflectivity regions extended close to the echo top.

For aggregates (cases b, c and d) the vertical Doppler velocity changed little between the echo top and the ground. The radar reflectivity of the lower levels gradually increased in the case of large snowfall intensity on the ground (case b). In the case of small snowfall intensity (case d), however, reflectivity varied sharply near the ground. The size spectra of aggregates on the ground (b, c, d) shows increasing concentration of particles with increasing altitude of echo top. The ratio of large particles also increase toward the echo top (since the slopes of the spectra become small). The sizes of crystals in aggergates were similar to each other during the snowfall. Therefore it is expected that the aggregates became large during falling down to the ground by

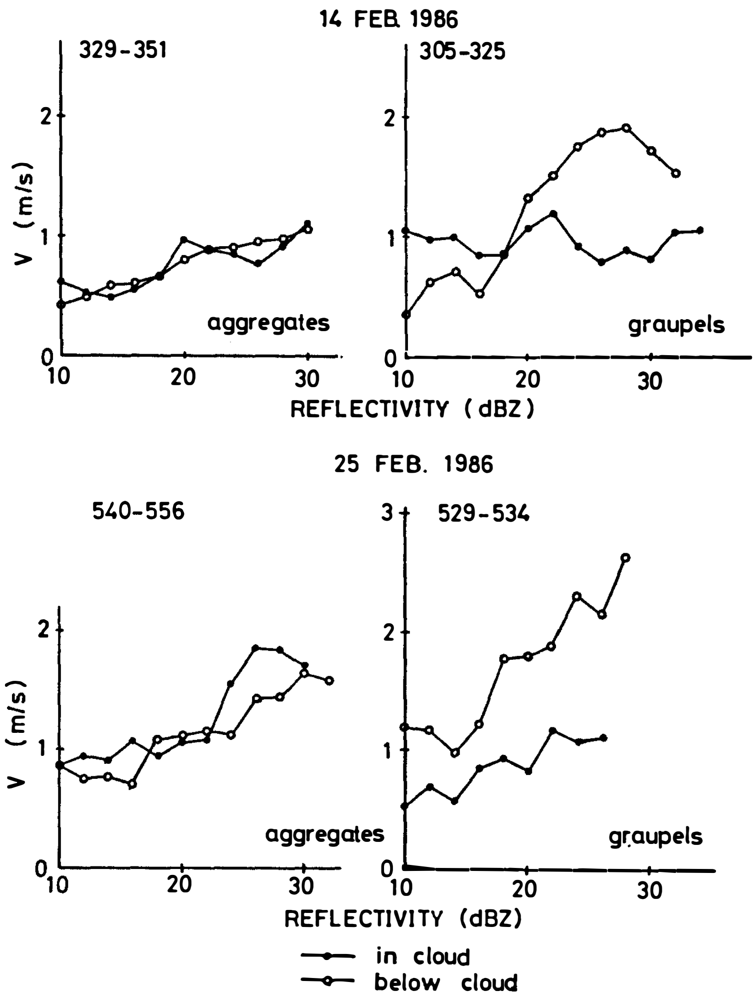

Fig. 8. The relationship between the reflectivity and vertical Doppler velocity for graupel cloud and aggregate cloud.

colliding with each other as shown by PASSARELLI (1978), and by KENNETH and PASSARELLI (1982). They indicated that aggregates advanced with descending altitude, judging from the height evolution of snow size spectra measured by an aircraft in natural clouds.

Figure 8 shows the relationship between the reflectivity and the vertical Doppler velocity for the two series of snowfall that brought the graupels and aggregates. The difference between "in clouds" and "below clouds" for graupel is greater than for aggregates. For aggregates it is difficult to distinguish "in cloud" from "below cloud". It is supposed that the vertical air motion in the aggregate region only depends on reflectivity, and doesn't change from "in cloud" to the ground. The vertical motion containing aggregates is small. For graupels the change of velocity with reflectivity is small in the clouds, but large below clouds. The large difference, about 1 m/s between "in" and "below cloud", indicates that the downdraft is prominent below clouds, especially in the high reflectivity region.

4. Summary

The vertical Doppler velocity was measured and simultaneously the diameter and the fall velocity of snow particles were measured at the radar site during a snowfall. The vertical air motion and the evolution of snow particles in the winter convective clouds were investigated in detail. The snow particles produced in the clouds were graupels and snowflake aggregates.

When the graupels were falling, the fall velocity was large at first and gradually decreased to about 10 min. The Doppler radar data suggest that graupels were formed near the cloud top where updraft prevailed and convective activity was large; they fell and separated vertically by their own fall velocity below the cloud base, where a downdraft was probably caused by falling graupels. Especially in the high reflectivity region, the downdraft was prominent below clouds.

On the other hand, the vertical air motion in the aggregate region only depended on reflectivity. It is expected that aggregates grew slowly in comparatively weak upcurrents between the cloud top and the ground. When the cloud top was high and the number concentration of particles was large, the ratio of large aggregates increased because particles aggregated themselves while falling along distance.

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