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ANNUAL VARIATION OF SNOWFALL AND RADAR ECHO STRUCTURE OF SNOW CLOUDS AT SYOWA STATION, ANTARCTICA

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Abstract: Snow clouds were observed with vertical pointing radar at Syowa Station from February 1988 to December 1989. In order to find the Z–R relationship, the snowfall rate was directly measured by using an electric balance at the ground. The annual amount of snowfall was estimated to be 400 mm in 1989 when we used $Z=16\cdot R^{1.3}$. The amount of snowfall was 120 mm in spring (from October to November), 170 mm in fall (from February to April), and 70 mm in winter (from June to July). It was less than 20 mm in summer (from December to January).

Two types of clouds were found to appear above Syowa Station: one had a low cloud top (less than 2 km) and the other had a higher cloud top. The former clouds occurred predominantly in winter and the latter in spring and fall. The higher type clouds are related to the warm front of a low pressure system. The activity of lower type clouds are related to the temperature and humidity in the clouds. These conditions might be connected with the area of sea ice.

1. Introduction

It is important to establish a method of measuring snowfall amount in Antarctica. The annual snowfall has been estimated from change in depth of accumulated snow near Syowa Station (for example, MURAKOSHI, 1958; NARUSE *et al.*, 1971). However, this is not necessarily the amount of snow that fell at the estimation site, since accumulated snow is often redistributed under windy conditions. KIKUCHI *et al.* (1981) estimated the annual amount of snowfall as 430 mm by using duration of precipitation and the average maximum precipitation intensity calculated from replicas of snowflakes on glass slides. But this estimation is rough and doesn't indicate the amount of each snowfall.

It is very difficult to measure the snowfall rate directly at the ground when wind blows hard. Recently FUJIYOSHI *et al.* (1990) succeeded in estimation of snowfall using radar. This indirect method can provide a good estimation of snowfall rate whether wind blows hard or not.

In this paper we will describe a method to estimate the amount of snowfall by using vertical pointing radar at Syowa Station, Antarctica, and show the change of the daily amount of snowfall through the year. Next we will show the radar echo structure of snow clouds. Finally we will discuss the causes of the difference type of clouds observed at Syowa Station.

2. Instrument

At Syowa Station (69°S, 40°E) located on the coast of Antarctica, vertical pointing radar was used to measure the amount of snowfall and the ice water content in the atmosphere continuously in 1988–1989. Characteristics of the radar were reported by WADA (1990). Radar echo intensity Z (dBZ) was sampled every 50 m up to 6.4 km at intervals of 10 s.

A highly sensitive snow gauge (KONISHI *et al.*, 1988) was used to measure snowfall rate. The gauge measures the weight of snowfall in a bucket on a balance automatically at one minute intervals and the weight data are stored in a computer connected to the balance by a cable. The minimum detectable snowfall rate of this gauge was 0.062 mm/hr. The snow gauge was shielded by wooden walls to protect the electric balance from strong wind. However, we used the weight data only when the wind was weaker than 5 m/s because the balance measured the weight of not only precipitation particles but blowing snow particles which fell into the bucket under strong windy conditions. As the radar echo intensity below the level of 400 m was influenced by ground clutter, the data at the level of 400 m were compared with those of a snow gauge.

3. Results

3.1. Estimation of the amount of snowfall

The vertical pointing radar was operated continuously from February 1988 to December 1989. The relationship between Z and R (mm/hr) is usually written by the following equation, $Z=B\cdot R^{\beta}$. Figure 1 shows the Z–R relationship on February 28, 1989. Each solid circle indicates the averaged value for 5 min. The coefficients B and β were determined from the regression line. We calculated the coefficients B and β only for cases in which the surface wind speed was smaller than 5 m/s and the snowfall continued for at least several hours. The total number of cases was 20 during the observation period from February to December 1989. The snowfall rate at Station was usually weak; the maximum snowfall rate averaged over 5 min rarely exceeded 1 mm/hr. The coefficient B ranged from 11 to 61 and β from 1.0 to 1.3. These values are almost the same as those summarized by SATO *et al.* (1981). The values of 16 and 1.3 for B and β, respectively, were chosen to estimate the snowfall rate from radar echo intensity in this paper. The coefficients calculated in all cases were similar to these coefficients.

Figure 2 shows the daily snowfall from February to December 1989. The precipitation was detectable by radar on more than 130 days. The daily snowfall was almost always less than 5 mm. The total amount of snowfall was 397 mm from

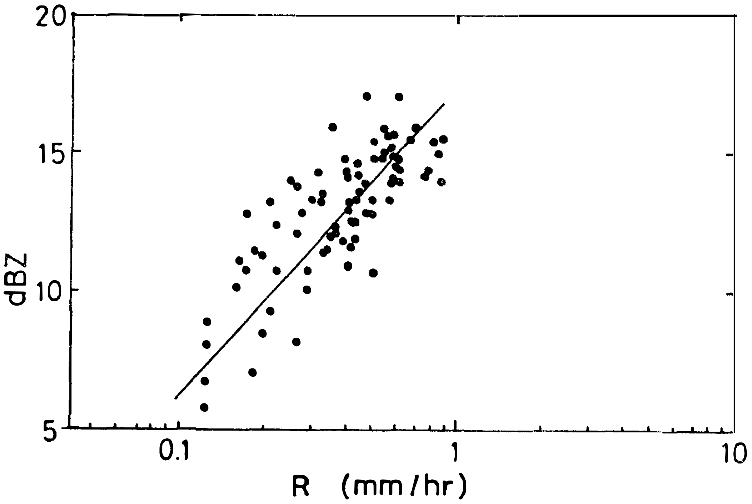

Fig. 1. One example of a Z–R relation at Syowa Station on February 28, 1989. Each circle shows the averaged radar reflectivity factor and snowfall rate for 5 min.

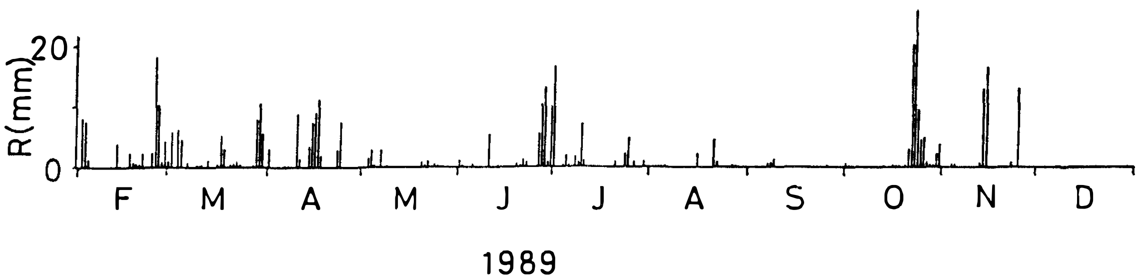

Fig. 2. Time variations of daily snowfall.

February to December. The data of snowfall in January were not shown in this figure, but there was little snowfall in January. Hence the annual amount of snowfall in 1989 at Syowa Station would be about 400 mm.

Figure 2 indicates that there were three snowy seasons at Syowa Station. The longest snowy season was from February to April in fall. The total amount of snowfall in this season was about 170 mm. Another season appeared in winter. The total amount of snowfall in this season was 70 mm. The amount of snowfall was small, since the air temperature is low and the precipitable water was little in this season. The other season was from October to November in spring; the total amount of snowfall in this season was 120 mm. The peak value of daily snowfall was larger in this season than in other seasons. This indicates that the amount of snowfall was larger for each snowfall event in this season than in other seasons.

3.2. Seasonal variation of cloud tops

The appearance frequency of echo tops is shown in Fig. 3. In fall from February to April the height of echo tops ranged widely from 1 km to over 6.4 km; most clouds appeared below 3 km. In winter (June and July) the height of the echo top was usually less than 2 km. It was usually larger than 4 km in spring (October and November). Figure 3 also shows the monthly mean temperature calculated from aerological sound-

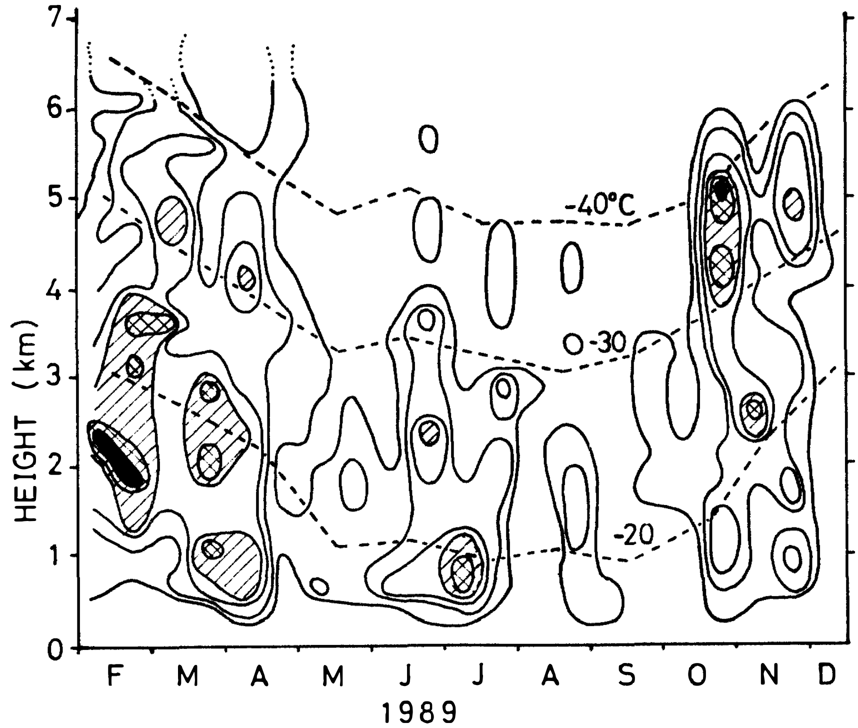

Fig. 3. Time variations of echo top height frequency. The frequency is summed every half month at 250 m height intervals. Contour lines are depicted every 2 hours of frequency. The hatched region indicates 8 hours, double hatched region 10 hours and black region 12 hours. The monthly average upper air temperatures are also depicted broken line.

ing data. The level of −40°C showed similar seasonal variation to that of the highest echo top. The same results were also found for snow clouds in Arctic Canada by FUJIYOSHI *et al.* (1982). Since spontaneous freezing of small droplets occurs at −40°C, the existence of supercooled droplets near the cloud top is suggested even in Antarctica.

Figure 4 shows the appearance frequency of the maximum echo intensity related to the echo tops. The maximum echo intensity is defined as the maximum value of echo intensity from the echo top to the ground. To see the difference in pattern of frequency between the seasons, three examples, in April, July and October were shown in this figure. It is expected that the maximum echo intensity would increase with increasing height of the echo top. All of the hatched regions above 2 km indicate a good correlation between them. On the other hand, the lower clouds below 2 km show a wide range of maximum echo intensity, and the maximum echo intensity does not depend on the echo top height. These facts suggest that the clouds were classified into two types, the lower type in which the echo top was below about 2 km and the higher type in which the echo top was above about 2 km. In July the frequency of the higher type was small. In October the distribution was similar to that in April, but in the case of the higher type of clouds, larger maximum echo intensity is found in October than in April. In comparison with monthly mean temperature, the lower type of snow clouds was formed in a layer warmer than −25°C.

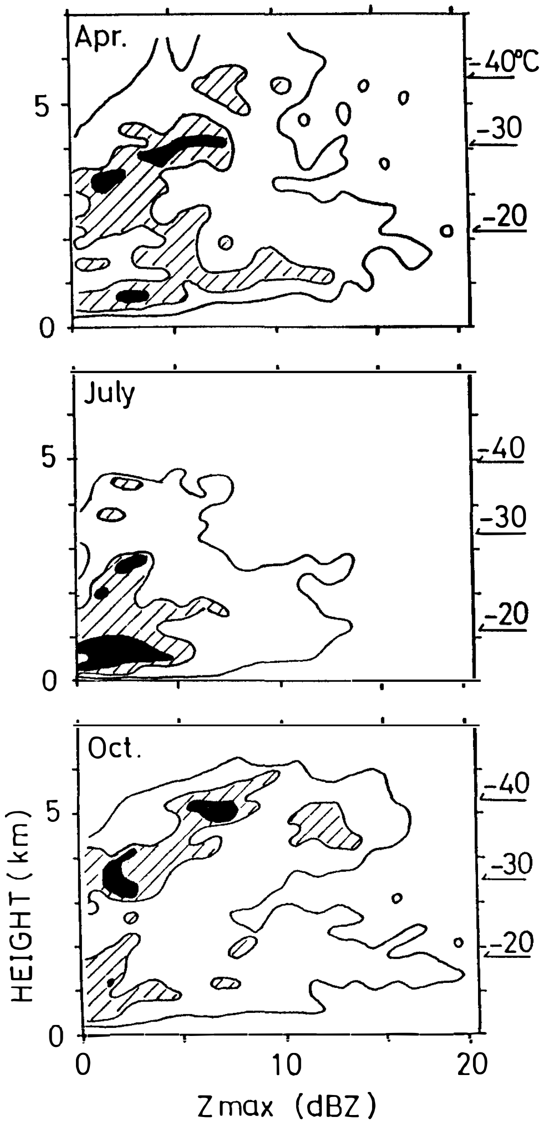

Fig. 4. Frequency of the maximum echo intensity related to echo top. The frequency is summed at 250 m height intervals for echo top, and each 2 dBZ for Z_{max}. Solid line shows 10 min, and hatched region 50 min and black region 100 min. Also the mean height of each temperature is shown.

4. Discussion

The clouds at Syowa Station on the coast of Antarctica were classified into two types by using vertical pointing radar. The higher type clouds having echo top temperature near −40°C often appeared in fall and spring. In these seasons low depression systems from middle latitudes frequently approach the coast of Antarctica. When the higher type clouds appeared above Syowa Station, the wind at 500 mb was usually from the north, which brought warm and moist air. Therefore it is expected that the higher type clouds would be produced by forced upward motion, as when a warm front accompanied an extratropical cyclone.

On the other hand, the lower type clouds appeared in all seasons when we observed. But a seasonal change was found in appearance frequency of these clouds. The occurrence rate of lower clouds was less in spring (October and November). It is expected that lower clouds would develop from the vapor and heat brought by cold air blowing over the warm sea surface. Therefore the available area of open sea to supply humid air to lower clouds might be less in spring than in fall. The difference of seasonal variation in occurrence of lower clouds would be connected with the annual variation of distance from the edge of sea ice, which grows large in early spring.

The maximum echo intensity in lower type clouds shows a wide range from 0 to 20 dBZ. The maximum echo intensities of the lower clouds were large enough to compare to the higher clouds. It is interesting to consider the mechanism of producing high echo intensity in lower type clouds. The size and number of snow particles must be increased rapidly with descent from the echo top to the height of maximum echo intensity in these clouds. Snow particles falling from lower type clouds were frequently aggregates of dendrites or dendrite crystals observed on the ground during weak wind. Since dendrite type crystals grow faster than other type crystals, columns or plates, and the range of temperature in these clouds spans $-15°C$, at which dendrite type crystals grow, it is expected that dendrite type crystals grew fast in the lower clouds and made the echo intensity increase rapidly.

In lower type clouds with weak echo intensity, snow particles would not grow large because the temperature or vapor is not suitable for their rapid growth. When the temperature on the ground was below $-15°C$, implying that the temperature in the clouds was much lower, the echo intensity was usually weak.

5. Summary

Continuous measurement of precipitation with vertical pointing radar reveals the annual variation of precipitation and radar echo structure of clouds in detail. To compare radar reflectivity with ground truth snowfall data, a highly sensitive snow gauge was used when the wind speed was weak. The yearly amount of snowfall was estimated to be 400 mm in 1989. The seasonal variation of snowfall suggests that precipitation occurred in all seasons except summer. The clouds were classified into two types: those with echo tops lower than 2 km and those with echo tops higher than that. In winter, the lower type clouds were predominant; in spring and fall, the higher type clouds were frequent.

The higher type clouds seem to be related to warm fronts associated with low pressure system. And the activity of the lower type clouds might be connected with the area of sea ice. Further work is needed to relate the cloud type to these other factors in individual cases.

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