



HOKKAIDO UNIVERSITY

Title	Studies on the Characteristics and Seasonal Variations of Precipitation Phenomena Obtained by Radar Observations at Syowa Station, Antarctica
Author(s)	Konishi, Hiroyuki
Degree Grantor	北海道大学
Degree Name	博士(理学)
Dissertation Number	乙第4904号
Issue Date	1996-03-25
DOI	https://doi.org/10.11501/3112093
Doc URL	https://hdl.handle.net/2115/51337
Type	doctoral thesis
File Information	000000297285.pdf



STUDIES ON THE CHARACTERISTICS
AND SEASONAL VARIATIONS OF
PRECIPITATION PHENOMENA OBTAINED
BY RADAR OBSERVATIONS
AT SYOWA STATION, ANTARCTICA

Hiroynuki Konishi

①

ABSTRACT.....1

Chapter 1. Introduction.....2

Chapter 2. Methods of observation.....3

2.1. Instruments.....3
2.2. Data sources.....3

Chapter 3. Evaluation of amount of precipitation.....4

3.1. Relation between radar reflectivity and rainfall rate.....4

3.2. Total amount of precipitation in 1989 at Syowa.....4

3.3. Relation of amount of precipitation and wind speed.....4

Chapter 4. Precipitation phenomena obtained by radar observations.....5

4.1. Classification of precipitation.....5

4.2. Frequency of occurrence of precipitation.....5

4.3. Frequency of occurrence of large amount of precipitation.....5

4.4. Frequency of occurrence of large amount of precipitation in 1989.....5

4.5. Frequency of occurrence of large amount of precipitation in 1989.....5

4.6. Frequency of occurrence of large amount of precipitation in 1989.....5

4.7. Frequency of occurrence of large amount of precipitation in 1989.....5

4.8. Frequency of occurrence of large amount of precipitation in 1989.....5

4.9. Frequency of occurrence of large amount of precipitation in 1989.....5

4.10. Frequency of occurrence of large amount of precipitation in 1989.....5

Chapter 5. Seasonal variations of precipitation phenomena in 1989 at Syowa Station, Antarctica.....6

5.1. Seasonal variations of amount of precipitation.....6

5.2. Seasonal variations of frequency of occurrence of precipitation.....6

5.3. Seasonal variations of frequency of occurrence of large amount of precipitation.....6

5.4. Seasonal variations of frequency of occurrence of large amount of precipitation in 1989.....6

5.5. Seasonal variations of frequency of occurrence of large amount of precipitation in 1989.....6

Chapter 6. Discussion.....7

6.1. A necessary condition for large amount of precipitation near Syowa Station.....7

6.2. Contribution to the snow accumulation near Syowa Station.....7

6.3. Contribution to the snow accumulation near Syowa Station.....7

6.4. Contribution to the snow accumulation near Syowa Station.....7

6.5. Contribution to the snow accumulation near Syowa Station.....7

6.6. Contribution to the snow accumulation near Syowa Station.....7

6.7. Contribution to the snow accumulation near Syowa Station.....7

6.8. Contribution to the snow accumulation near Syowa Station.....7

6.9. Contribution to the snow accumulation near Syowa Station.....7

6.10. Contribution to the snow accumulation near Syowa Station.....7

Chapter 7. Conclusions.....8

Acknowledgments.....9

References.....9

Figures and Tables.....10

Hiroyuki Konishi

Contents

ABSTRACT.....	1
Chapter 1. Introduction.....	4
Chapter 2. Methods of observation.....	9
2.1. Instruments.....	9
2.2. Data sources.....	10
Chapter 3. Estimation of amount of precipitation.....	12
3.1. Relation between radar reflectivity and snowfall rate obtained by snow gauge of electric balance type.....	12
3.2. Total amount of precipitation in 1989 at Syowa Station, Antarctica.....	15
Chapter 4. Characteristics of precipitation phenomena over the coastal region around Syowa Station, Antarctica.....	17
4.1. Cloud vortex associated with extratropical cyclones....	17
4.1.1. Classification of vertical structure of precipitating clouds.....	17
4.1.2. Synoptic scale features for the cloud types classified.....	20
4.1.3. Vertical structure of cloud vortex in mature stage..	22
4.1.4. On the case of the cloud vortex that caused the largest amount of precipitation in 1989.....	23
4.2. Cloud evolution across the coast near Syowa Station....	25
4.2.1. Enhancement of precipitation in clouds with large liquid water content across the coast near Syowa Station.....	25
Chapter 5. Seasonal variations of precipitation phenomena in 1989, at Syowa Station, Antarctica.....	28
5.1. Seasonal variations of the amount of precipitation.....	28
5.2. Seasonal change of characteristics of clouds with respect to cloud height.....	30
5.3. Seasonal variations of cloud characteristics with respect to liquid water content.....	32
5.4. Seasonal tendency of trajectory of low pressure center..	34
Chapter 6. Discussion.....	37
6.1. Necessary conditions for large amount of precipitation near Syowa Station.....	37
6.2. Contribution to the snow accumulation near Syowa Station.....	38
Chapter 7. Conclusions.....	41
Acknowledgements.....	45
References.....	46
Figures and Tables.....	50

ABSTRACT

Long-term observations of precipitating clouds were carried out by a vertical pointing radar, PPI radar and a 37 GHz microwave radiometer at Syowa Station ($69^{\circ}00'S$, $40^{\circ}35'E$), Antarctica in 1989. The results obtained include the characteristics and seasonal variations of snowfalls. The former revealed the cause of precipitation near Syowa Station, Antarctica.

It is concluded from the observations that precipitation near Syowa Station, Antarctica is mainly brought by cloud vortices associated with extratropical cyclones which advance to high latitude while developing to a mature stage. It is proposed that the outer side of the cloud vortex is composed of layer clouds above the warm front formed by warmer air advancing southward from low latitude. The warmer air is considered to be raised above the colder and drier air circulating westward around the polar high along the coast near Syowa Station, Antarctica. The inside of the vortex is composed of convective clouds formed in colder air rotating around the low center along the well-developed spiral. Therefore the cloud vortex is concluded to be created by the occluded front composed of the cold front up-gliding above the warm front.

Precipitation from an occluded front crossing over Syowa Station was often observed when the low pressure center was stationary northwest of Syowa Station. The time-height cross sections of radar echoes in this case are considered to be normal cross sections of cloud vortex. It is concluded from the observations that the necessary conditions to bring large amount of precipitation to the coastal region near Syowa Station, Antarctica are that the low pressure system is in its mature stage, locates

northwest of the region, and is stationary. Especially, a low pressure in its mature stage northwest of the station would bring a large amount of precipitation for a long time when the low pressure center moves westward in accordance with the orientation of the cloud band of cloud vortex.

The seasonal variations of clouds and precipitation were analyzed corresponding to the seasonal changes of air temperature and sea ice area. The echo top height of stratified deeper clouds accompanied by the warm front changed with season corresponding to the change of height of -40°C . On the contrary the occurrence frequency of convective lower clouds decreased in winter and spring seasons when the air temperature is the lower and the sea ice area is the larger. The seasonal variations of the amount of vertically integrated liquid water content obtained by microwave radiometer also showed a similar trend corresponding to the seasonal change of sea ice area. The clouds having large amount of water content of liquid phase were frequently observed in fall when the open sea ice area expanded to Syowa Station. However, clouds in liquid phase were seldom observed in the austral winter and spring seasons when the sea ice area expanded to lower latitudes.

The air temperature and the sea ice area influence not only activities of cloud systems but also activities and trajectories of low pressure system accompanied by cloud vortex. The occurrence frequencies of cloud vortex which brought snowfall to Syowa Station increased in fall and spring seasons corresponding to activity of the circumpolar trough. However, the activities of cloud systems that brings precipitation are weakened in spring when the sea ice area expands to low latitudes, because of less supply

of heat and vapor. Thus the activities of cloud vortex are also weakened above the sea ice. In comparison with fall and spring, precipitation occurred frequently in fall associated with low pressures, whereas, precipitation occurred occasionally in spring associated with low pressures. Therefore if the amount of precipitation caused by each low pressure system varies, the amount of precipitation in spring can be expected to change more often from year to year than that in fall.

In 1989, the amount of precipitation in spring brought by a few snowfall events was as large as the amount of precipitation in fall brought by frequent snowfall events. Radar observations revealed that there were three abundant snowfall seasons at Syowa Station and the amount of snowfall was uniform in all season except summer. The amounts of precipitation in fall, winter and spring seasons were 74, 74 and 53 mm respectively. The amounts of precipitation in fall and winter were large at Syowa Station in 1989. However, it is expected that the amount of snow in the continent would be small in winter from the distributions of precipitation measured by the PPI radar. Deeper clouds having much liquid water content caused a large amount of precipitation in the coastal region near Syowa Station, Antarctica. Therefore the season which contributes the most to the snow accumulation around Syowa Station, Antarctica should be fall because there are many deeper clouds with much liquid water content in that season.

Chapter 1. Introduction

The Antarctic ice sheet plays a critical role as a cold source in the global climate system. The mass of the ice sheet is largely determined by the balance between the increase by precipitation and the decrease by the sum of the outflow and evaporation. The estimation of amount of precipitation is important to comprehend the water budget in Antarctica. However, in order to estimate the amount of precipitation, there are few detailed observations carried out in Antarctica due to difficulties of observations. Since Antarctica is surrounded by sea ice, it is difficult to transport large equipment for observations to Antarctica. Moreover, the conditions of Antarctica are severe with low temperature and strong wind. Such conditions suppress detailed observations of snowfall.

The Japanese Antarctic Research Expeditions (JARE) attempted for several years to comprehend the Antarctic climate system as a link in the Antarctic Climate Research (ACR) project, which is under the umbrella of World Climate Research Program (WCRP). The author participated as one of the wintering members in the 30th JARE (Feb. 1989 - Jan. 1990) to study clouds and precipitation near the coast around Syowa Station by using meteorological radars and a microwave radiometer. The present paper describes the characteristics and seasonal variations of precipitation phenomena through analysis of observational data obtained in 1989. The only previous works concerning precipitation in Antarctica observed by radar are Whinnery et al. (1979) and Warburton et al. (1981). Both of them were carried out at Palmer Station at Antarctic Peninsula. The former used the radar data to ascertain the relationships between radar reflectivity from

precipitating storm and the precipitation rate, and the latter obtained the radar data to study cellular structure of storms and the effects of the mountain barrier on storm motions.

It is important to establish a method of measuring snowfall amount in Antarctica. Measurements of precipitation by using snow gauge present severe problems, since it is almost impossible to distinguish between precipitation and drifting snow in strong winds that often accompany precipitation. The classical methods using snow stakes to measure accumulated snow depth have large errors in amount of precipitation in strong wind. Some reports showing the annual amount of snowfall, for example, Murakoshi (1958) and Naruse et al. (1971), are based on data obtained using the snow stakes at Syowa Station. Several attempts to estimate the amount of snowfall have been carried out by members of JARE. Kikuchi et al. (1981) sampled the precipitating particles at Syowa Station on glass slides to make replicas and estimated the amount of precipitation as 400 mm through a year by multiplying the durations of snowfall by the snowfall rate calculated from the replicas of precipitation particles. Kobayashi (1985) and Takahashi (1985) derived the annual amount of snowfall as about 200 mm by extrapolation of the vertical distribution of blowing snow measured by using a 30 meter tower at Mizuho Station.

Estimations of amounts of snowfall over the whole of Antarctica have been carried out by other methods. Budd (1966) estimated the annual accumulation rates by combining several data obtained from measurement of snow stakes and from snow-pit stratigraphy along traverse routes. He found that the amount of precipitation is relatively high over marginal ice slopes in

relation to the amounts in the interior. The amount is about 400 mm around Syowa Station. Schwerdtfeger (1984) reported the changes of cloudiness and water vapor at some stations in Antarctica and estimated the snowfall rate in point of vapor transport. Bromwich (1988, 1990) and Connolley and King (1993) also estimated the amount of snowfall to calculate the moisture flux by using upper sounding data observed at some stations directly and using analysis data generated by a numerical weather prediction scheme.

In the present study, a method how to estimate the amount of snowfall by using continuous meteorological radar data through a year at Syowa Station is described. This indirect method provides a good estimation of snowfall rate (Fujiyoshi et al, 1990) in comparison with those in the previous work in Japan. Moreover, this method can provide the amount of snowfall in each series of snowfall events because the radar reflectivity converted to snowfall intensity is measured at short time intervals automatically whether wind blows hard or not. The analysis of radar data also provides useful information on meso-scale structure of clouds causing precipitation. The studies of estimation of amount of snowfall in Antarctica in the previous work seldom refer to the structure of precipitation clouds because the studies emphasize on results of precipitation but not on causes of precipitation.

Clouds and precipitation near Antarctica are thought to be produced by water vapor transported from the sea surface at lower latitudes surrounding Antarctica. Carleton (1992) noted that synoptic scale cyclones are important in the supply of moisture to Antarctica. Knowledge of synoptic climatology over the South-

ern Hemisphere tended to be incomplete before satellite images became available because of the lack of conventional surface and upper sounding data over extensive regions of the Southern Hemisphere. Subsequent analyses of many satellite pictures have made it possible to determine the characteristics of synoptic climatology on extratropical cyclonic cloud vortices (Troup and Streten, 1972). Streten and Troup (1973) investigated the seasonal pattern of cyclonic evolution and decay over the Southern Hemisphere by using satellite data. They noted that decay of low pressure system is frequently observed close to Antarctica. The present study shows the characteristics of precipitation phenomena at Syowa Station and associates them with the precipitation clouds by using the data of synoptic charts and satellite images. The radar observations provided useful data to propose a conceptual model concerning the structure of cloud vortex associated with extratropical cyclones.

The present study also deals with seasonal variations of precipitation phenomena. Since the sea ice edge varies seasonally from 200 to 1500 km off Syowa Station and the surface temperature varies from 0 to -40°C , precipitation phenomena affected by these factors must be changed with the season. The seasonal changes of circulation in the Southern Hemisphere are related to biannual oscillations of the circumpolar trough, which have been analyzed by means of daily synoptic weather maps (van Loon, 1984). The symmetric circumpolar zone of low pressure at high latitudes retreats toward the coast of Antarctica in March and October (Streten, 1980). The clouds and precipitation around Syowa Station were also examined for the seasonal oscillation.

According to precipitation phenomena based on radar obser-

uations around Syowa Station, some new findings are discussed about the necessary conditions for a large amount of precipitation near Syowa Station and the contribution to snow accumulation in Antarctica.

Chapter 2. Methods of observation

2.1. Instruments

Long-term observations of precipitating clouds were carried out by a vertical pointing radar, PPI radar and a 37 GHz microwave radiometer at Syowa Station ($69^{\circ}00'S$, $40^{\circ}35'E$), Antarctica in 1989. The location of Syowa Station is shown in Fig. 2-1. Syowa station is situated on the north side of the Ongul Islands near the east coast of Lutzow-Holm Bay. The sea ice area extends north of the station for a minimum of 200 km in February and a maximum of 1500 km in October.

The vertical pointing radar gave reflectivity with a range interval of 50m up to 6.4 km at time intervals of 10 sec. The wavelength of the radar is 3.2 cm and the detailed characteristics of the radar are specified by Wada (1990). A PPI radar detects the horizontal distributions of precipitation and the evolution of precipitating clouds near the coast within a 64 km radius of Syowa Station. Radar data was recorded every 18 minutes at three different elevation angles of 2.0° , 3.5° and 6.0° , in order to produce Constant Altitude PPI (CAPPI). The specifications of vertical pointing radar and PPI radar are summarized in Table 2-1 by Konishi (1992).

A 37 GHz microwave radiometer was also used to obtain the liquid water content (LWC) in clouds. The microwave radiometer data is collected every 1 minute (Konishi and Wada, 1991) and is converted to the amount of vertically integrated liquid water content by the methods described by Wada (1992).

A highly sensitive snow gauge (Konishi et al., 1988) was used to measure snowfall rate. The weight of snow fallen in a bucket on a balance was measured automatically at one minute

intervals and the weight data was sent to a computer by a cable connected to the balance. The minimum detectable snowfall rate of this gauge was 0.062 mm/hr. The balance 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/sec because the balance measured the weight of not only precipitation particles but also blowing snow particles which fell into the bucket under the strong windy conditions.

The instruments were installed around the Earth Science Laboratory, which is located in southwest of Syowa Station. Figures 2-2 and 2-3 show a schematic view of instruments and a photograph of instrument located around the laboratory. Vertical pointing radar and snow gauge were set beside each other to compare the radar reflectivity and snowfall rate. PPI radar was set on a small hill to reduce shadow area. The shadow area from the PPI radar beam for the ground at an elevation angle of 2.0 degrees is hatched in Fig. 2-4 because there are steep slopes along the coast of Antarctica south and east of the station. The radar detected mainly the precipitating echo in the northern semicircle area with radius of 64 km.

Precipitation particles were also observed and photographed under a polarization microscope at the radar site.

2.2. Data sources

Surface synoptic data such as temperature, humidity, pressure and wind velocity and direction were measured every hour and upper air sounding data were obtained twice a day at 00Z(03LT) and 12Z(15LT) at Syowa Station. NOAA satellite data were also received and processed for at least one orbit per day at Syowa

Station. The satellite carries several sensors including an Advanced Very High Resolution Radiometer (AVHRR), which views the earth's surface with the high resolution of about 1 km. The AVHRR image data was used to detect cloud vortices as shown in Fig. 2-5. All satellite images in this paper treat the same area as shown in the figure. The area of satellite images contains the coastal region near Syowa Station. A coastal region of continent is denoted by the shaded area at the lower panel of the figure and the location of Syowa Station is denoted by SYW.

Synoptic charts were used to trace the trajectories of low pressure center in the format depicted twice a day by using European Center for Medium-Range Weather Forecast (ECMWF) analysis grid data at 1000 hPa every 2.5 degrees.

Annual changes of the sea ice extent were surveyed by using the weekly reports of sea ice limit issued by the NAVY-NOAA joint center.

Chapter 3. Estimation of amount of precipitation

3.1. Relation between radar reflectivity and snowfall rate obtained by snow gauge of electric balance type

The vertical pointing radar was operated continuously from February 1988 to December 1989 to estimate the amount of precipitation. The snowfall rate at every minute was also measured by a highly sensitive snow gauge of electric balance type under calm wind conditions from February to December in 1989. The relationship between radar reflectivity factor Z (mm^6/m^3) and snowfall rate R (mm/hr) is usually expressed as $Z=B \cdot R^\beta$. Three examples of the Z - R relationship are drawn in Fig. 3-1 for different types of snow particles in a series of snowfall observed on 21 May, 24 October and 1 July 1989. The figure compares the averaged radar reflectivity, dBZ ($10\log Z$), calculated from the data of 30 pulses of vertical pointing radar and corresponding snowfall rate measured by the gauge for 5 minutes. Because the radar reflectivity below the level of 400 m was influenced by ground clutter, the reliable data at the lowest level of 400 m was compared with those of the snowfall rate. The snowfall rates were usually weak in all cases in comparison with those at middle latitudes. The maximum snowfall rates were 0.5, 0.3 and 0.5 mm/hr in these cases, respectively. On the other hand, the maximum radar reflectivity were 7, 12 and 16 dBZ , respectively. Comparing between cases of graupels on 21 May and aggregates of dendrites on 1 July, the radar reflectivity factors of the former were about 7 times greater than those of the latter at the same snowfall rate. Therefore, the regression lines for Z - R relations are expected to be much different between the aggregates of dendrites and graupel particles.

The coefficients B and β for each snowfall are determined by a regression line for the data of snowfall rates and radar reflectivity factors. In this paper the coefficients B and β were calculated only for the cases in which the surface wind speed was weaker than 5 m/sec and the snowfall continued for at least several hours. Since snowfall is usually accompanied by strong wind, only 14 days were observed in total during the observational period from February to December 1989. The snowfall rates at Syowa Station were usually weak compared to those at middle latitudes and the maximum snowfall rate averaged for 5 minutes rarely exceeded 1 mm/hr. The coefficients B and β obtained in 1989 are shown in Table 3-1 with type of snow crystals and daily mean temperature for the cases. The values of coefficient B ranged from 7.6 to 63.0 and β from 1.02 to 1.52. These values are almost the same as those summarized for various types of solid precipitation by Sato et al. (1981). The values of coefficient β , which represents the slope of the regression line, were almost the same in all cases, although the values of coefficient B were much different. Therefore the slope of regression line would not change so much even if the coefficient β is fixed at averaged value of 1.3.

Since the radar reflectivity factor is proportional to the sixth power of the snow particle size, the radar reflectivity factor for large particles like aggregates will be large compared to that for densely rimed particles or graupel particles at the same snowfall rate. The differences of radar reflectivity factor at the same snowfall rate imply that the differences of apparent density of particles reflect the masses per unit volume, due to different amounts of open space. Since the value of coefficient B

is defined as the value of radar reflectivity factor to snowfall intensity of 1 mm/hr, the values of coefficient B provide information on the apparent densities of snow particles. The values of coefficient B will be large when the apparent densities are small, such as in the case of aggregates, and the values of coefficient B will be small when the apparent densities of snow particles are large, such as in the case of graupel or heavily rimed crystals. The apparent densities of snow particles can be estimated from the values of coefficient B.

The snowfall rate calculated from the Z-R relation by taking the maximum value of coefficient B to be 63 is about 5 times larger than that by taking the minimum value of B to be 7.6, at the same radar reflectivity factor by using the coefficient β of 1.3. If we use the same values of coefficients B and β for all precipitation, the snowfall rates may contain large errors. We must use the best Z-R relation for each type of snow particle to estimate the snowfall rates accurately by using radar data. However, it is impossible to detect the types of snow particles continuously in strong wind conditions as often prevail in Antarctica. Because the types of snow particles are approximately defined by the air temperature, the values of coefficient B can be parametrized by air temperature. The large coefficient B is induced at higher temperature when the types of snow particles are aggregates of dendrites, however, the small coefficient B is induced at lower temperature when the types of snow particles are columns or bullets. The dependency between coefficient B and temperature in Table 3-1 is expressed in Fig. 3-2. As it is shown in the figure that the relation between coefficient B and daily mean surface temperature is distributed around the regression

line, the values of coefficient B are related to the temperature. In this paper the values of coefficients B and β are chosen as the values on the regression line at each temperature and the constant value of 1.3 respectively, to estimate the snowfall rate from echo intensity of vertical pointing radar.

3.2. Total amount of precipitation in 1989 at Syowa Station, Antarctica

Figure 3-3 shows the amount of daily snowfall in 1989 calculated from vertical pointing radar data by using the coefficient of the Z-R relation mentioned in Section 3.1. The precipitation detected by the radar was more than 130 days. Almost all daily amounts of snowfall were less than 5 mm. The total amount of snowfall was deduced to be 204 mm in 1989. Since the correlation coefficient of the regression line in Fig. 3-1 is 0.73, the error of amount of snowfall is about 36%. Compared with values in earlier works near Syowa Station, the value 204 mm is less, however, the comparison with other results is meaningless because the methods of measurement are much different. It is thought that our results are much reliable because the measurements were carried out at short time intervals continuously through the year.

Figure 3-3 indicates that there were three snow abundant seasons at Syowa Station. The longest snowy season was from February to April in the austral fall. The total amount of snowfall in this season was about 74 mm. Another season appeared in winter. The total amount of snowfall in this season was 74 mm. The other season was from October to November in spring; the total amount of snowfall in this season was 53 mm. The peak value of daily

snowfall in this season was 11.0 mm/day, larger than those in other seasons. This indicates that the amount of snowfall was larger for each snowfall event in this season than those in other seasons. The seasonal variation of snowfall suggests that the precipitation occurred evenly in all seasons except summer.

Also the upper panel in Fig. 3-3 represents the pressure variation, which deviated from the averaged sea surface pressure for 30-days. The figure indicates that the snowfall usually occurred when the pressure was lower than the normal mean level. This fact suggests that the snowfall was brought by low pressure systems. Carleton (1992) also noted that synoptic scale cyclones are important in the supply of moisture as clouds and precipitation in Antarctica. However the snowfall did not always occur when the pressure is lower than the normal mean level. Some lows do not bring snowfall to Syowa Station.

Chapter 4. Characteristics of precipitation phenomena over the coastal region around Syowa Station, Antarctica

4.1. Cloud vortex associated with extratropical cyclones

4.1.1. Classification of vertical structure of precipitating clouds

The vertical structure of precipitating cloud was observed continuously from 1 January to 19 December in 1989 by vertical pointing radar at Syowa Station. Figure 4-1 shows the occurrence frequency of duration of echo at 1-hour intervals observed by the vertical pointing radar. The longest duration of echo reached 55 hours. When the echo observed for long duration, a blizzard usually caused with strong wind on the ground and suppressed the various observations of precipitation such as amount of precipitation by sensitive gauge and sampling of precipitating particles. However observations using radar were not affected by the blizzard.

Since the cloud system accompanied by low pressure is usually as large as several hundred kilometers in diameter, the clouds associated with the low pressure system would cover Syowa Station for long duration. The occurrence frequency of duration longer than 10 hours is 53 cases in the observation period. The sum of appearance duration of the 53 cases is 50% of that of all cases and the total amount of precipitation of them 66% of that of all cases. Hence it is concluded that the cases of the long duration contribute large amounts of snowfall to Antarctica. So the present paper describes only cases of long duration of echo to investigate the characteristics of precipitation phenomena over the coastal region around Syowa Station.

The 53 cases of long duration of echo are classified into

three types by the time-height cross section showing the vertical structure of the echo observed by the vertical pointing radar. The typical time-height cross sections of three types are shown in Figure 4-2. The echoes of the type-A consist of a pair of deep and shallow echoes. The deep echo appeared over 6 to 10 hours before the shallow echo appeared. Type-B echoes are composed of only high level echo without precipitation on the ground for long period over 10 hours. Type-C echoes show short periodic structure such as convective cells. The number frequencies of type-A, type-B, type-C and other types are 21, 11, 4 and 17, respectively.

The thermal and kinetic vertical structures corresponding to the cases in Fig. 4-2 are shown in Fig. 4-3 by equivalent potential temperature, wind speed and wind direction obtained from upper soundings. The equivalent potential temperature of type-A indicates that the warm air was present in the upper part of echoes at the beginning when the high level echo appeared; however, the air temperature decreased when the low level echo appeared. The temperature difference between both conditions was greater than 20 degrees around 4 km height at 15 LT on 4 March and at 3 LT on 5 March. Vertical stability was suspected to be small above 4 km at 15 LT on 4 March, but larger at 3 LT on 5 March. Therefore it is expected that the air mass was changed during the passage of the type-A echoes above Syowa Station. The neutral layer was observed in the warm air, around 6 km on 17 February. The equivalent potential temperature of type-B indicates that the echo exhibited in a stable layer and the profiles changed little with time. The wind profile suggested that the low pressure center was located north of Syowa Station because

the wind blew westward at every height. On the contrary, the potential temperature of type-C shows that the echo was expected in the neutral layer of potential temperature after convective mixing.

The type-A echoes appeared most frequently in 1989 as mentioned above. Figure 4-4 shows 6 cases of time-height cross section of type-A echoes expressed as similar as Fig. 4-2(a). The time scale of the horizontal axis in Fig. 4-4 is 6 times shorter than that in Fig. 4-2. The type-A echoes are observed in all seasons as shown in the figure. Since the height of the deep echo top changes with season at about the -35°C level (dotted lines), the echo top would depend on temperature. The solid triangles depicted on the horizontal axis indicate the time of minimum surface pressure during the passage of a type-A echoes. The time of the minimum surface pressure corresponds to roughly the change from the deep echo to the shallow echo. The deep echo appeared when the pressure decreased and the shallow echo appeared when the pressure increased. These facts suggest that boundary of two echoes seems to be a frontal structure dividing warm and cold air masses.

The horizontal structure of the type-A echoes was analyzed by using the PPI radar data and NOAA satellite images. The composite charts of PPI radar for one of the typical cases observed on 4 March and 5 March 1989 are shown in Fig. 4-5. The lower part of the figure shows the horizontal structure of type-A echo composed of time-distance cross section using the PPI radar echoes along a line 10 km north of Syowa Station. The time-height cross section of radar echo using vertical pointing radar data is also shown for comparison in the middle part of the figure. The PPI

radar data suggests that the type-A echoes consisted of layer echoes before 21 LT on 4 March and line echoes in the latter period. The former echoes were consistent with deep echoes and the latter line echoes were consistent with shallow convective echoes in comparison with time-height cross section. The NOAA/AVHRR image indicates that the cloud band of cloud vortex was above Syowa Station at 16 LT on 4 March as shown in upper part of the figure. The cloud band of cloud vortex passed above Syowa Station from north to south. The orientation of cloud band of cloud vortex extends from east to west at the southern periphery, when the type-A echo appeared above Syowa Station. On the other hand, the orientation changed to NE-SW around the rear edge of the band as the type-A echo passed away. The change of orientation of the band is also found in composite charts of PPI radar data. Hence it is expected from the NOAA image that the type-A echoes would be cross sections across the cloud band of cloud vortex associated with an extratropical cyclone.

4.1.2. Synoptic scale features for the cloud types classified

Synoptic analysis over the Southern Hemisphere tended to be incomplete before using satellite data because of the lack of conventional surface and upper-air data. Satellite data has been used to research the climatology of cloud vortex for the Southern Hemisphere from the 1970's. Satellite data plays an important role in climatological studies on hemispheric and global scales. The increase of satellite data provides more complete synoptic information on cloud patterns over the Southern Hemisphere (Troup and Streten, 1972). Troup and Streten classified the pictures to obtain with synoptic climatologies of extratropical cyclonic

cloud vortex. Figure 4-6 shows schematic cloud patterns associated with defined vortex types (Streten and Troup, 1973). They state that the vortex develops from W to A, B, C, D moving toward high latitude. Hence the vortex cloud might be considered to bring considerable precipitation to the coastal region of Antarctica, corresponding to types C and D. The type C is a mature stage of the vortex with spiraling of cloud band around a definite center; type D is a dissipating stage of vortex with spiral banding. Four examples of cloud vortex near Syowa Station obtained from NOAA satellite in 1989 are shown in Fig. 4-7. These vortices had spiral bands as shown in type C of Fig. 4-6.

The pass and location of vortex and axis of trough in the Southern Hemisphere have been analyzed in earlier works. The location of the circumpolar trough and the frequency of the low center in the trough are shown in Fig. 4-8 (Streten, 1980). He states that the circumpolar trough lies between Antarctica and the broad stream of westerlies. The latitude of the axis of the trough averaged over a 5-year period is shown by the cross-hatched area in the figure. The relative frequency of existence of the center of lows for individual 10° longitudes for individual months in the trough is shown by single hatched histograms along 60°S . The high frequency region near Syowa Station appears at $20\text{--}30^\circ\text{E}$, northwest of the station.

The trajectory of the center of the low is considered for each echo type. Figure 4-9 shows the pass of low pressure centers when type-A or type-B echoes appeared above Syowa Station. Open circles show the position of the center at the beginning when the precipitating echo firstly appeared above Syowa Station and solid bars show the path of the low during the echo appeared

above Syowa Station. When the type-A echo appeared, the low center was usually northwest of Syowa Station. On the other hand when the type-B echo was observed at Syowa Station, the low center was usually north of Syowa Station. One of the reasons that the type-A echo appeared more frequently than the type-B echo are that the pressure center appeared frequently at northwest region of Syowa Station as shown in Fig. 4-8.

4.1.3. Vertical structure of cloud vortex in mature stage

The precipitation at Syowa Station mainly occurs from clouds associated with low pressure systems. Such a low pressure frequently appears as cloud vortex in the mature and dissipating stages. The conceptual model of cloud vortex structure is proposed in Fig. 4-10 incorporating the results described above. The cloud vortex is formed on the boundary between the easterly cold air stream and warm air in lower latitudes. If the center of the low stays in the northwest of Syowa Station where the lows appear most frequently in the circumpolar trough, the cloud vortex progresses toward Syowa Station from lower latitude and type-A echoes appear. The type-A echo is considered to be the normal cross section of the band such as an occluded front. On the contrary, if the low moves east along the coast near Syowa Station, the south edge of the cloud vortex covers Syowa Station and a type-B echo appears without precipitation on the ground surface. Hence the type-B echo would show a different section of the same band from the type-A echo. If the center of the low is in the vicinity of Syowa Station, the type-C echo appears as the convective cells. The convective cells correspond to the vertical mixing at the center of the low.

The cloud vortex is analogous to the rainbands associated with extratropical cyclones in the Northern Hemisphere described by Matejka et al. (1980). They describe the structures and micro-physical structures of six types of rainbands. The structure of the former clouds of the type-A in the present study is expected to be the same as that of warm front in their study with an unstable layer above the cold stable layer. However the unstable layer in the former clouds of the type-A is not shown clearly in the present study. It is expected that the unstable layer would be present at lower latitude but changed to a neutral or stable layer by vertical convective mixing while the unstable layer was approaching Syowa Station. The structure of the latter clouds of the type-A is similar to the wavelike rainbands located in a potentially unstable layer behind a cold front aloft and near the surface occluded front. Wang and Hobbs (1983) note that the orientation of the band is parallel to the winds near their upper level, which correspond to the orientation of the line echo in the type-A echo shown in Fig. 4-5.

4.1.4. On the case of the cloud vortex that caused the largest amount of precipitation in 1989

The largest amount of precipitation of one series of snowfall in 1989 at Syowa Station was 16.7 mm on 22-24 October. The time-height cross section for this case is shown in Fig. 4-11. The echo lasted for about 50 hours with deeper echoes than 4 km. The precipitating clouds were not convective but had stratified structure determined from PPI radar data which are not shown in this paper. The time-height cross section also indicates that the clouds are of stratus type because the echo structure did not

change much with time. The vertical profiles of equivalent potential temperature shown in the upper right panel in the same figure indicate that the warm air entered at high altitude and the cloud was in the stable layer. Therefore the clouds causing the largest amount of precipitation are expected to be the same as those produce the echoes in the early part of the type-A echo by analogy with radar echo structure and vertical profiles of sounding data.

The trajectory of the low pressure center shown in the upper left panel in the same figure indicates that the low at lower latitude approached at first from northwest of Syowa Station when the early part of the echo appeared above Syowa Station, but turned west later along the coast. So the surface pressure at Syowa Station decreased during the approach of the low pressure center before 08 LT on 23 October, but gradually increased after that when the low pressure center travels to the west. Therefore the precipitation would be caused to persist by the same condition as the echoes in the early stage of a type-A echo before the time of minimum pressure shown by a solid triangle in Fig. 4-4. The cloud vortex would cross Syowa Station until the center of the low turned west. After that the precipitation brought by layer echoes that are similar to the former echoes in early stage of the type-A. Since the cloud band should return to west following the movement of the low center, the echo directly above Syowa Station should move backward again. Consequently the precipitation at Syowa Station was large in comparison with other cases of precipitation because the high level echo with intense reflectivity remained for a long time in this case.

4.2. Cloud evolution across the coast near Syowa Station

4.2.1. Enhancement of precipitation in clouds with large liquid water content across the coast near Syowa Station

In this section, the amount of precipitation is described in relation to mixed-phase clouds and solid-phase clouds. Mixed-phase clouds and solid-phase clouds are defined conventionally here as those of more than 30 mg/cm^2 and less than 10 mg/cm^2 in vertically integrated liquid water content (LWC) calculated from the microwave radiometer data under the sufficient echo reflectivity of X-band radar. The horizontal distributions of daily snowfall in the 8 cases are shown in Fig. 4-12. The left side panel shows 4 cases of mixed-phase clouds and the right side shows 4 cases of solid-phase clouds. The amount of snowfall was calculated from PPI radar data at 2.0° elevation angle using $Z=53 \cdot R^{0.78}$, which is deduced from comparison between the snowfall rate at Syowa Station and radar reflectivity factor at 10 km north of Syowa Station sweeping at 6.0° elevation angle. The place of PPI radar data compared to snowfall rate is decided in consideration of the drifting distance due to the horizontal wind. Since the height attained 1000 m at a distance of 10 km at 6.0° elevation angle, 1000 seconds are needed for snow particles to reach the ground at a falling speed of 1 m/sec, which corresponds to a distance of 10 km drift in a horizontal wind of 10 m/sec.

The snowfall distributions show that there were small amount of precipitation near the periphery of the dotted circles. Since the radar echo height was 2.2 km at a distance of 64 km at 2.0° elevation angle, and the heights of echo tops were mostly lower than 4 km at Syowa Station (Konishi et al., 1991), the radar beam

reached the upper part of clouds or passed above the cloud top near the periphery of the circle. Thus the radar echo intensity was often small near the periphery.

The snowfall distributions show that the increase of the amount of snowfall near the coast was appeared in both cases. A remarkable increase of precipitation occurred within 50km of the coastline. The clouds approaching continent would develop near the coast. The increase of snowfall near the coast appeared more clearly in the mixed-phase clouds. One of the reasons for this is orographic lifting. On the other hand, the enhancement of snowfall near the coast is small in solid-phase clouds, although the wind direction and wind speed were not so different from the cases of solid-phase clouds.

The differences of snowfall distribution shown in the figure suggest that the ability of mixed-phase clouds to produce precipitation is larger than that in solid-phase clouds. A cloud system landing on the coast from the north ascends along the topography and the air temperature decreases by adiabatic cooling. Since the slope is steep near the coast at Syowa Station, the altitude attains about 500m at a distance of 10km inland from the coastline. Therefore the temperature of clouds should decrease after the clouds glided up along the slope of the land, and the water content should increase by adding new condensed water. Figure 4-13 shows the increase of condensed water (ΔWC), calculated using sounding data, after the air column is lifted by 500m adiabatically. The water content (WC) before ascending is the sum of solid and liquid water content in unit column calculated from vertically pointing radar data and microwave radiometer data, respectively. The figure indicates that almost clouds

had water content less than 100 mg/cm^2 before ascending, but received 0 to 200 mg/cm^2 of new condensed water after ascending. Most mixed-phase clouds receive more than 100 mg/cm^2 and most solid-phase clouds receive less than 100 mg/cm^2 . Thus the increase of snowfall near the coast occurred in mixed-phase clouds as the result of orographic lifting. The horizontal distributions of snowfall suggest that the solid-phase clouds bring little snowfall. The water supply over inland areas will be mainly caused by mixed-phase clouds with precipitation beyond 50km inland from the coast line.

Chapter 5. Seasonal variations of precipitation phenomena in 1989, at Syowa Station, Antarctica

5.1. Seasonal variations of the amount of precipitation

Seasonal variations of precipitation phenomena are described in this chapter. Changes of the surface air temperature and sea ice extent were investigated, these might affect precipitation at Syowa Station. Seasonal variations of surface air temperature shown in the upper panel in the Fig. 5-1 are the averaged values at intervals of 10 days measured at Syowa Station. In comparison with the air temperature in a normal year depicted by the broken line, the air temperature in March and September 1989 was considerably lower. The minimum temperature in 1989 was recorded on 11 September as -39.6°C . Hence the winter season in 1989 lasted longer than that in a normal year. Assuming that the winter season is defined as the duration of low temperature in the year, the season was decided from May to September in this paper. The fall and spring seasons are defined as similarly the duration of tendency in temperature to decrease and increase respectively, the seasons are from February to April and from October to November respectively. The sea ice extent along the longitude of 40°E is also shown in the lower panel in the figure. The sea ice edges are defined as boundary of ice concentration of 80% derived from weekly reports of satellite data obtained by the NAVY-NOAA joint center. The fall season defined by the air temperature corresponds with the season of minimum extent of the sea ice area. The winter season corresponds with the season of expansion of the sea ice area, and the spring season corresponds with the season of rapid reduction of the sea ice area.

Figure 5-2 shows the seasonal change of the 10-day snowfall

rate at Syowa Station in 1989. As also shown in Fig. 3-3, there were three snow abundant seasons: the fall, winter and spring season. The total amounts of precipitation at each season were 74, 74 and 53 mm respectively. The seasonal variations of snowfall suggest that the precipitation occurred evenly in all seasons except summer. But there were some periods with no or little snowfall in winter and spring as shown in Fig. 5-2. The decrease of snowfall can be attributed to the extremely low amount of vapor because of low temperature and the expansion of sea ice area. The amount of precipitation shown in Fig. 5-2 was derived from vertical pointing radar data, which show the results of only one observation point of Syowa Station. Thus the value is less representative of the area around Syowa Station than that measured by PPI radar within 64 km around Syowa Station. The monthly accumulated snowfall rate estimated from the PPI radar data at 2.0° elevation angle is shown in Fig. 5-3. The small amount of snowfall near the periphery of the observation circle is due to the radar beam reaching the upper parts of precipitating clouds or passing above the cloud tops as mentioned in Fig. 4-12.

The snowfall distribution shows that the localization of snowfall appeared every month near the coast near Syowa Station. The increase of snowfall was caused by orographic effects along the slope near the coast. However, careful investigation reveals that there are some differences in distribution of snowfall among fall, spring and winter. In fall and spring seasons, the peaks are 10-20 km into the continent. On the contrary, in winter, the peak is on the coast or on the sea, and the snowfall is enhanced less than that in fall and spring. The differences of snowfall distribution suggest that the amount of snowfall to

over all of near Syowa Station is larger in fall and spring than in winter.

5.2. Seasonal change of characteristics of clouds with respect to cloud height

The appearance frequency of the echo top observed by vertical pointing radar is shown in Fig. 5-4. The frequency of radar echo is summed every half month at height intervals of 250 m and contoured every 2 hours. The hatched, double hatched and shaded regions indicate 8, 10 and 12 hours respectively. In fall from February to April, the echo top height ranged from 1 km to over 6.4 km and most of the echoes were observed below 3 km. In winter, specifically June and July, the echo top height was usually lower than 2 km. The large frequency was exhibited at higher level than 4 km in spring of October and November. The annual variations of occurrence time of the radar echo indicate a semi-annual oscillation similar to those derived from surface pressure analysis in the Southern Hemisphere in earlier works (for example, van Loon, 1984). Figure 5-4 also shows the monthly mean temperature depicted by the dotted lines derived from aerological sounding data. The level of -40°C showed similar seasonal variation to that of the highest echo top. The same results were found for snow clouds in Arctic Canada by Fujiyoshi et al. (1982). Since spontaneous freezing of small supercooled droplets occurs at -40°C , the existence of supercooled droplets near the cloud top is suggested even in Antarctica.

Figure 5-5 shows the appearance frequency of the maximum echo intensity related to the echo top. The maximum echo intensity is defined as the maximum value of echo intensity from the echo top

to the ground. To compare the differences in frequency pattern among the seasons, three examples of monthly distribution were chosen in this figure for April, July and October. It is expected that the maximum echo intensity would increase with increasing the 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 echoes below 2 km show a wide range of maximum echo intensity which did not tend to depend on the echo top height. These facts suggest that the echoes were classified into two types, namely the lower type in which the echo top height was below about 2 km and the higher type in which the echo top height 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 echoes larger maximum echo intensity is found in October than in April. In comparison with the monthly mean temperature, the lower type of snow cloud was formed in a layer warmer than -25°C .

The higher type echoes often appeared in fall and spring seasons. The seasons correspond to the time when the axis of the circumpolar trough approaches the coast of Antarctica in a half-yearly cycle. The higher type echoes were certainly associated with low pressure systems as mentioned in chapter 4. Therefore it is expected that the higher type echoes would be produced by the forced upward motion like a warm front accompanied by extratropical cyclones. On the contrary the lower type echoes appeared independently from those in all seasons. However, a seasonal change was also found in appearance frequency. The occurrence rate of lower echoes was less in spring (October and November). It is expected that the lower echoes would be developed with the

gain of the vapor and heat when the cold air blew on the warm sea surface. Therefore the available area of open sea to supply humid air to the lower echoes might be less in spring than in fall. The difference of seasonal variation in occurrence of lower echoes would be connected with the annual variation of distance from the coast to the limit of sea ice, which grows up to its maximum in early spring.

5.3. Seasonal variations of cloud characteristics with respect to liquid water content

The annual variations of occurrence frequency are shown in Fig. 5-6, comparing mixed-phase and solid-phase clouds in 1989. We define conventionally liquid and solid phase clouds as clouds whose vertically integrated LWC is greater than $30\text{mg}/\text{cm}^2$ and less than $10\text{mg}/\text{cm}^2$ respectively as similar to those mentioned in section 4.2.1. The hatched columns show the frequency of solid-phase clouds and double-hatched columns show that of mixed-phase clouds. Open columns in between them show the frequency of clouds with medium LWC. The lower panel in the figure shows that the mixed-phase clouds appear mainly in fall from February to late May, and solid-phase clouds appear in all seasons, more frequently in winter and early spring from late June to November. The seasonal variation of the cloud types suggests that the clouds are affected by some factors changing with the seasons such as air temperature, humidity, number of ice nuclei, sea ice area, and wind direction.

It is well known that the clouds observed at Syowa Station were usually produced above the warm sea around the station with much supply of water vapor and transported above the sea ice to

the coast by northerly wind. The clouds are modified in their structure on the way to the coast due to lower temperature and less vapor supply. It is considered, therefore, that the air temperature and distance from the Syowa Station to the sea ice edge are likely to correlate with characteristics of clouds such as the amount of water content in the mixed-phase and solid-phase. Figure 5-6 also shows the seasonal variations of sea ice limit along the longitude of 40°E . The farthest edge of sea ice from Syowa Station was about 1500km in October. If the cloud system in October moves at 40km/hour from sea to Syowa Station, the time required to pass above the sea ice is over 40 hours. On the contrary, in February the nearest edge to Syowa Station is within about 150km. The traveling time of cloud systems is one tenth compared with October. This suggests that the cloud system is more influenced by the sea ice area in October than in February. The seasonal variation of the frequency of solid-phase clouds is correspond to the seasonal variation of the sea ice edge.

The relation between the distance from the sea ice edge to Syowa Station and cloud types observed at Syowa Station is shown in Fig. 5-7. The main feature is that mixed-phase clouds (black circle) appear when the sea ice edge is located within 300km from Syowa Station and solid-phase clouds (hexagonal mark) mostly appear when the sea ice edge is farther than 800km. This suggests that convective activity becomes suppressed during the passage over sea ice. Note that most generation of supercooled droplets in clouds is accompanied by convective activity. Figure 5-7 also shows the relation between cloud type and air temperature at 2 km height. This figure shows that the cloud type does not depend on

temperature when the sea ice edge is farther than 800 km from Syowa Station. However, when the sea ice edge is within 300 km of Syowa Station, the cloud type seems to depend on the air temperature. In this case, solid-phase clouds appear frequently as the temperature decreases to -15°C . Thus it was concluded that the occurrence of solid-phase clouds depended on air temperature.

5.4. Seasonal tendency of trajectory of low pressure center

The analyses of frequency and trajectory of the low pressure are needed to understand the characteristics of snowfall at Syowa Station, because the precipitating clouds were mainly associated with a low pressure system as mentioned above. Trajectories of the low pressure center are shown in Fig. 5-8 to progress south of the latitude of 60°S in the area between 0° - 45°E in 1989. The trajectories indicate that the low pressure mainly moves east, though it sometimes stays put or move west at high latitude near the continent. The well-developed lows often dissipate near the coast after they progress to high latitude. Cross marks in the figure show the dissipating positions of low pressure center. The lows are classified by trajectory into two groups: one is dissipating near the coast, another is moving to the east along the coast. The traveling lows often appear in winter and spring, especially in May. In late winter and spring seasons (August-November) some lows pass to the east and retreat equatorward. Since the polar high spreads to lower latitudes and grows strong in winter, it is considered that the low pressure systems can not approach to the continent but move along the coast. The sea ice extent depicted with shaded areas in Fig. 5-8

would also affect the low pressure trajectories because there are less water vapor and heat fluxes above sea ice than that above open sea.

Seasonal variations of trajectories of low pressure centers are summarized in Table 5-1. In total 64 lows dissipated in the area and 29 lows moved to the east. The ratio between dissipating lows and moving lows changed with the season as the percentage of dissipating lows decreased to 81, 72 and 58% in fall, winter and spring respectively. The lower values of percentage in spring than other seasons suggest that the polar high would spread and strengthen with progress of the seasons.

The numbers in parentheses in the table show the frequency of precipitation lasting more than 10 hours in each type of low pressure. Almost all of long duration of precipitation occurred in dissipating lows. The low pressures usually approach to the continent during developing stage and stay during their mature stage, and disappear near the coast. Therefore the dissipating lows in the area contribute more water supply near Syowa Station than passing lows. The difference of trajectory of low pressure center is considered to be corresponded to the difference of echo type at Syowa Station. Table 5-1 also shows the numbers of echoes of type-A and type-B classified by using the time-height cross sections of vertical pointing radar as mentioned in chapter 4. The type-A echoes were investigated using the normal cross section of the vortex cloud band associated with a low which stayed northwest of Syowa Station. On the other hand, the type-B echoes were investigated using the cross section of the south periphery of vortex cloud band moving along the coast in front of the radar site. Therefore it is considered that the type-A

echoes were caused by a dissipating low in the area and the type-B echoes were caused by a passing low. Thus it is supposed that the seasonal variations of the frequency ratio between type-A echo and type-B echo would correspond to those of two trajectory types of the low pressure center.

Chapter 6. Discussion

6.1. Necessary conditions for large amount of precipitation near Syowa Station

As mentioned above, the precipitation at Syowa Station mainly came from the clouds associated with extratropical cyclones from lower latitudes. Clouds causing much precipitation usually constituted a cloud vortex accompanied by a mature low pressure system as mentioned by Troup and Streten (1972). The trajectories of low pressure center are shown in Fig. 6-1 with thick solid lines indicating the duration when the precipitating echo lasted longer than 10 hours over Syowa Station. This figure shows that the long lasting precipitation at Syowa Station was produced by low pressures with centers northwest or north of the station. However, the lows located north of Syowa Station often advanced eastward, covering Syowa Station with no precipitation echo such as a cross section of the type-B. On the other hand, lows northwest of Syowa Station often brought large amounts of precipitation from cloud vortex as shown by the type-A echoes. Consequently, the first necessary condition is that the low center is northwest of the station in order to produce a large amount of precipitation there.

It is also found in Fig. 6-1 that thick solid lines representing long lasting precipitation frequently exist near the cross marks and show short movement. These facts imply that the lows which bring long precipitation are in their mature stage, usually accompanied by a distinct cloud vortex which causes considerable precipitation. The second and third necessary conditions are that the low is in its mature stage and stationary in order to produce a large amount of precipitation at the

station.

Moving velocities of lows were investigated further to confirm the third necessary condition. The frequency distribution of zonal velocity is shown in Fig. 6-2 with an open histogram for all lows and hatched histogram for lows which caused long lasting precipitation at Syowa Station. The figure shows that the mean zonal velocity of all lows is 4 deg/12hours, however, the zonal velocity of lows which caused long lasting precipitation at Syowa Station is 2.5 deg/12hours corresponding to 10 km/hour. The solid line in the figure shows the percentage of relative frequency of long lasting precipitation at each velocity. The line indicates that the ratio of the long lasting precipitation increases as the speed decreases to zero. Therefore it is concluded that long lasting precipitation was caused by stationary lows. Especially in the case of a low retreating westward, a large amount of precipitation might be caused as mentioned in section 4.1.4.

6.2. Contribution to the snow accumulation near Syowa Station

Radar observations revealed that there were three snow abundant seasons at Syowa Station and the amount of snowfall was uniform in all seasons except summer. However, it is expected that the amount of snow is small in winter, from the distributions of amount of precipitation measured by the PPI radar as shown in Fig. 5-3. Thus the main seasons contributing to the snow accumulation are fall and spring. However, there are some differences of characteristics of precipitation between these two seasons. The differences are thought to be attributable to the different extents of sea ice area. In fall the sea ice area retreats to its minimum in the year, but in spring it expands to

its maximum in the year and then retreats rapidly as shown in the upper panel of Fig. 6-3. Clouds over the sea ice area acquire less vapor on the way to the continent. Thus the frequencies of low level clouds were small in spring as shown in Fig. 5-4, there were many snowfall events in fall but only a few events in spring as shown in the middle panel of Fig. 6-3. Nevertheless the maximum daily snowfall rate appeared in spring. This appears to be because lows develop mostly in spring since the circumpolar troughs advance to higher latitudes. The circumpolar trough intensifies in fall and spring seasons as shown by the zonal mean sea surface pressure through the year (Hsu and Wallace, 1976) in the lower panel of Fig. 6-3.

If the number of snowfall events changes from year to year due to some cause such as changing trajectory or frequency of lows, it is expected that the inter-annual variations of amount of precipitation would be less in fall but greater in spring. The amount of precipitation summed for several snowfall events does not affect the total amount of precipitation in fall because precipitation in fall occurs in many snowfall events. On the contrary, in spring, precipitation occurs in only a few snowfall events. Moreover each snowfall event in spring brought much precipitation in comparison with other seasons, because the large extent of sea ice area in spring dissipates small cloud systems which approaching the continent without supply of water vapor and heat. Therefore the frequency of snowfall events varies more in spring than in other seasons. Furthermore since the sea ice extent in spring retreats to the south rapidly, it is expected that the location of sea ice edge would also vary from year to year, producing variations in the amount of precipitation from

year to year. Therefore the amount of precipitation around Syowa Station consists mainly of a large constant component in fall and a yearly fluctuating component in spring.

Clouds with large liquid water content caused large amounts of snowfall as shown in Fig. 4-12 and were frequently observed in fall corresponding to the minimum sea ice extent as shown in Fig. 5-6. Therefore the contribution to accumulation of snowfall around Syowa Station is mostly caused by the clouds produced in fall because there are many deeper clouds with much liquid water content in that season.

Chapter 7. Conclusions

Precipitation phenomena at Syowa Station, Antarctica were observed continuously by using two kinds of radars in 1989. The results obtained include characteristics and seasonal variations of snowfall.

It is concluded from the observations that precipitation near Syowa Station is mainly brought by cloud vortices associated with extratropical cyclones which advance to high latitude while developing to mature stage. Lows in their mature stage are accompanied by cloud vortices around a definite center (Streten and Troup, 1973). It is proposed that the outer side of the cloud vortex band is composed of layer clouds as that above the warm front formed by the warmer air advancing southward from low latitude and rising above the colder and drier air circulating westward around the polar high along the coast near Syowa Station. The inside of the vortex is composed of convective clouds formed in colder air rotating around the low center along the well-developed spiral. Therefore the cloud vortex is concluded to be created by the occluded front composed of the cold front upgliding above the warm front.

Precipitation from an occluded front crossing over Syowa Station was often observed when the low pressure center stayed northwest of Syowa Station. The time-height cross sections of radar echoes in this case are considered to be normal cross sections of cloud vortex as shown in the type-A echo. No precipitation echoes with high level clouds such as the type-B were observed when the low advanced eastward. The echoes are considered to be cross section along south periphery of the cloud vortex. Convective echoes such as type-C echo were observed when

the low pressure center was located near Syowa Station. Therefore the echoes are expected from clouds near the low pressure center. The relative frequencies of echoes which appeared for the long duration greater than 10 hours were 40, 20 and 10% for the type A, B and C respectively. It is concluded from the observations that the necessary conditions are that the low pressure is in its mature stage, locates northwest of the station and is stationary in order to bring much precipitation to the coastal region near Syowa Station. Especially, a low pressure in its mature stage northwest of the station would bring a large amount of precipitation for a long time in case the low moves westward in accordance with the direction of the cloud vortex.

The seasonal variations of clouds and precipitation were analyzed corresponding to the seasonal changes of air temperature and sea ice area. The echo top height of stratified higher level clouds accompanied by the warm front changed with season corresponding to the change of height of -40°C . On the contrary the frequency of convective lower clouds decreased in winter and spring seasons when the air temperature is lower and the sea ice area is larger. The seasonal variations of the amount of vertically integrated liquid water content obtained by microwave radiometer also showed a similar trend corresponding to the seasonal change of sea ice area; clouds having large amount of water content of liquid phase were frequently observed in fall when the open sea area expanded to Syowa Station. However, clouds in liquid phase were seldom observed in winter and spring seasons when the sea ice area expanded to lower latitudes.

The air temperature and the sea ice area influence not only activities of cloud systems but also activities and trajectories

of low pressure center accompanied by cloud vortices. It has been shown in earlier works that the activities of low pressure system are enhanced biannually in fall and spring seasons when the circumpolar trough develops and advances to high latitudes. Hence the frequencies of cloud vortices brought increased snowfall at Syowa Station in fall and spring corresponding to activity of the circumpolar trough. However the activities of cloud systems that brings precipitation are weakened in spring when the sea ice area expands to low latitude, because of less supply of heat and vapor. Thus the activities of cloud vortices are also weakened above the sea ice area. In comparison between fall and spring, the precipitation in fall comes from clouds associated with a number of low pressure systems approach the continent, whereas, the precipitation in spring comes from only a few low pressure systems. Therefore if the amount of precipitation caused by each low pressure system varies, the amount of precipitation in spring can be expected to change more from year to year than that in fall.

In 1989, the amount of precipitation in spring brought by a few snowfall events was as large as the amount of precipitation in fall brought by frequent snowfall events. Radar observations revealed that there were three abundant snow seasons at Syowa Station and the amount of snowfall was uniform in all season except summer. The amounts of precipitation for each season were 74, 74 and 53 mm for fall, winter and spring, respectively. However, it is expected that the amount of snow at Syowa Station would be small in winter from the distributions of precipitation measured by the PPI radar. Deeper clouds having much liquid water content caused a large amount of precipitation in the coastal

region near Syowa Station. Therefore the season which contributes to the snow accumulation around Syowa Station should be fall because there are many deeper clouds with much liquid water content in that season.

Acknowledgements

The author would like to express his deep gratitude to Dr. T. Endoh, the Institute of Low Temperature Science, Hokkaido University, for his continuous encouragements, many discussions throughout this study. And the author also would like to express his thanks to Prof. K. Kikuchi, Prof. S. Kanari, Dr. H. Uyeda and Dr. Y. Asuma, Graduate School of Science, Hokkaido University, for their valuable advice and useful suggestions in preparing this paper.

The author also would like to express his thanks to Dr. Wada, National Institute of Polar Research for his advice to maintain the observation instruments and the methods of analysis and the discussions on the results.

This study was carried out as a link in the chain of the project of Antarctic Climate Research (ACR). The author also wish to thank the wintering all members of the 30th Japanese Antarctic Research Expedition for their supports in setting up and maintaining the observation instruments. And especially wish to thank the wintering members of JMA for their generous offering of useful data.

The author also would like to express thanks to Prof. Yamashita, Osaka Kyoiku University, for his continuous encouragements and helpful supports to have a chance to study at Syowa Station.

References

- Bromwich, D.H. (1988): Snowfall in high southern latitudes. *Rev. Geophys.*, 26, 149-168.
- Bromwich, D.H. (1990): Estimates of Antarctic precipitation. *Nature*, 343, 627-629.
- Budd, W.F., (1966): Glaciological studies in the region of Wilkes, Eastern Antarctica, 1961. ANARE Sci. Rep. Ser. A, 88, 1-149.
- Carleton, A.M. (1992): Synoptic interactions between Antarctica and lower latitudes. *Aust. Meteor. Mag.*, 40, 129-147.
- Connolley, W.M. and King, J.C. (1993): Atmospheric water-vapour transport to Antarctica inferred from radio sonde data. *Quart. J. Roy. Meteor. Soc.*, 119, 325-342.
- Fujiyoshi, Y., Takeda, T. and Kikuchi, K. (1982): Observation of wintertime clouds and precipitation in the Arctic Canada (POLEX-North). Part 3: Radar observation of precipitating clouds. *J. Meteor. Soc. Japan.*, 60, 1227-1237.
- Fujiyoshi, Y., Endoh, T., Yamada, T., Tsuboki, K., Tachibana, Y. and Wakahama, G. (1990): Determination of a Z-R relationship for snowfall using a radar and high sensitivity snow gauges. *J. Appl. Meteor.*, 29, 147-152.
- Hsu, C.-P.F. and Wallace, J.M., (1976): The global distribution of the annual and semiannual cycles in sea level pressure. *Mon. Weather Rev.*, 104, 1597-1601.
- Kikuchi, K., Sato, N. and Kondo, G. (1981): On the precipitation intensity at Syowa Station, Antarctica. *Proceedings of the third symposium polar meteorology and glaciology*, 167-177.
- Kobayashi, S. (1985): Annual precipitation estimated by blowing snow observation at Mizuho Station, East Antarctica, 1980.

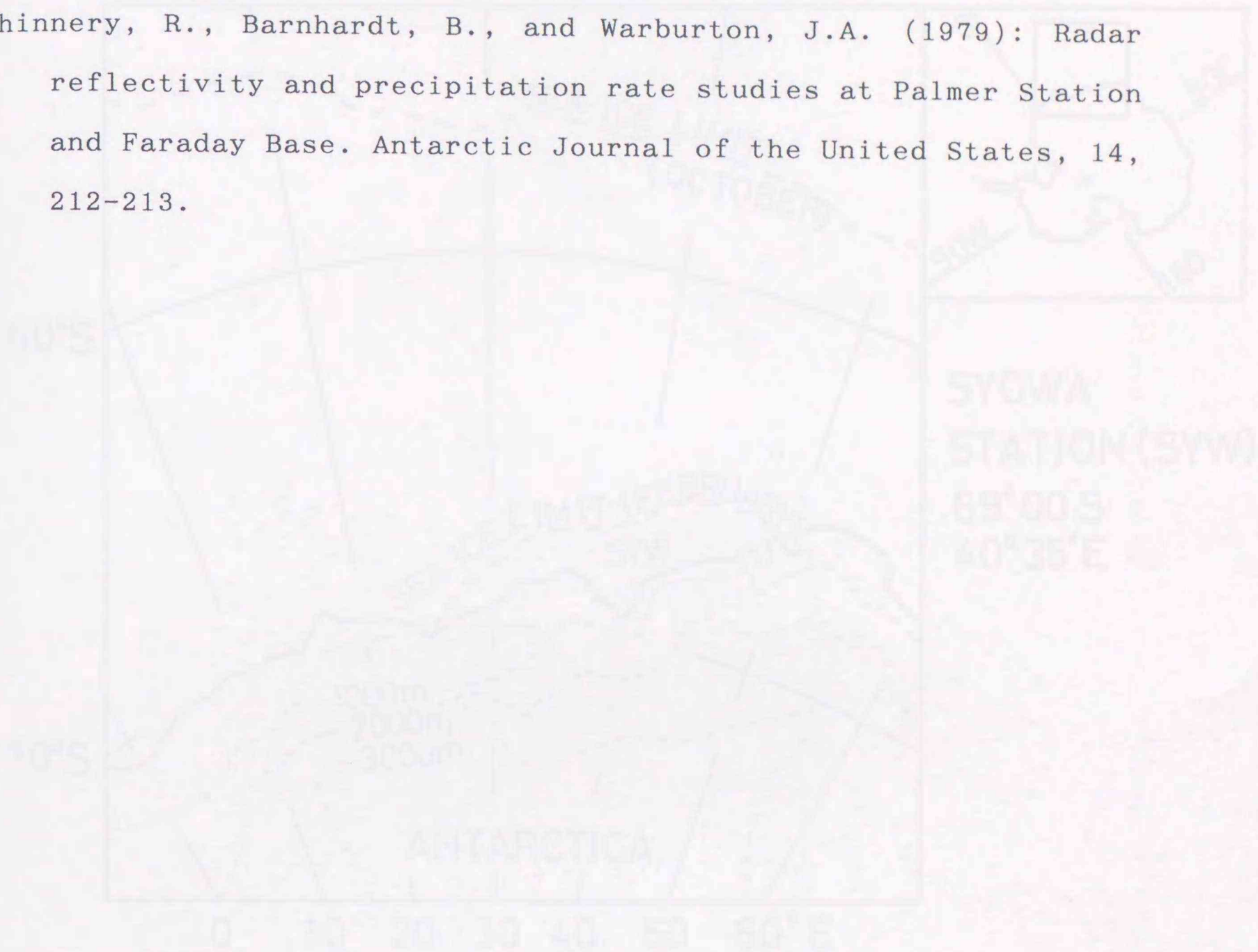
- Mem. Nat'l Inst. Polar Res., Spec. Issue, 39, 117-122.
- Konishi, H. (1992): Antarctic climate research data, Part 5, PPI radar data at Syowa Station, Antarctica from February to December 1989. JARE Data Rep., 173 (Meteorology 28), 60pp.
- Konishi H., Endoh, T. and Wakahama, G. (1988): A new snow gauge using an electric balance (in Japanese with English summary). Seppyo, 50, 3-7.
- Konishi, H., Murayama, S., Kakegawa, H., Wada, M. and Kawaguchi, S. (1991): Annual variation of snowfall and radar echo structure of snow clouds at Syowa Station, Antarctica. Proc. NIPR Symp. Polar Meteorol. Glaciol., 5, 90-96.
- Konishi, H. and Wada, M. (1991): Antarctic climate research data, Part 3: Radar and microwave radiometer data at Syowa Station, Antarctica in 1989. JARE Data Rep., 165 (Meteorology 26), 111pp.
- Matejka, T.J., Houze, R.A. and Hobbs, P.V. (1980): Microphysics and dynamics of clouds associated with mesoscale rainbands in extratropical cyclones. Quart. J. Roy. Meteor. Soc., 106, 29-56.
- Murakoshi, N. (1958): Meteorological observations at the Syowa Base during the period from March, 1957 to February, 1958 (in Japanese with English summary). Nankyoku Shiryo (Antarct. Rec.), 4, 1-22.
- Naruse, R., Endo, Y., Ishida, T. and Ageta, Y. (1971): Observations of snow accumulations and sea ice at Syowa Station, Antarctica. Nankyoku Shiryo (Antarct. Rec.), 40, 57-64.
- Sato, N., Kikuchi, K., Barnard, S.C. and Hogan, A.W. (1981): Some characteristic properties of ice crystal precipitation in the summer season at South Pole Station, Antarctica. J. Meteor.

- Soc. Japan, 59, 772-780.
- Schwerdtfeger, W. (1984): Weather and climate of the Antarctic. (Development in Atmospheric Science, 15), Amsterdam, Elsevier, 261pp.
- Streten, N.A. (1980): Some synoptic indices of the Southern Hemisphere mean sea level circulation 1972-1977. Mon. Wea. Rev., 108, 18-36.
- Streten, N.A. and Troup, A.J. (1973): A synoptic climatology of satellite observed cloud vortices over Southern Hemisphere. Quart. J. R. Meteor. Soc., 99, 56-72.
- Takahashi, S. (1985): Estimation of precipitation from drifting snow observation at Mizuho Station, Antarctica in 1982. Mem. Nat'l Inst. Polar Res., Spec. Issue, 39, 69-79.
- Troup, A.J., and Streten, N.A. (1972): Satellite-observed Southern Hemisphere cloud vortices in relation to conventional observation. J. Appl. Meteor., 11, 909-917.
- van Loon, H. (1984): Interannual variations in the half-yearly cycle of pressure gradients and zonal wind at sea level on the Southern Hemisphere. Tellus, 36a, 76-86.
- Wada, M. (1990): Antarctic climate research data, part 2. Radar and microwave radiometer data at Syowa Station, Antarctica from March to December 1988. JARE Data Rep., 153(Meteorology 24), 97pp.
- Wada, M. (1991): Estimation of vertically integrated liquid water contents in the atmosphere. Nankyoku Shiryo(Antarctic Record), 35, 1-11.
- Wang, P.-Y. and Hobbs, P.V. (1983): The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones. X: Wavelike rainband in an occlusion.

J. Atmos. Sci., 40, 1950-1964

Warburton, J.A., Reinhardt, E. and Young, L.G. (1981): X-band weather radar-Palmer Station operation in the forecasting mode. Antarctic Journal of the United States, 16, 200-201.

Whinnery, R., Barnhardt, B., and Warburton, J.A. (1979): Radar reflectivity and precipitation rate studies at Palmer Station and Faraday Base. Antarctic Journal of the United States, 14, 212-213.



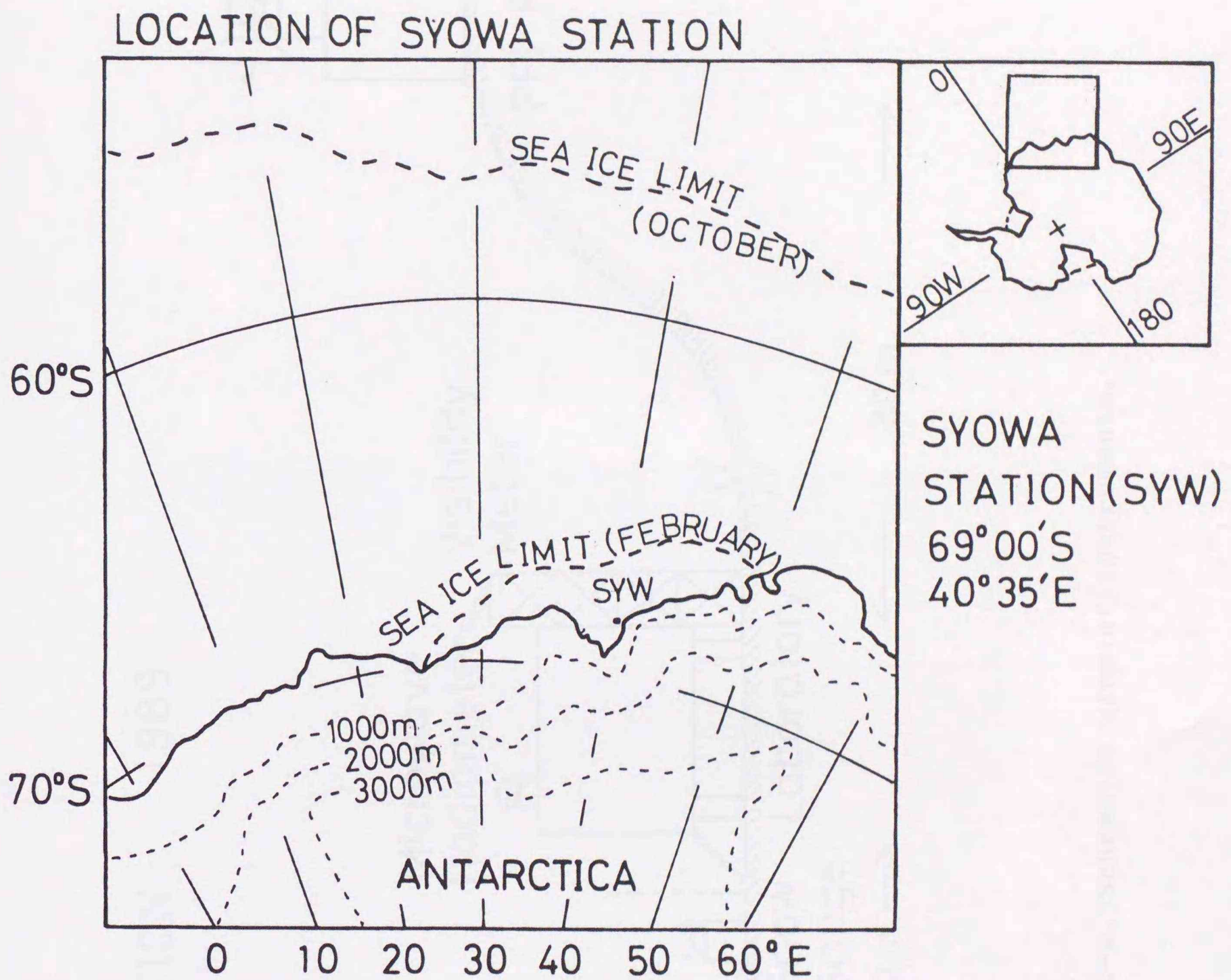


Figure 2-1. Location of Syowa Station (SYW) (69°00'S, 40°35'E).

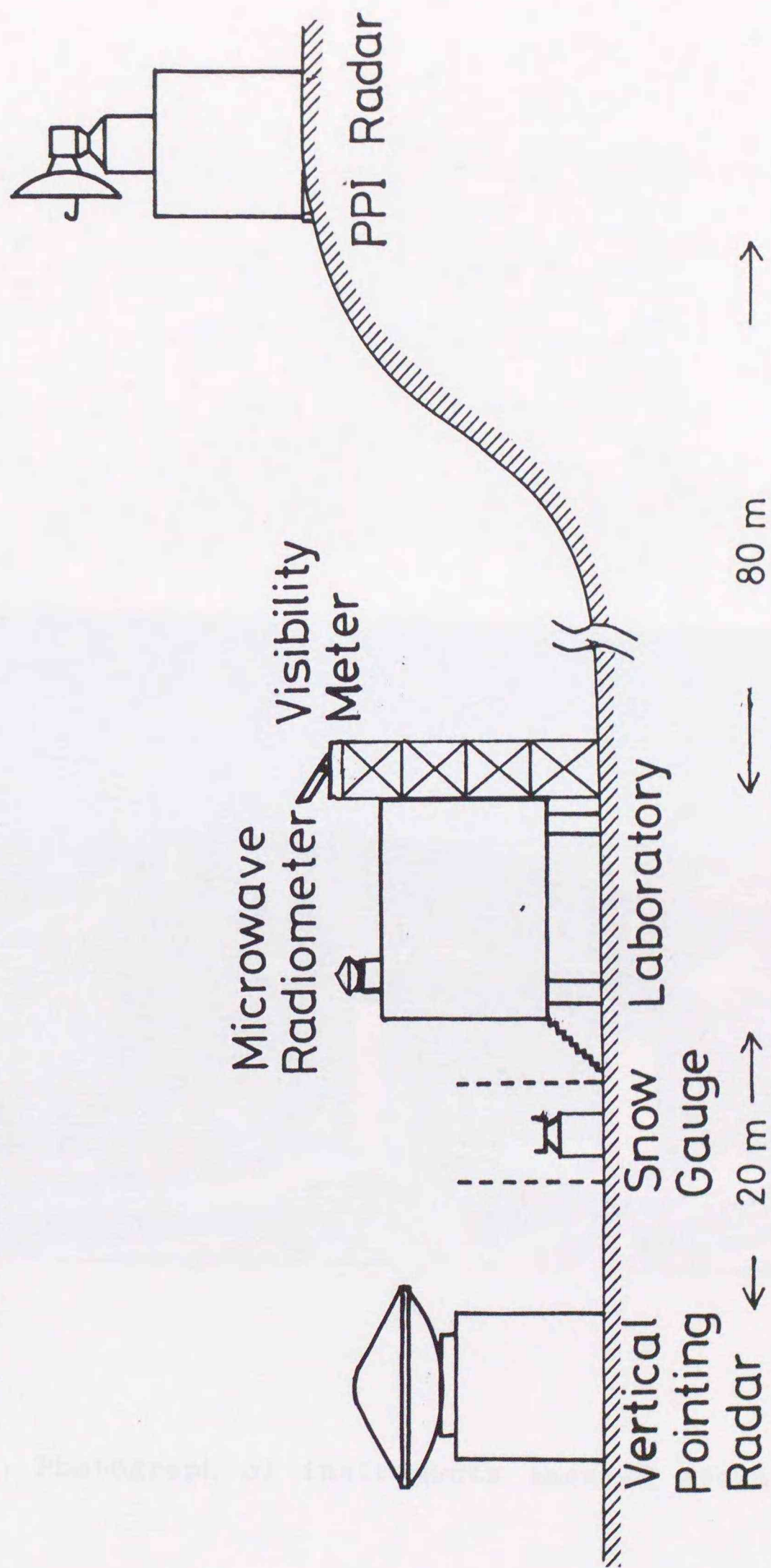


Figure 2-2. Schematic view of instruments.



Figure 2-3. Photograph of instruments located around the laboratory.

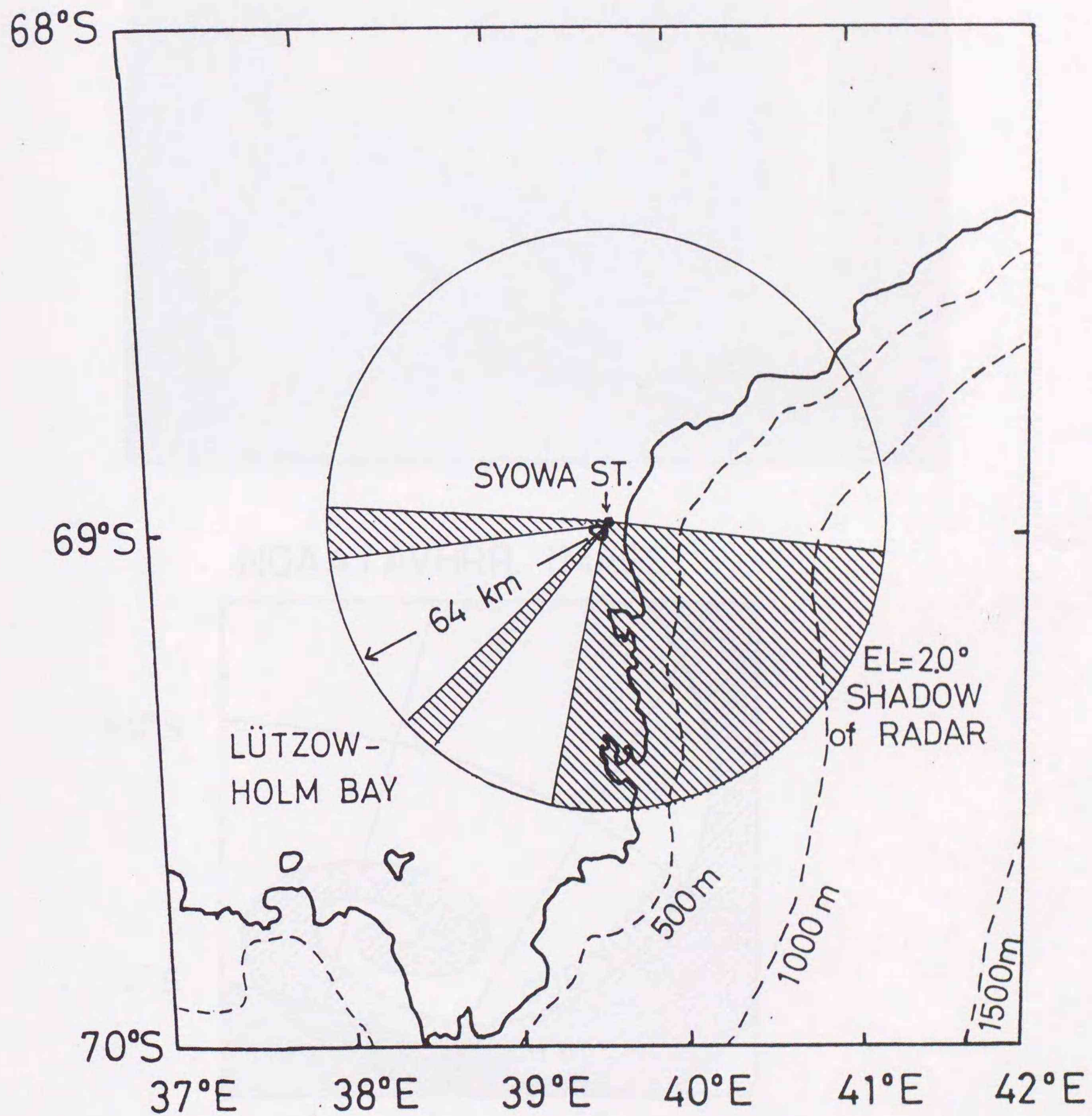
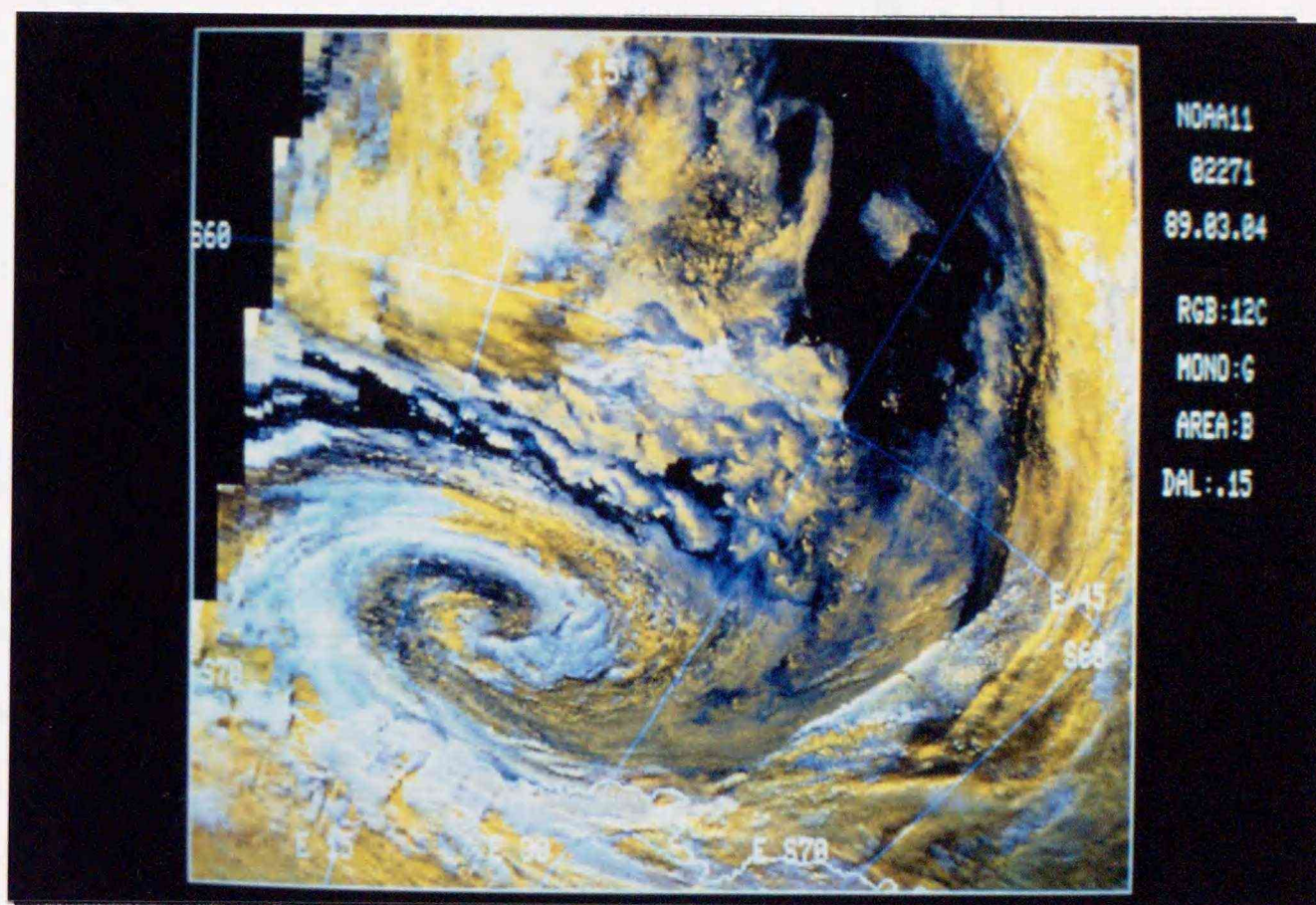


Figure 2-4. Detectable range of PPI radar. The radar detects the precipitating echo within 64 km in radius. The hatched area shows the shadow caused by the ground blocking the radar beam at an elevation angle of 2.0 degrees.



NOAA / AVHRR IMAGE

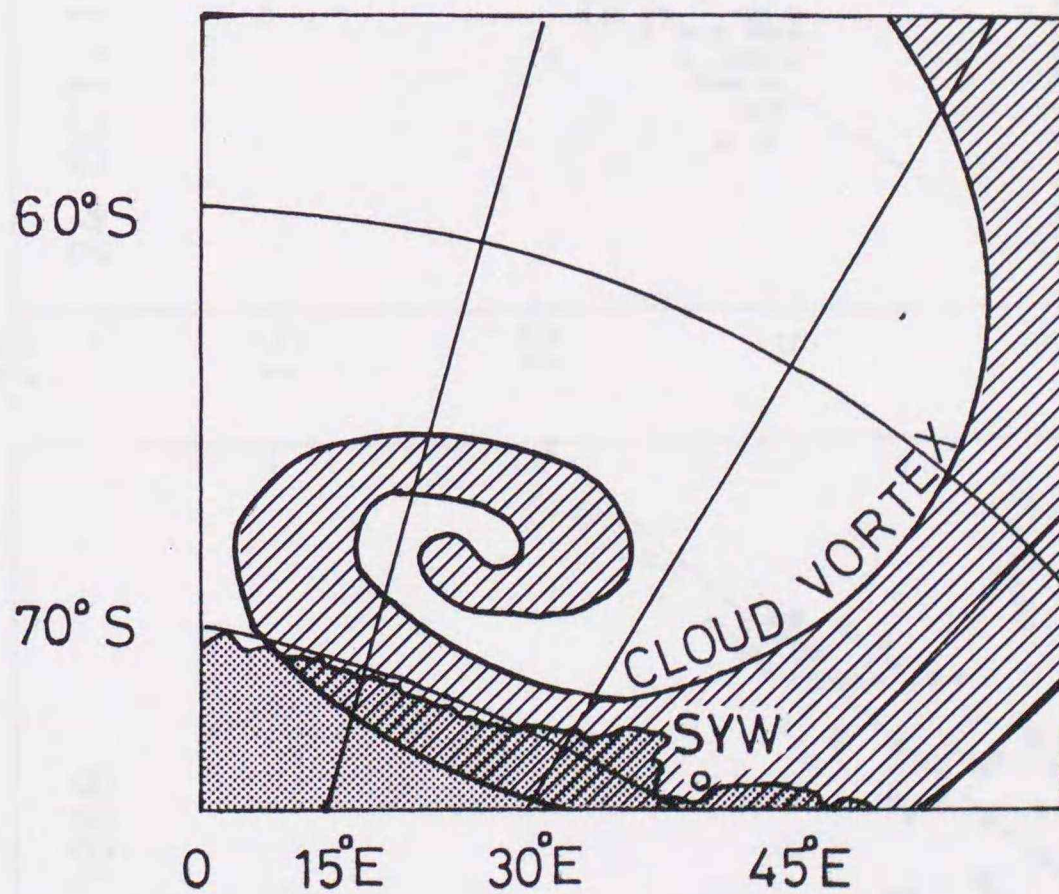


Figure 2-5. Typical cloud vortex observed by NOAA/AVHRR image near Syowa Station in 1989. The upper part of the figure shows the image of cloud vortex and the lower part of the figure shows the schematic pattern of cloud vortex by hatched area in the map of the same area of the upper AVHRR image. The shaded area shows the continent.

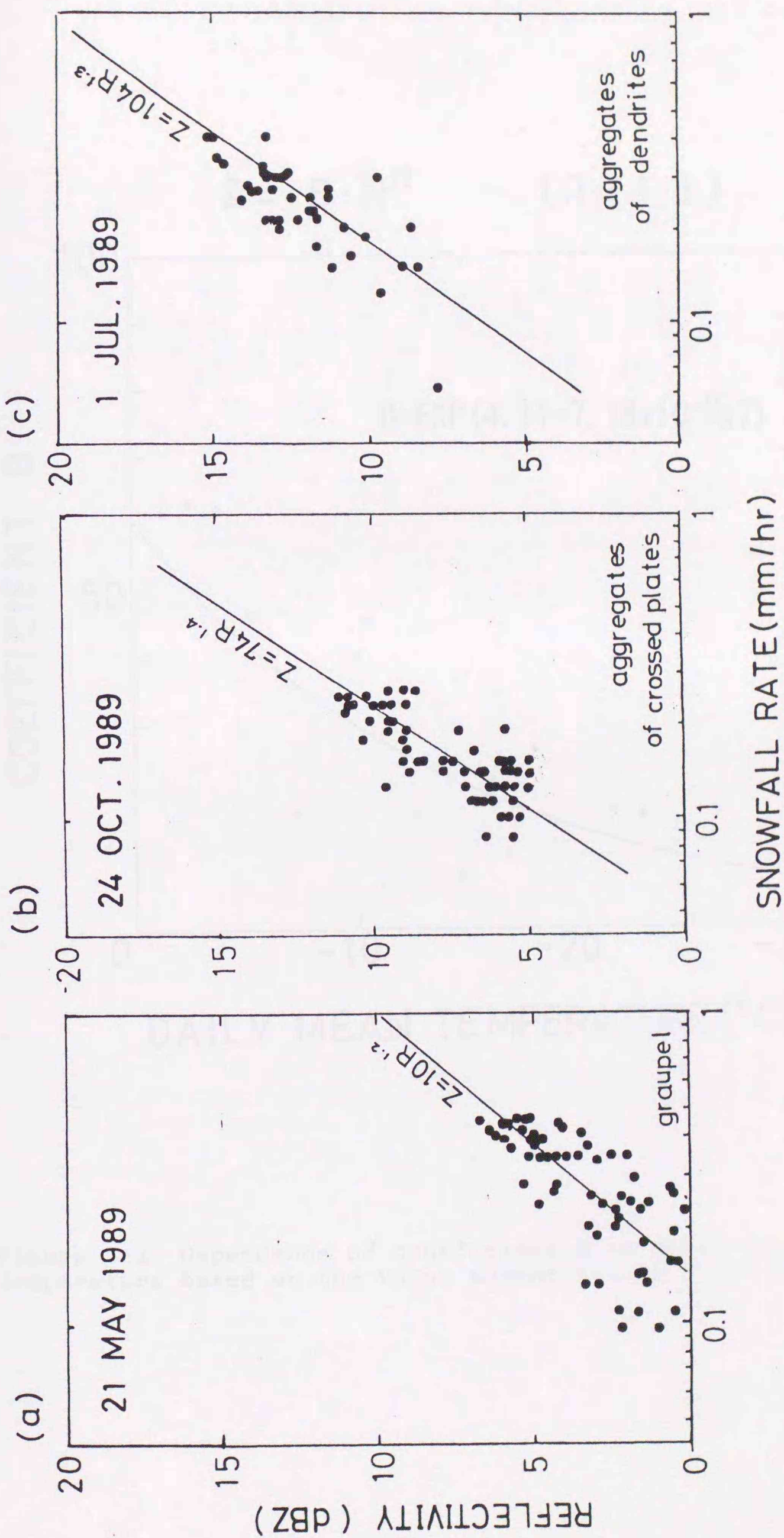


Figure 3-1. Relationship between radar reflectivity factor at 400 meter height and snowfall rate at the ground observed in a series of snowfalls at Syowa Station. Each solid circle represents a 5 minute averaged value. The types of crystals were mainly graupel, aggregates of crossed plates, and aggregates of dendrites in cases (a), (b) and (c) respectively.

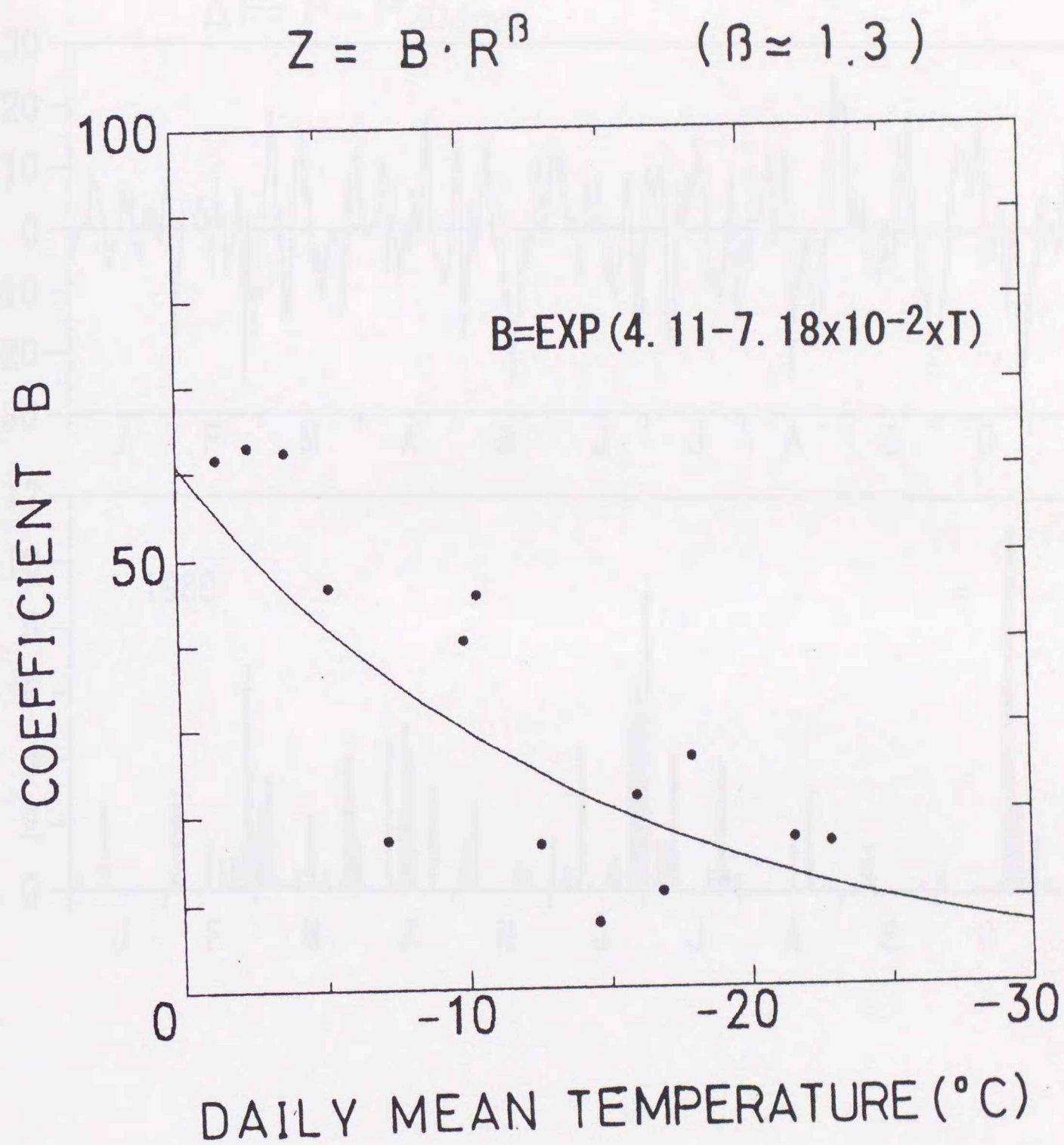


Figure 3-2. Dependence of coefficient B on daily mean surface air temperature based on the value summarized in Table 3-1.

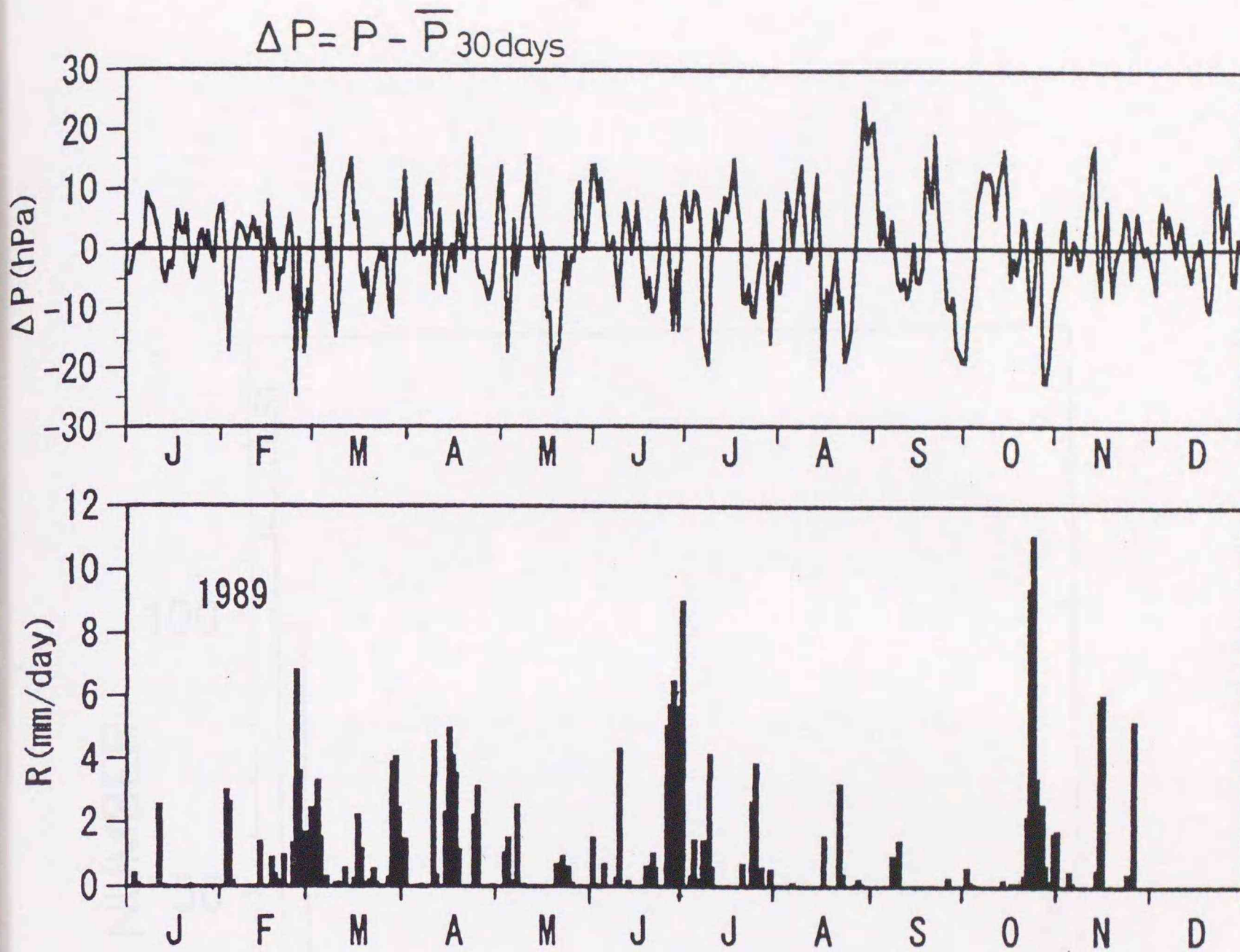


Figure 3-3. Amount of daily snowfall rate and deviation of sea surface pressure at Syowa Station. The upper figure shows the deviation of surface pressure from pressure averaged over 30 days. The lower figure shows the daily snowfall rate calculated from vertical pointing radar data.

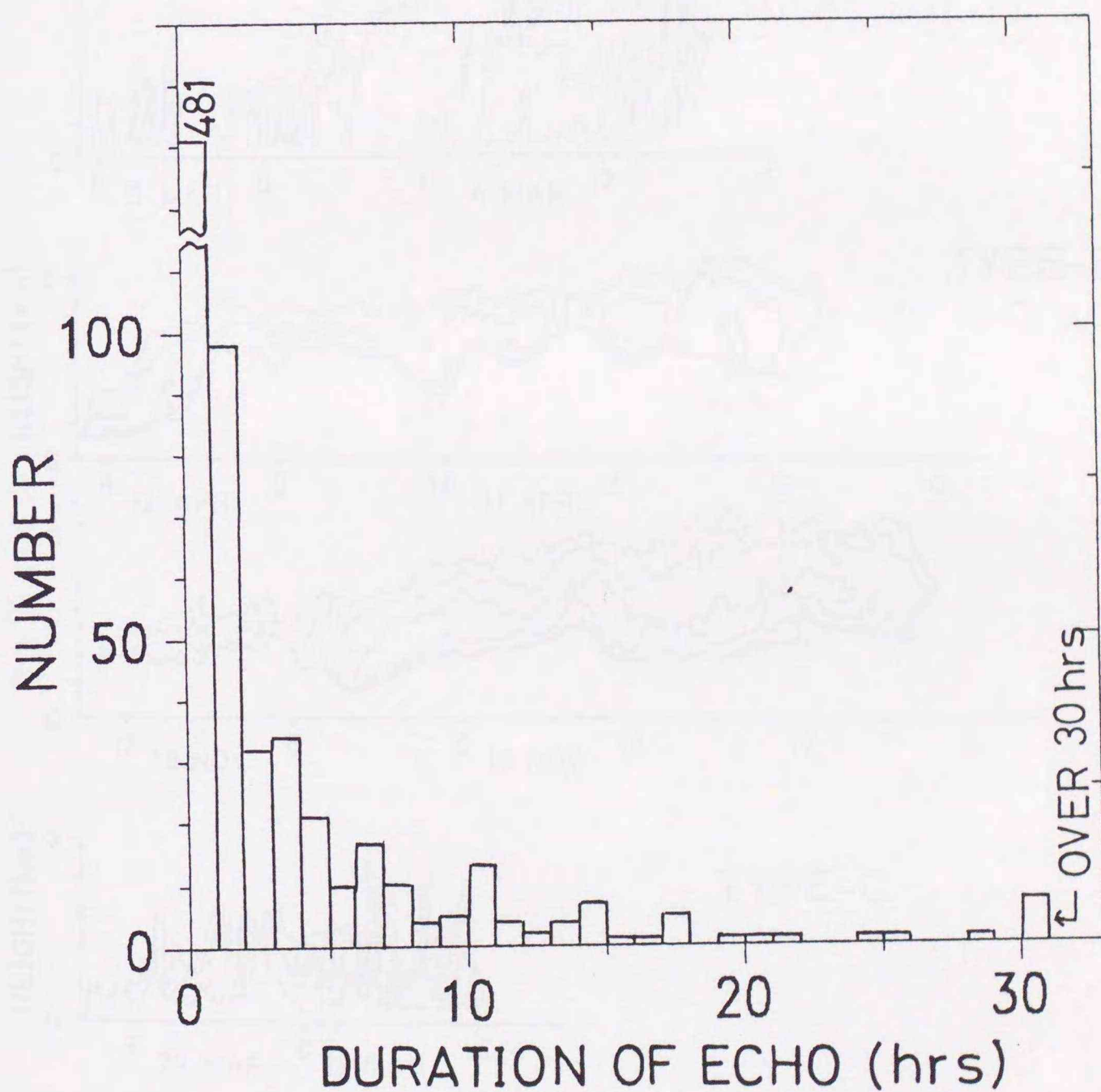


Figure 4-1. Histograms showing the frequency of appearance duration of echoes observed by vertical pointing radar at Syowa Station in 1989.

TIME-HEIGHT CROSS SECTION

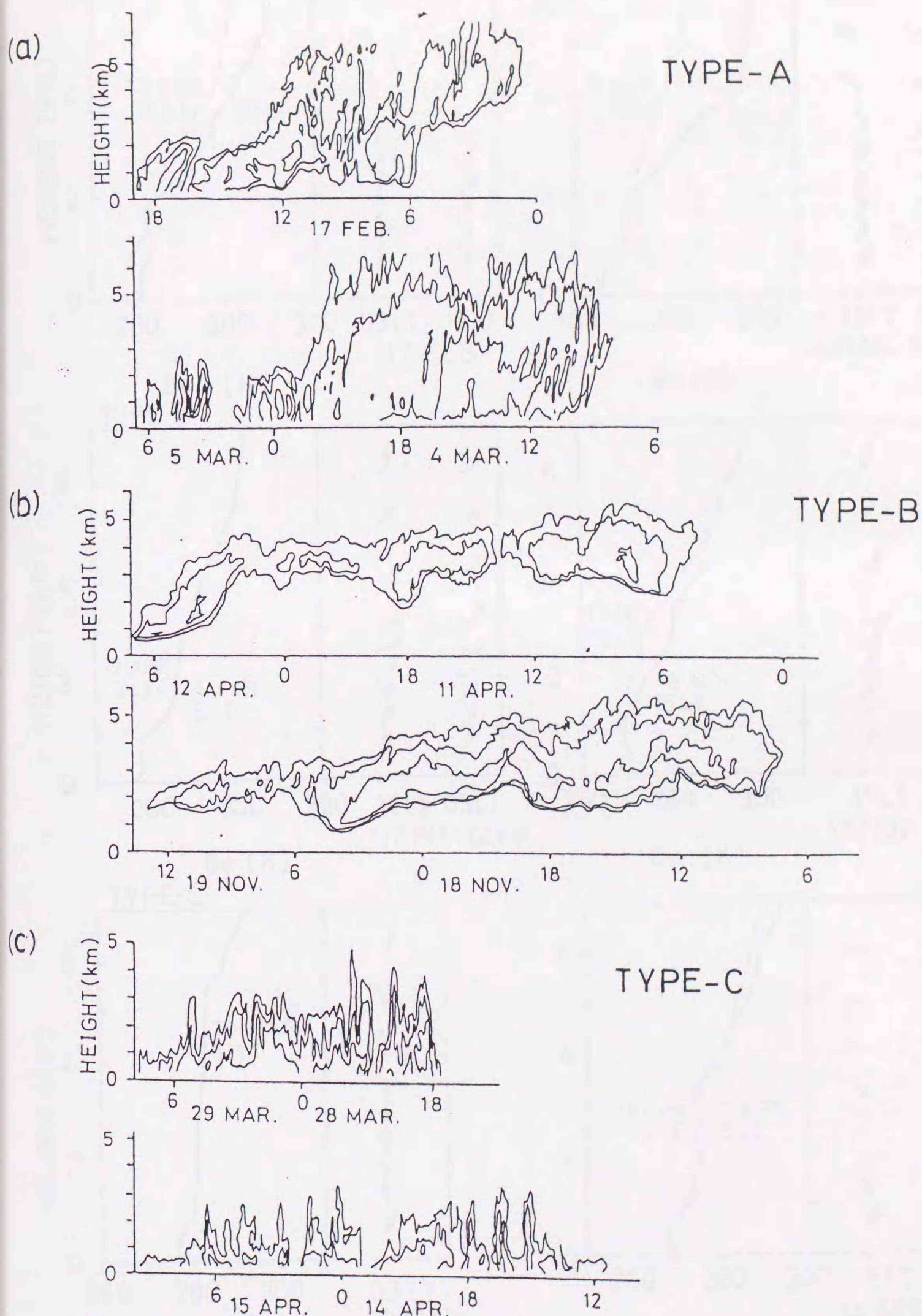


Figure 4-2. Three types of time-height cross section observed by vertical pointing radar. (a): A pair of early deep echoes and later shallow echoes defined as type-A echo in this paper. (b): A high level echo without precipitation on the ground for over 10 hours defined as type-B. (c): The shallow echo with short periodic convective cells defined as type-C. The radar echo intensity is contoured at 2, 12 and 20 dBZ.

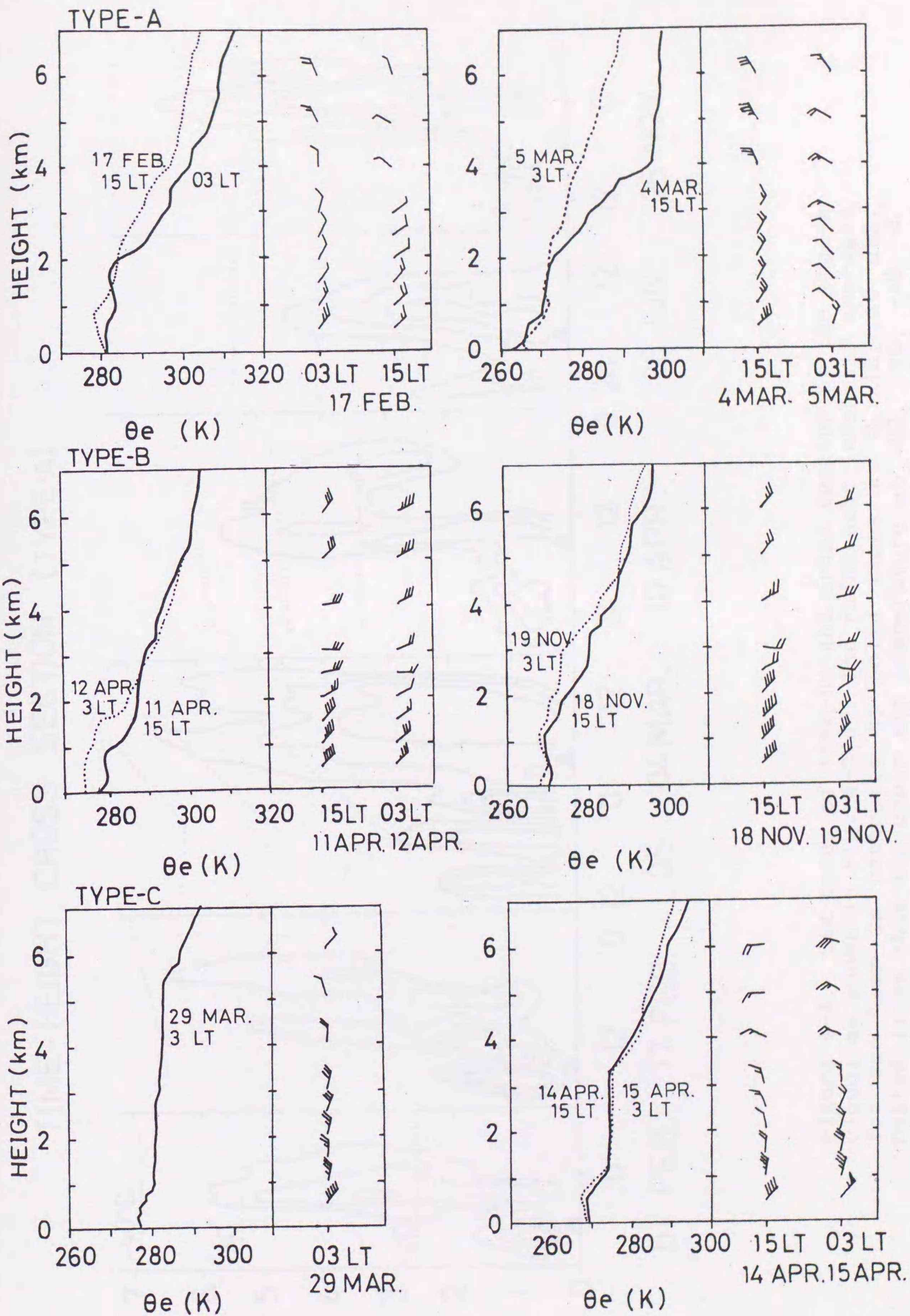


Figure 4-3. Vertical profiles of equivalent potential temperature and wind for the same 6 cases shown in Fig. 4-2.

TIME-HEIGHT CROSS SECTION (TYPE-A)



Figure 4-4. Six cases of time-height cross section of the type-A clouds as shown in Fig. 4-2(a). The radar echo intensity averaged for one hour is contoured by solid lines at 2, 12, 20 dBZ. Dotted lines show the upper air temperature at -20, -30, -40 °C. The solid triangle on the horizontal axis shows the time of minimum surface pressure during the passage of the echo.

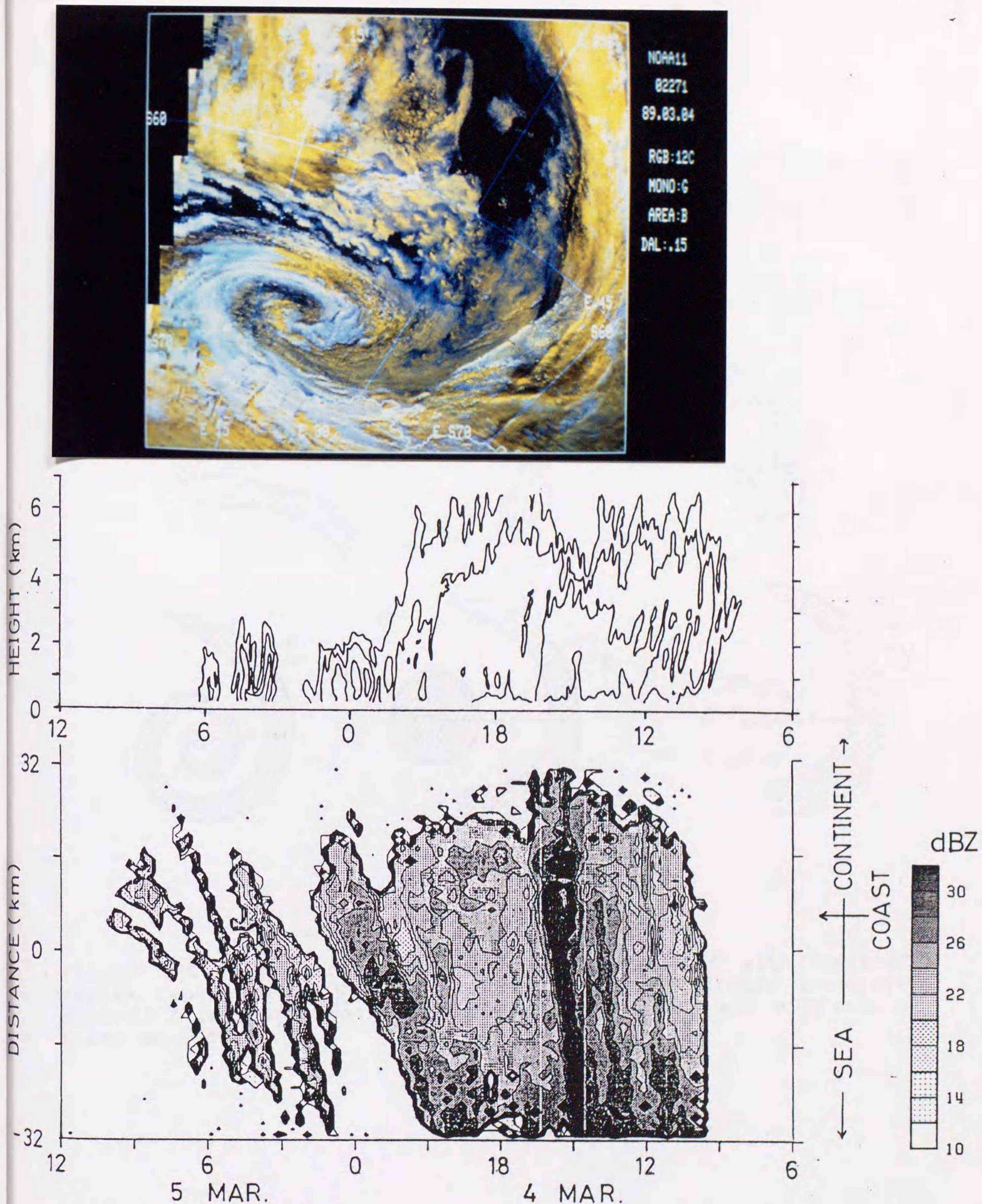


Figure 4-5. Echo structure of the type-A clouds observed on 4 March and 5 March 1989. The lower part of the figure shows a horizontal structure of type-A echo composed of time-distance cross section using the PPI radar echo along a line 10 km north of Syowa Station. The middle part of the figure shows the vertical structure of the type-A echo composed of time-height cross section using the vertical pointing radar echoes corresponding to the horizontal structure in the lower panel. The upper part of the figure shows NOAA satellite image corresponding to the radar echoes.

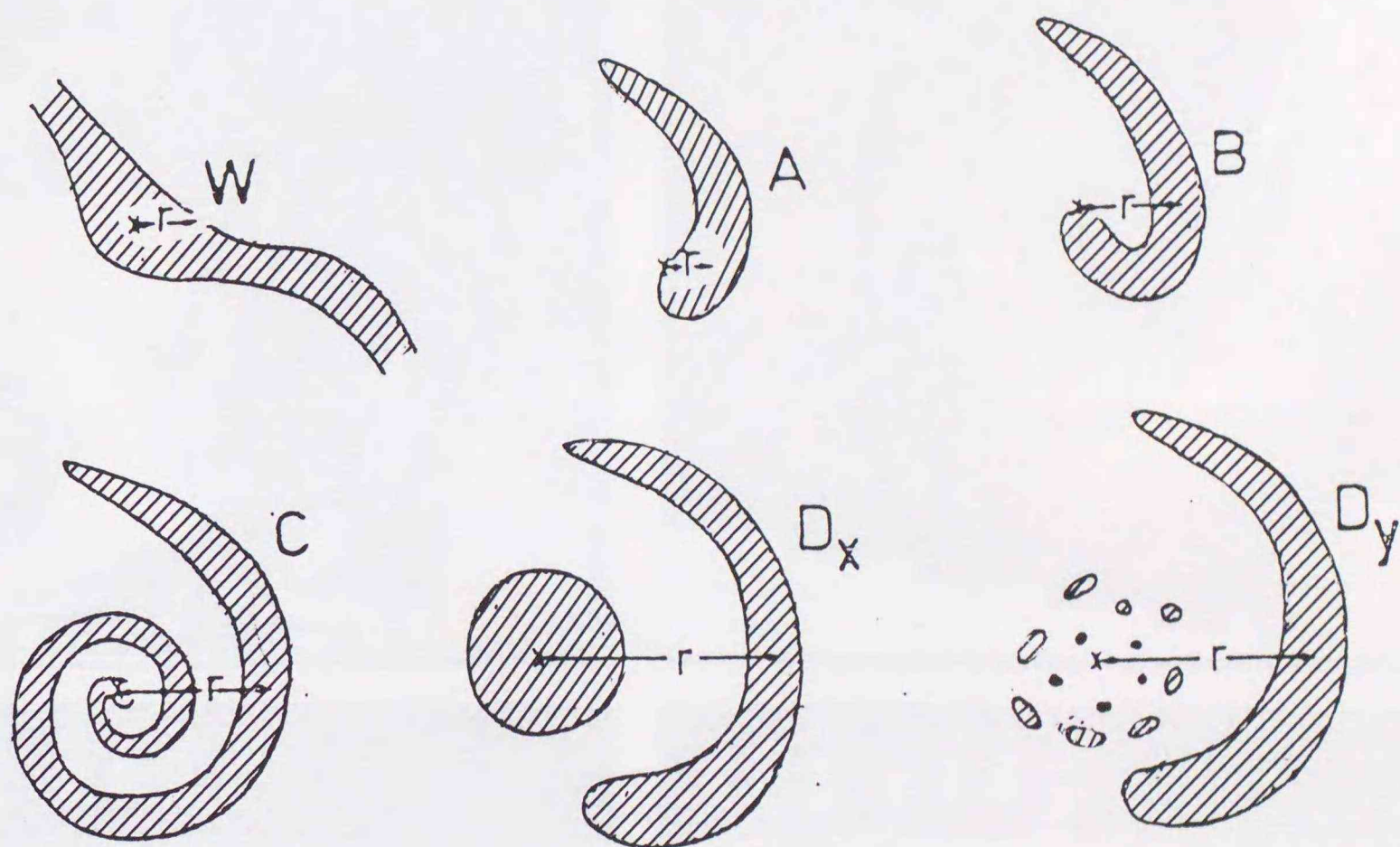


Figure 4-6. Schematic cloud patterns associated with defined vortex types (after Streten and Troop, 1973). Cloudy area are shaded. X indicates point taken as vortex center and r distance taken as radius.

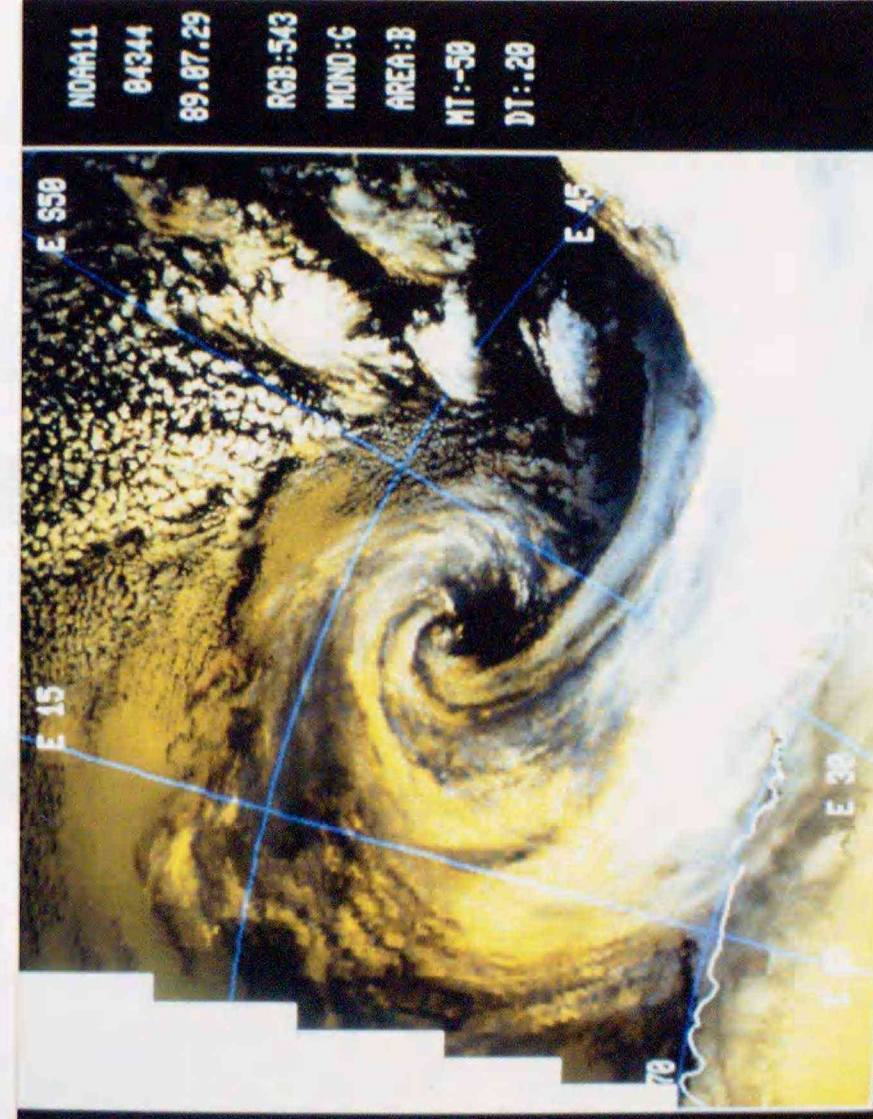
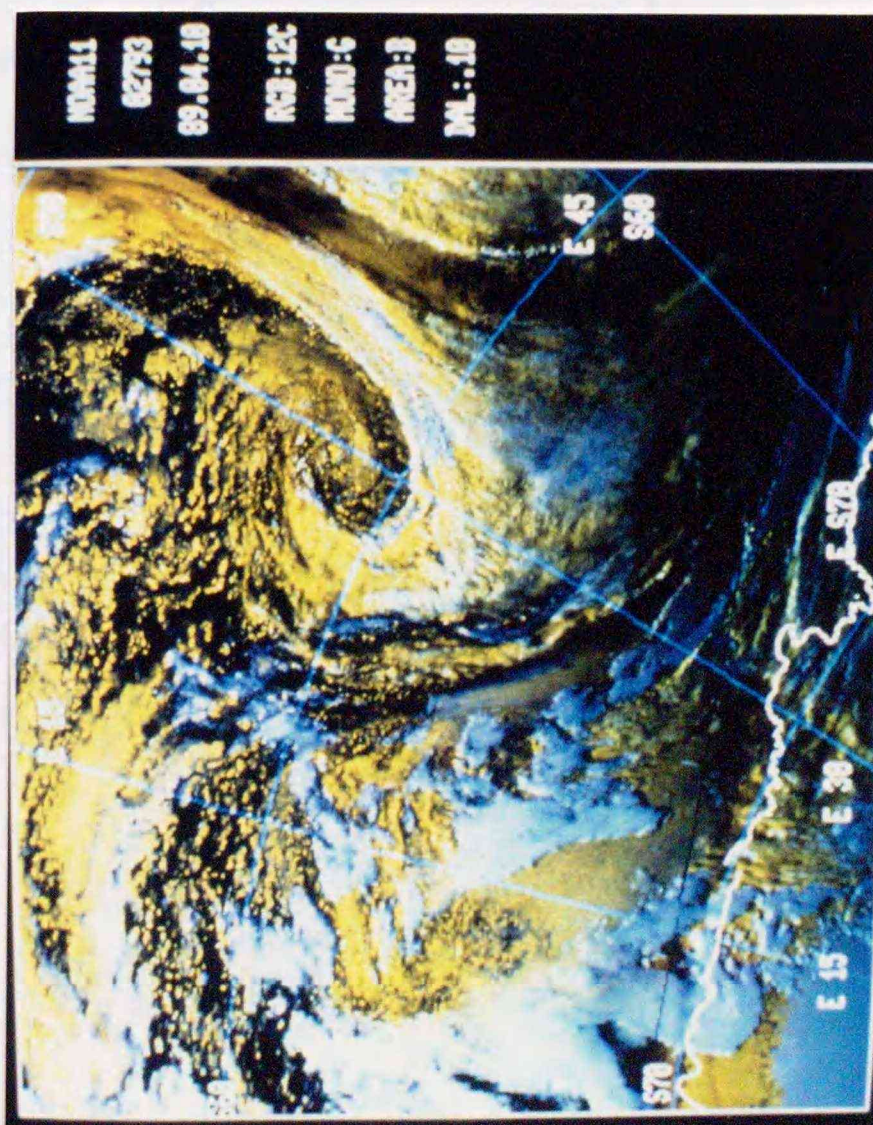
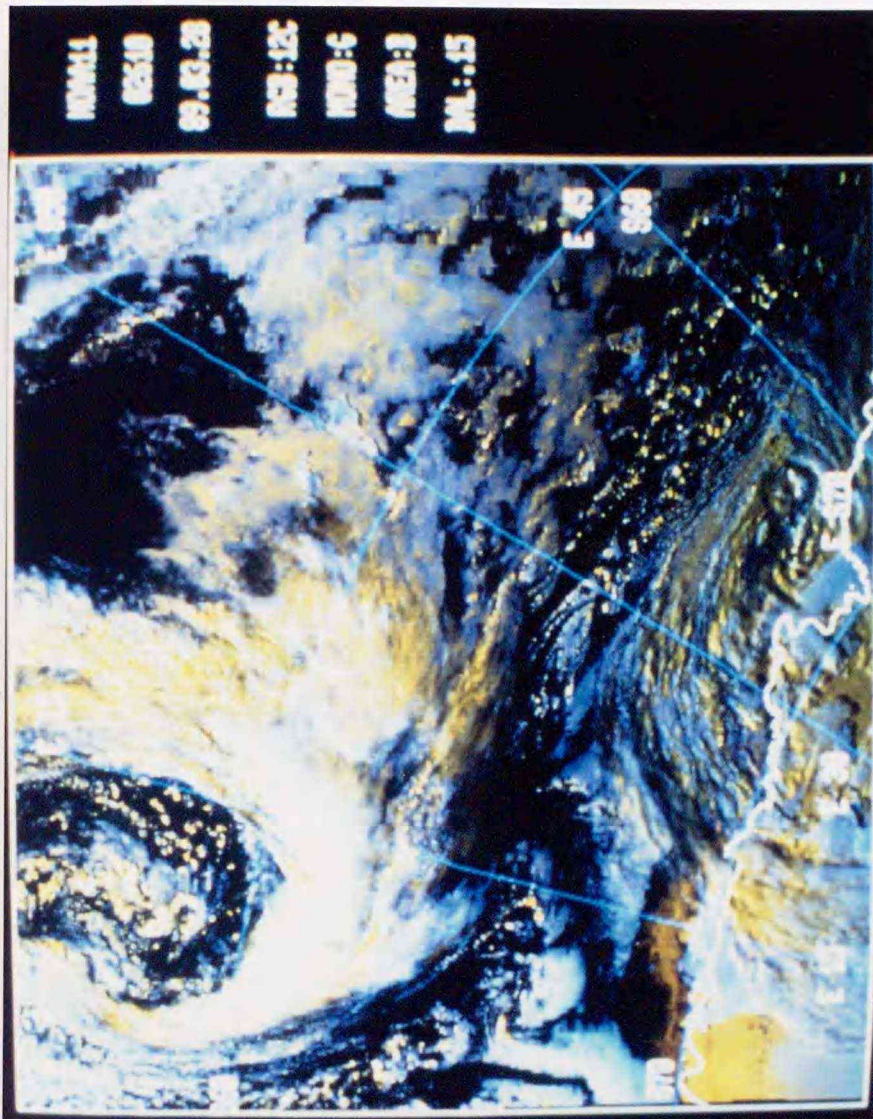
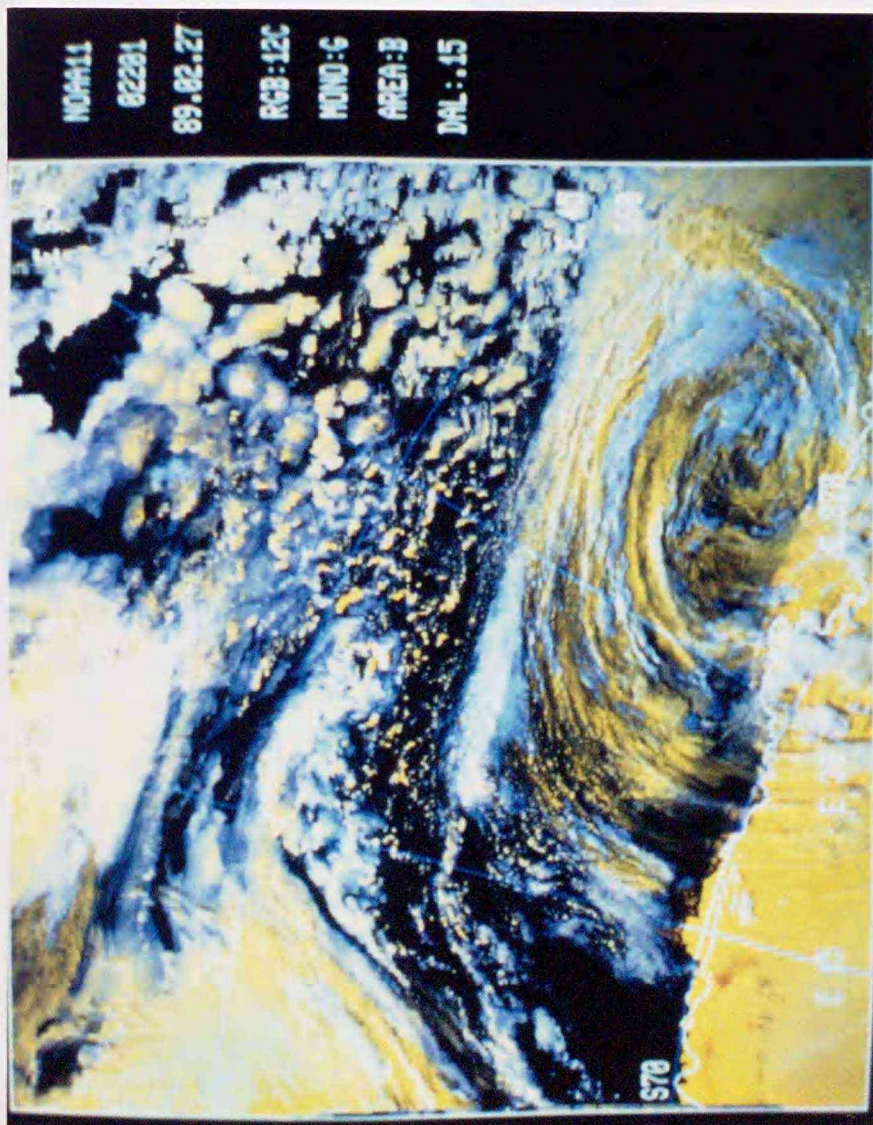


Figure 4-7. Examples of cloud vortices observed by NOAA/AVHRR image near Syowa Station in 1989.

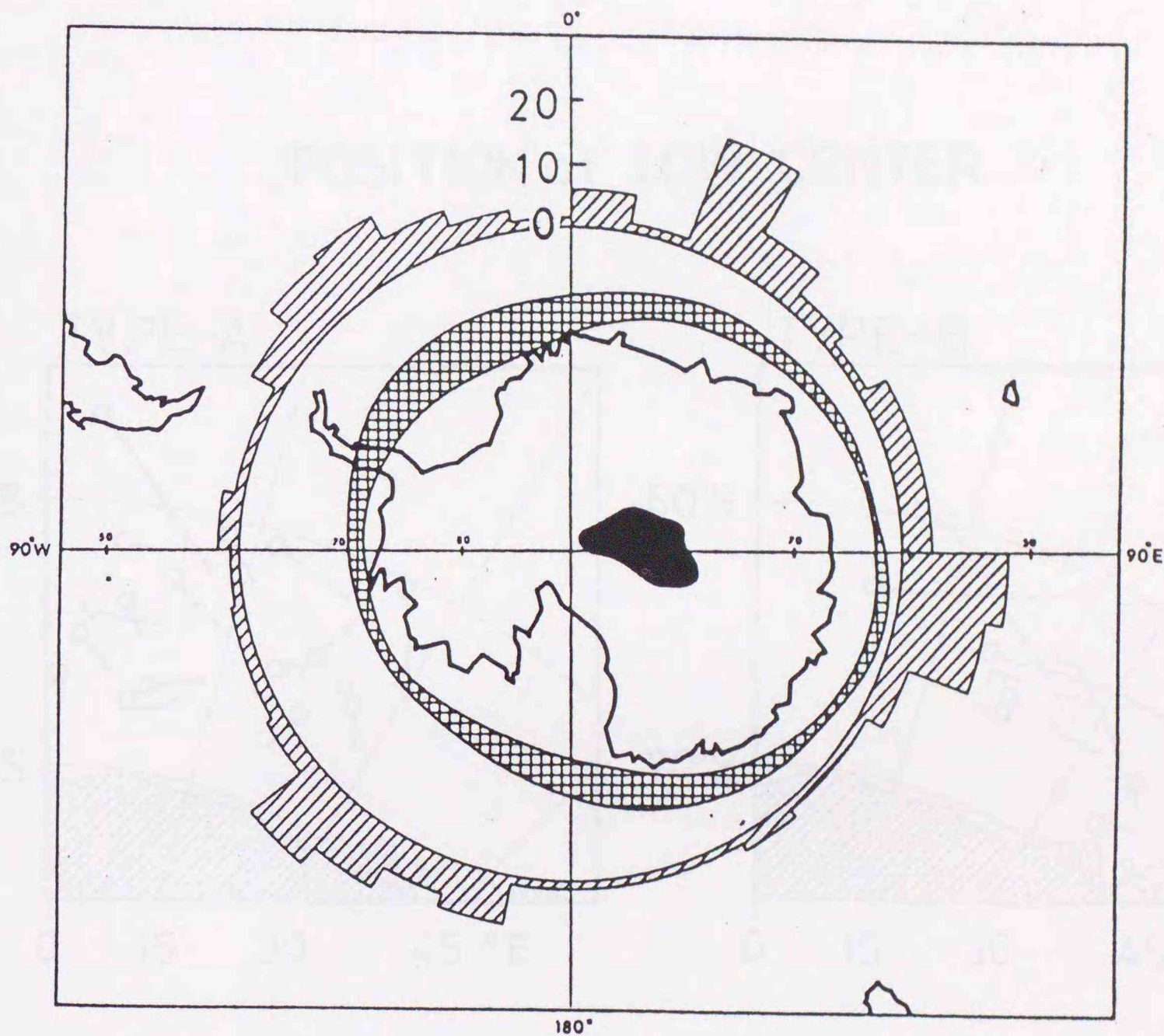


Figure 4-8. Location of circumpolar trough and the existence frequency of low centers in the trough (after Streten, 1980). The cross hatched area shows the circumpolar trough region and single hatched histograms, depicted along 60°S, show the relative existence frequency of monthly mean pressure centers in the trough.

POSITION of LOW CENTER

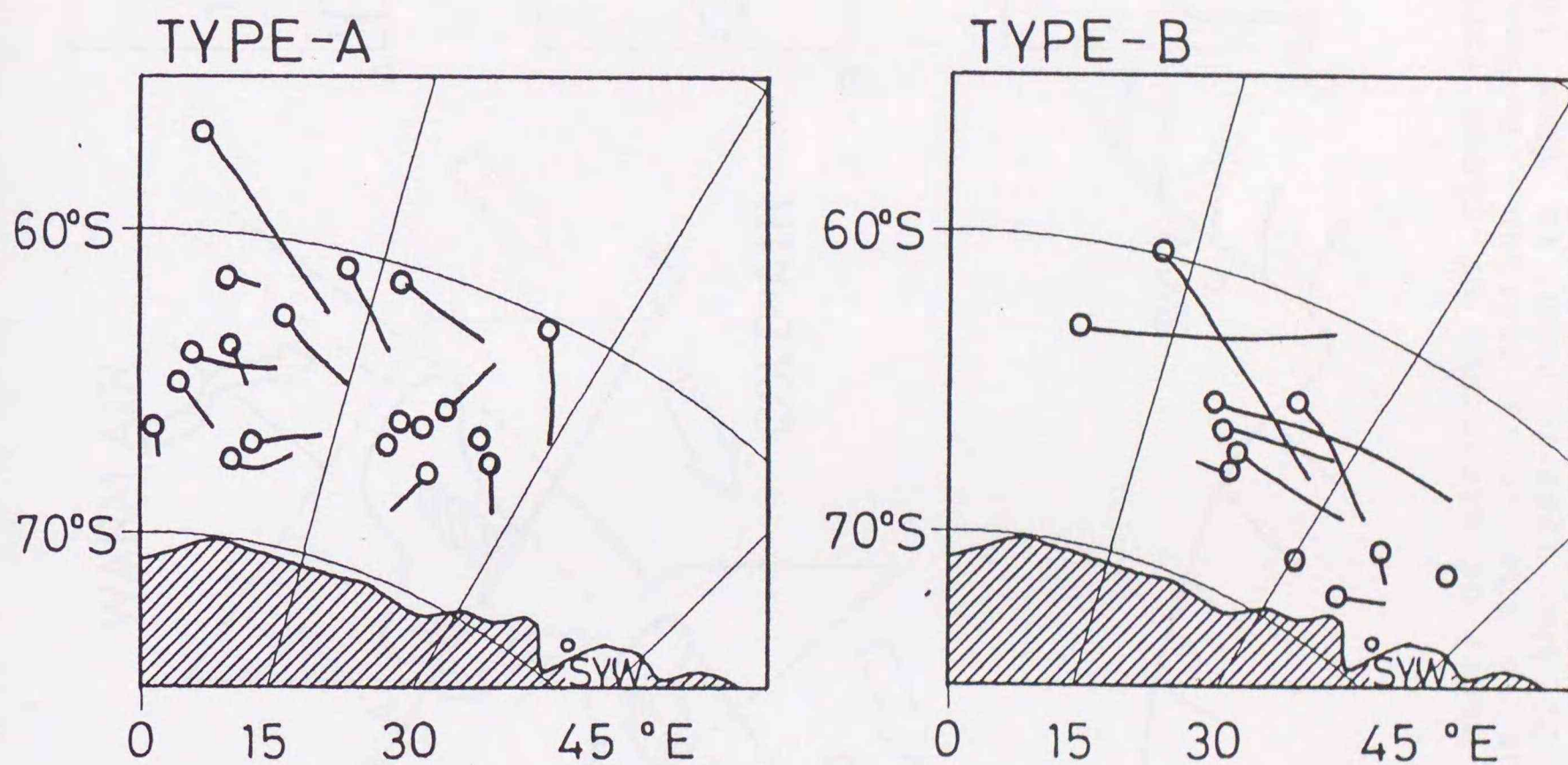


Figure 4-9. Trajectories of low pressure center for the type-A and type-B echoes which appeared over Syowa Station. Open circles show the positions of centers when the echoes firstly appeared over Syowa Station. Solid bars show the trajectories of the low center during the time when the echoes covered Syowa Station.

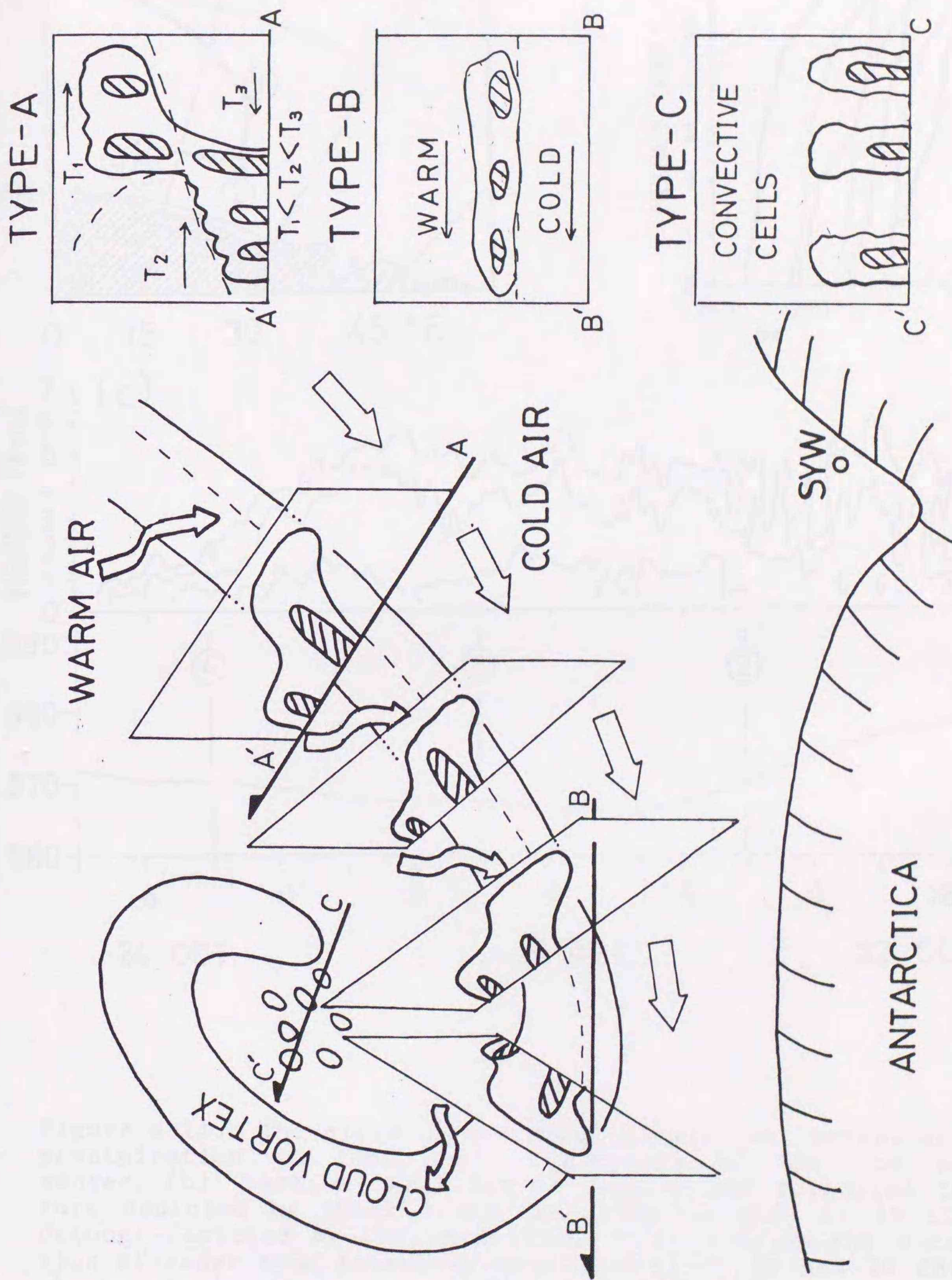


Figure 4-10. Conceptual model of structure of cloud vortex. The type-A echo corresponds to the cross section normal to the cloud vortex (i.e. A-A'); the type-B echo is from the south periphery of the cloud vortex (i.e. B-B'). The type-C echo is considered to be from convective cells near the low pressure center.

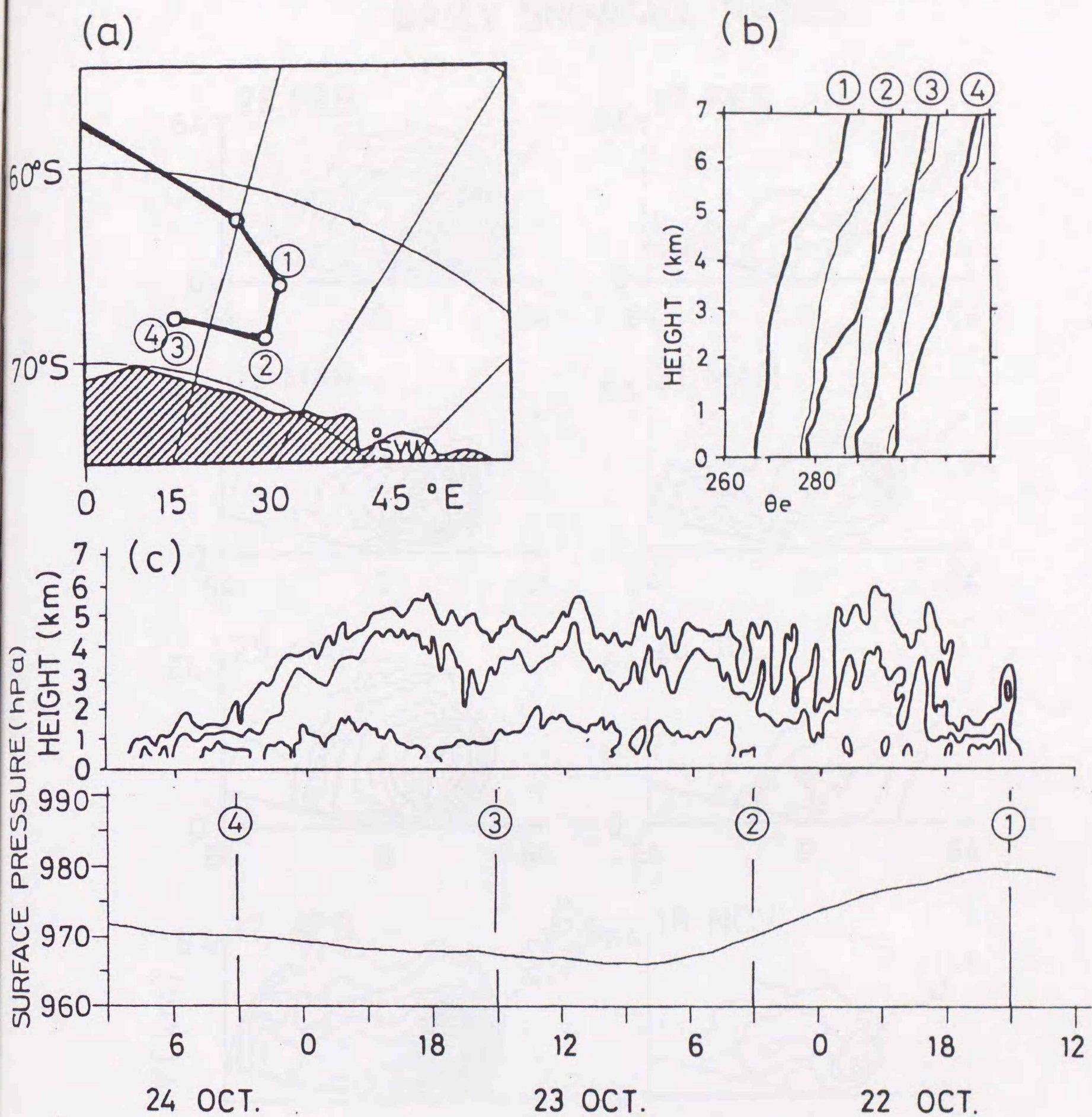


Figure 4-11. The cloud vortex which caused the largest amount of precipitation in 1989. (a): Trajectory of the low pressure center. (b): Vertical profiles of equivalent potential temperature depicted by thick lines comparing to that at 15 LT on 22 October depicted by the thin lines. (c): Time-height cross section of radar echo intensity contoured at 2, 12 and 20 dBZ using the vertical pointing radar data and change of surface pressure. Numbers in circles represent the chronological order of the event. 1: 15LT 22 OCT., 2: 3LT 23 OCT., 3: 15LT 23 OCT., 4: 3LT 24 OCT.

DAILY SNOWFALL RATES

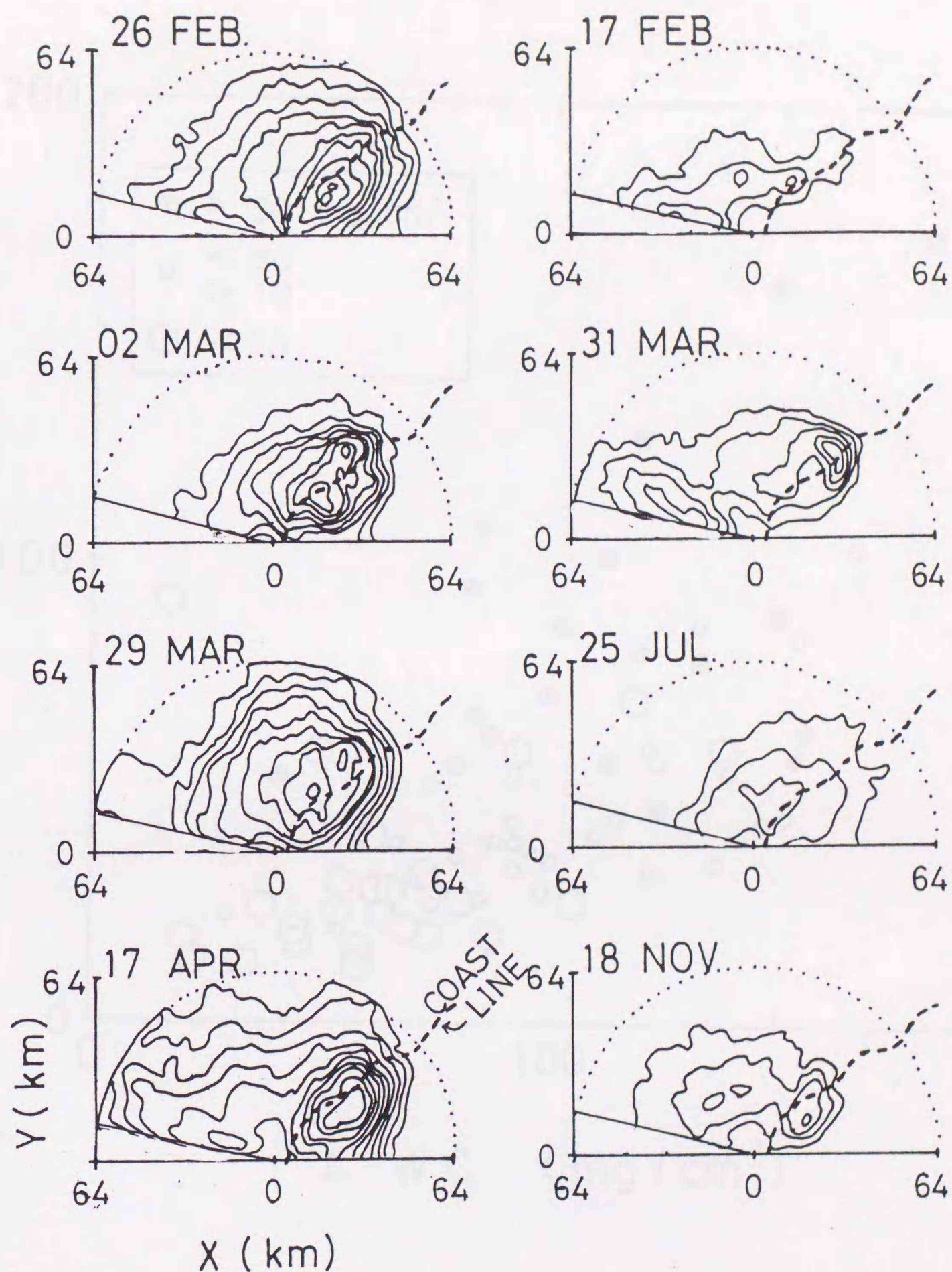


Figure 4-12. Daily snowfall rates obtained by PPI radar data. Left groups are for mixed-phase clouds and right groups are for solid-phase clouds. Snowfall rates are contoured every 2 mm/day by solid lines. The northern coast of Antarctica is drawn as a broken line.

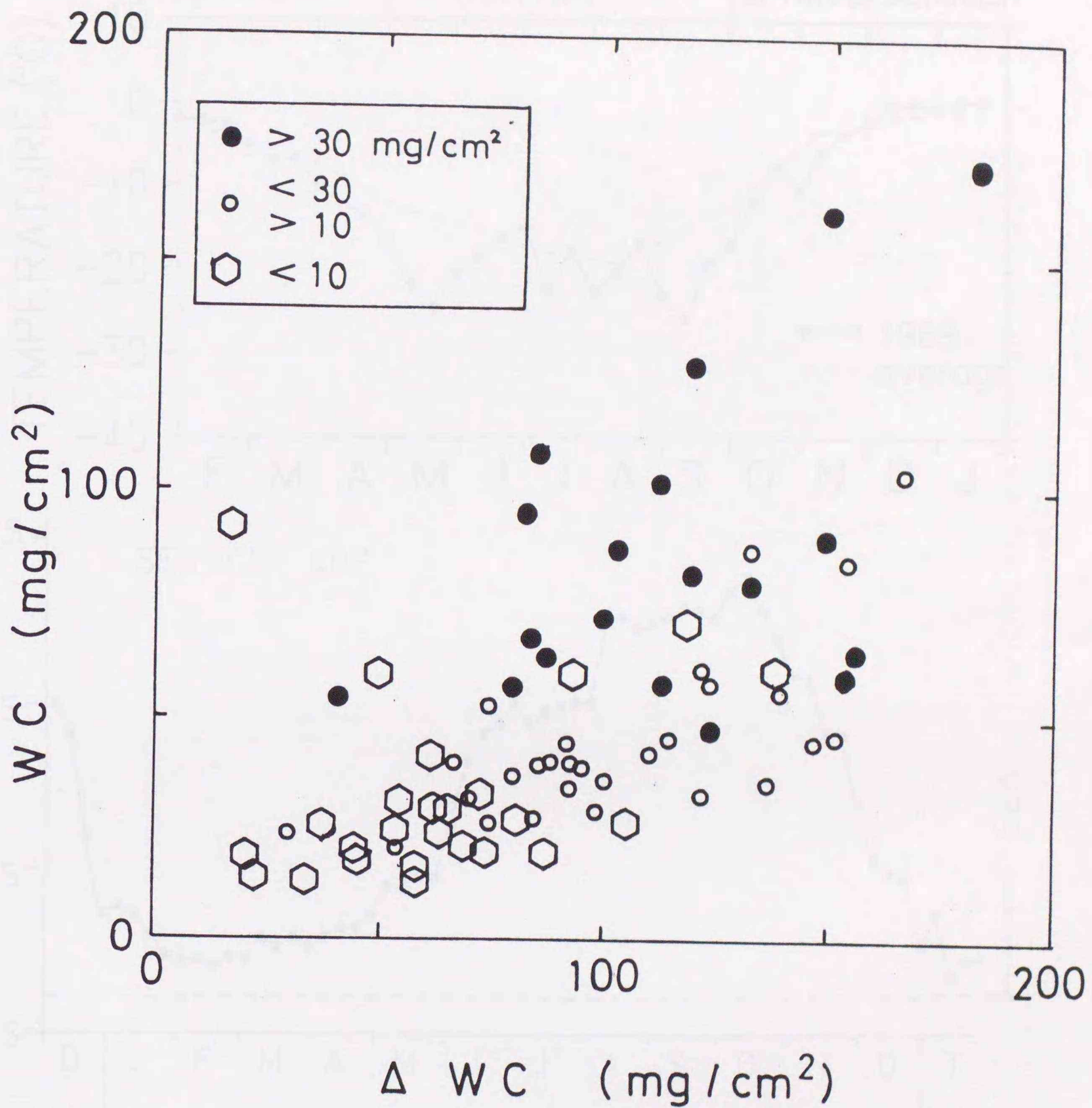


Figure 4-13. Increase of new condensed water after the clouds lifted 500m adiabatically. The hexagonal mark represents mixed-phase clouds, the solid circle represents solid-phase clouds and the open circle represents the intermediate clouds. WC: measured original water content, ΔWC : new condensed water content after lifting calculated from sounding data.

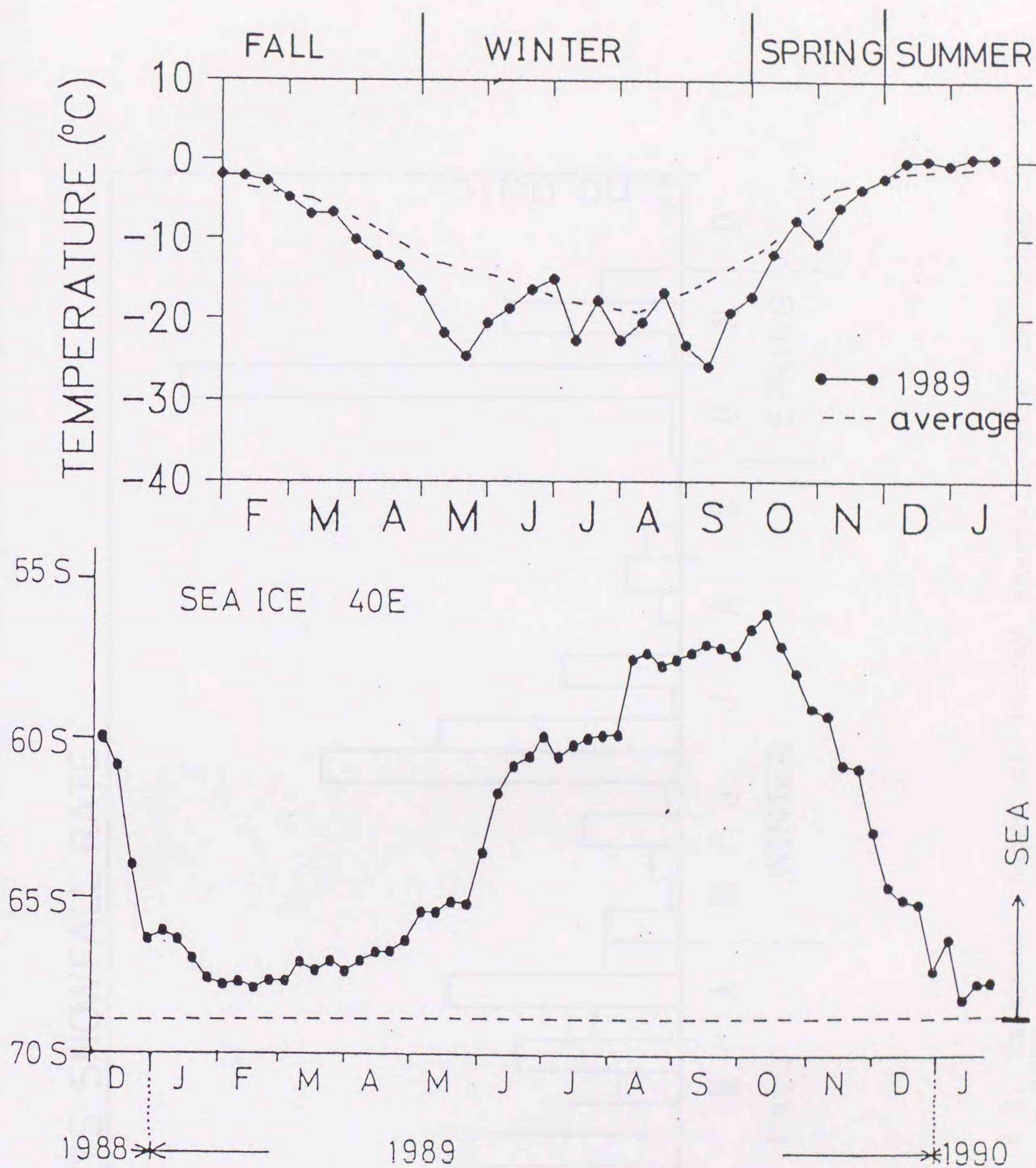


Figure 5-1. Seasonal variations of surface air temperature and the extension of sea ice edge along the longitude 40°E. The upper figure shows the 10-days averaged temperature observed at Syowa Station drawn by a solid line. The averaged value is also drawn by a dashed line. The lower figure shows the sea ice edge defined as the boundary of ice concentration larger than 80%.

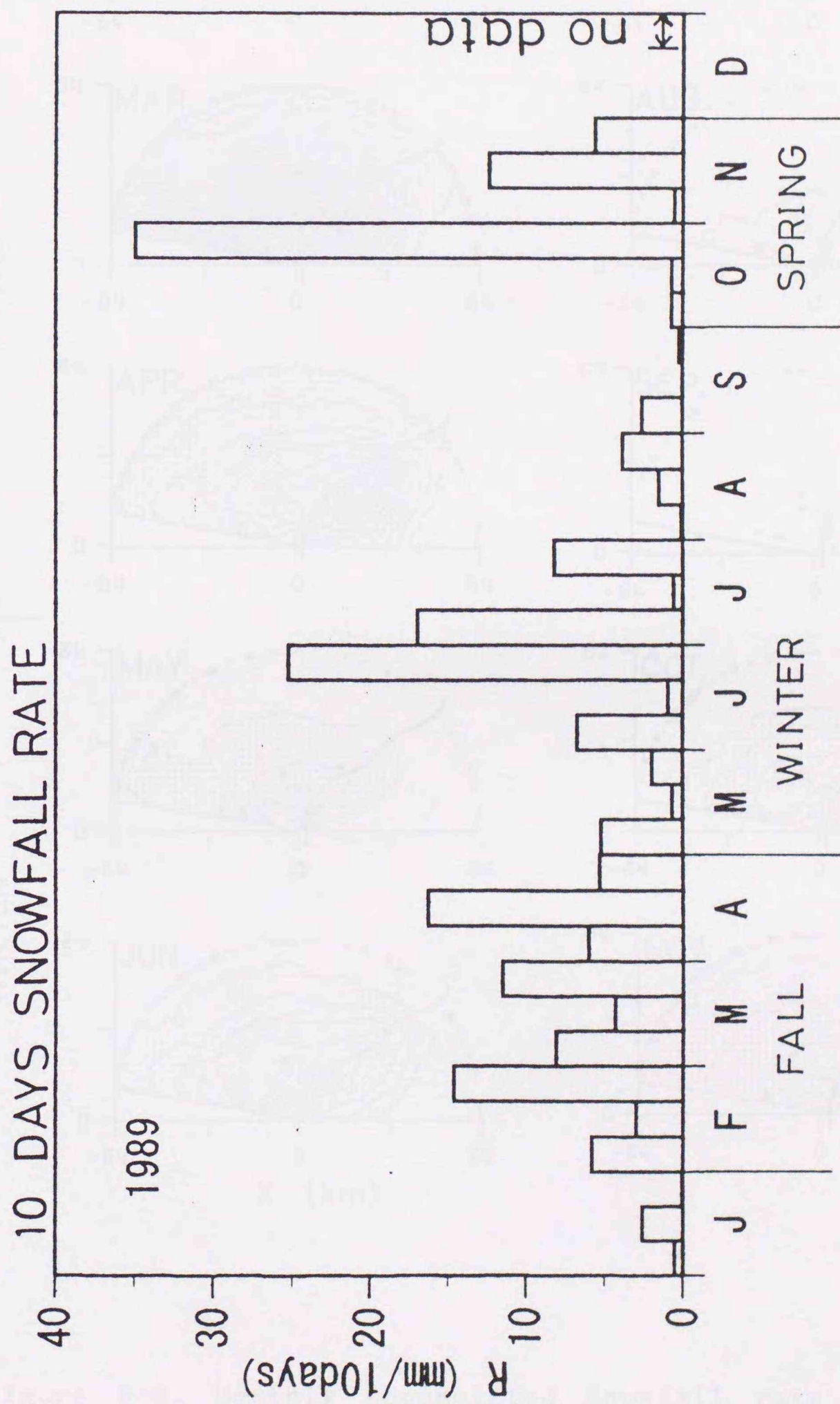


Figure 5-2. Seasonal change of 10-day snowfall rate at Syowa Station in 1989.

MONTHLY SNOWFALL RATES

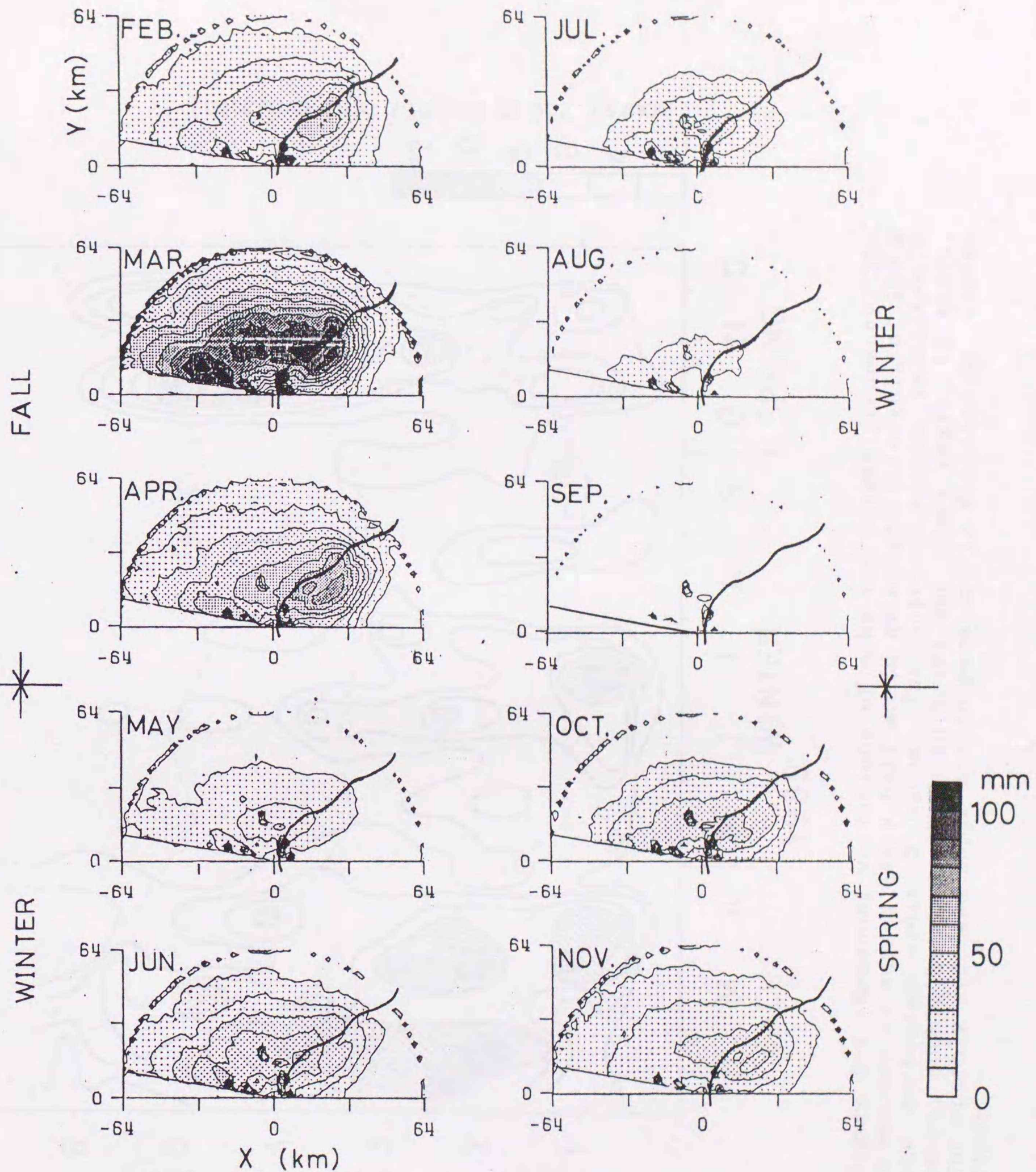


Figure 5-3. Monthly accumulated snowfall rate obtained by PPI radar. The amount of snowfall is contoured every 10 mm/month. The thick solid line shows the coast of Antarctica.

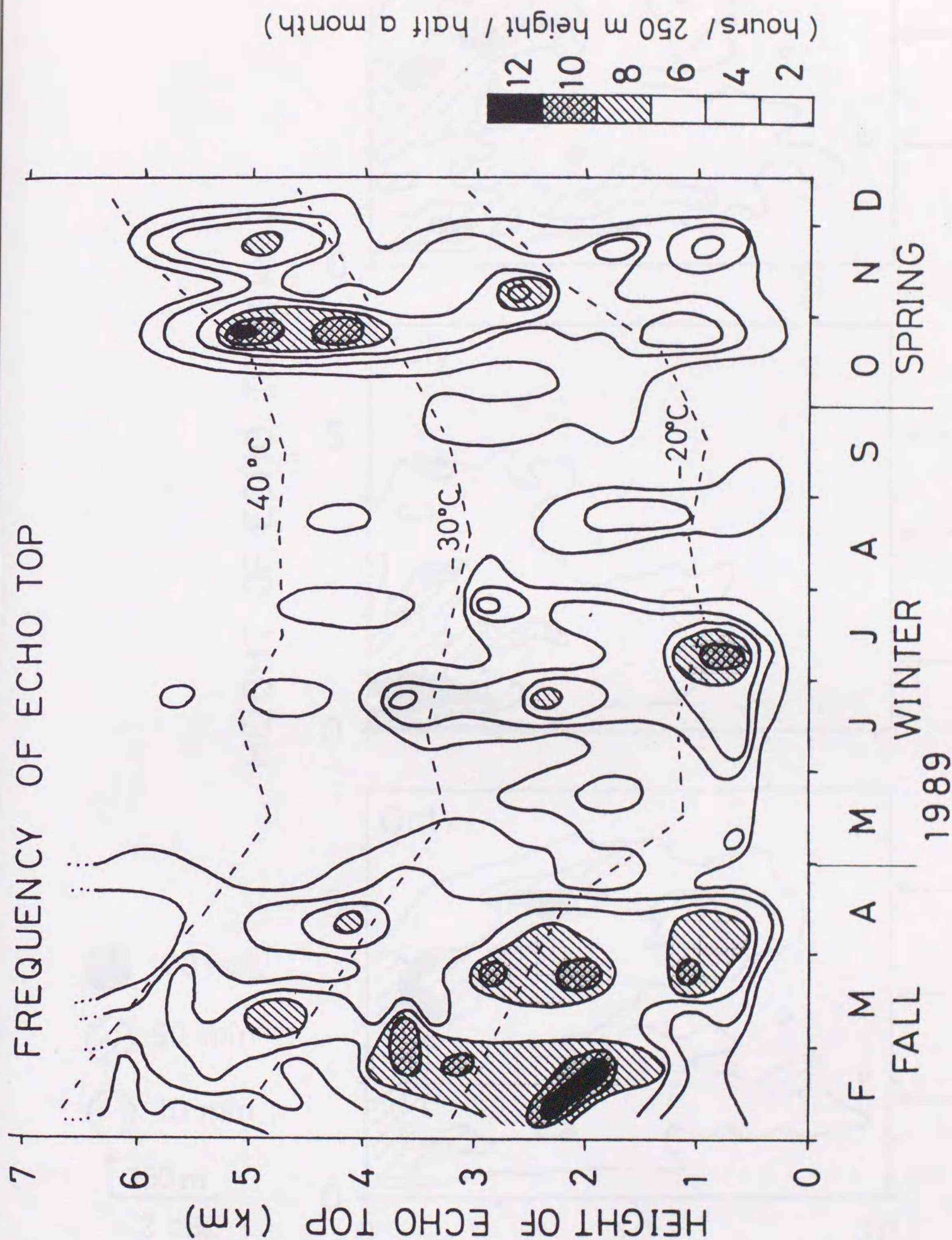


Figure 5-4. Seasonal variations of echo top height frequency. The frequency is summed every half month at height intervals of 250 m and contoured every 2 hours. The hatched region indicates 8 hours, double hatched region 10 hours and black region 12 hours. The monthly averaged upper air temperature is depicted by dashed lines.

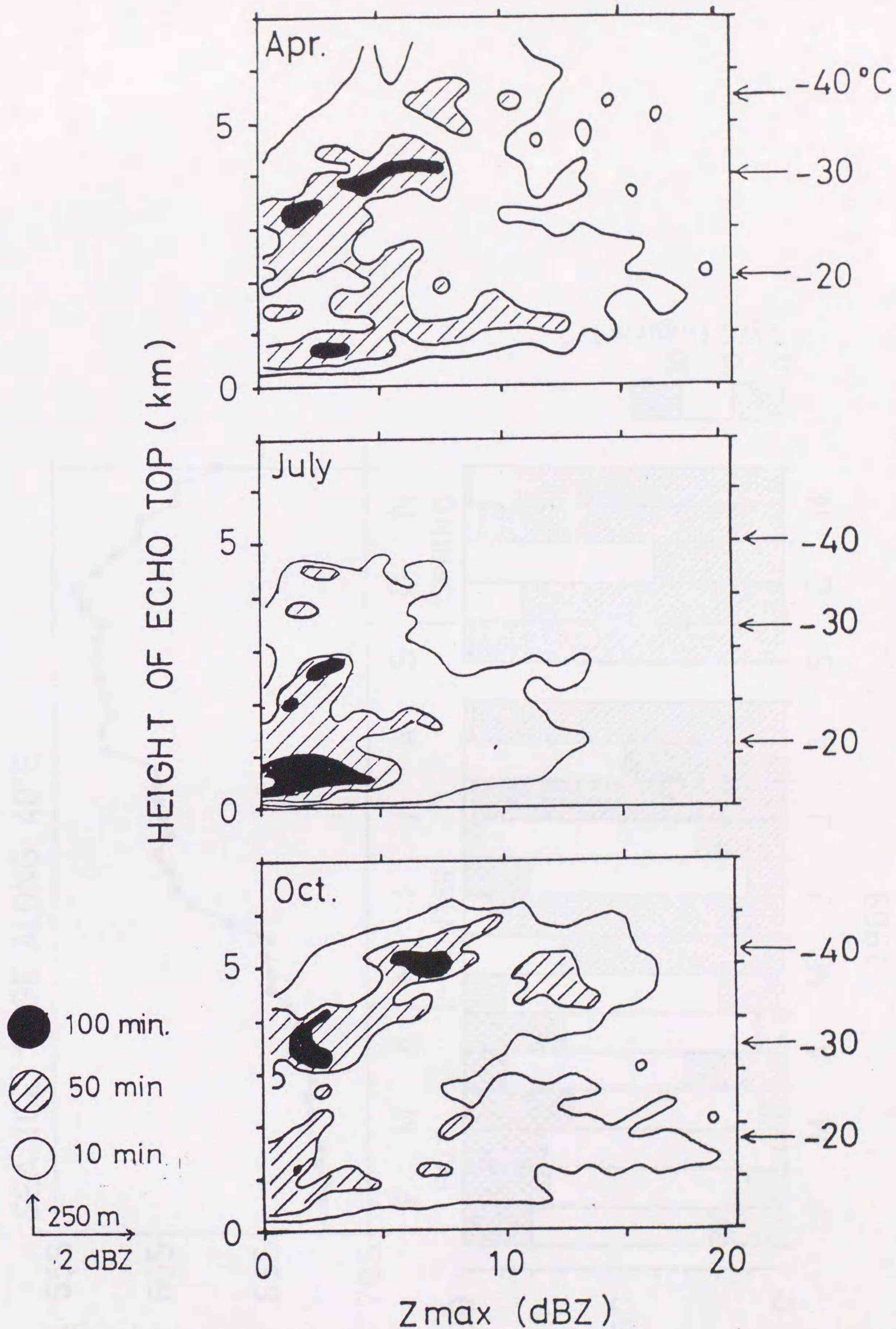


Figure 5-5. Frequency of the maximum echo intensity related to echo top. The frequency is summed at 250 m height intervals for echo top, and each 2 dBZ for Z_{max} . The solid line shows 10 min, the hatched region 50 min and the shaded region 100 min. The monthly mean heights of temperatures at -20, -30 and -40 °C are also shown.

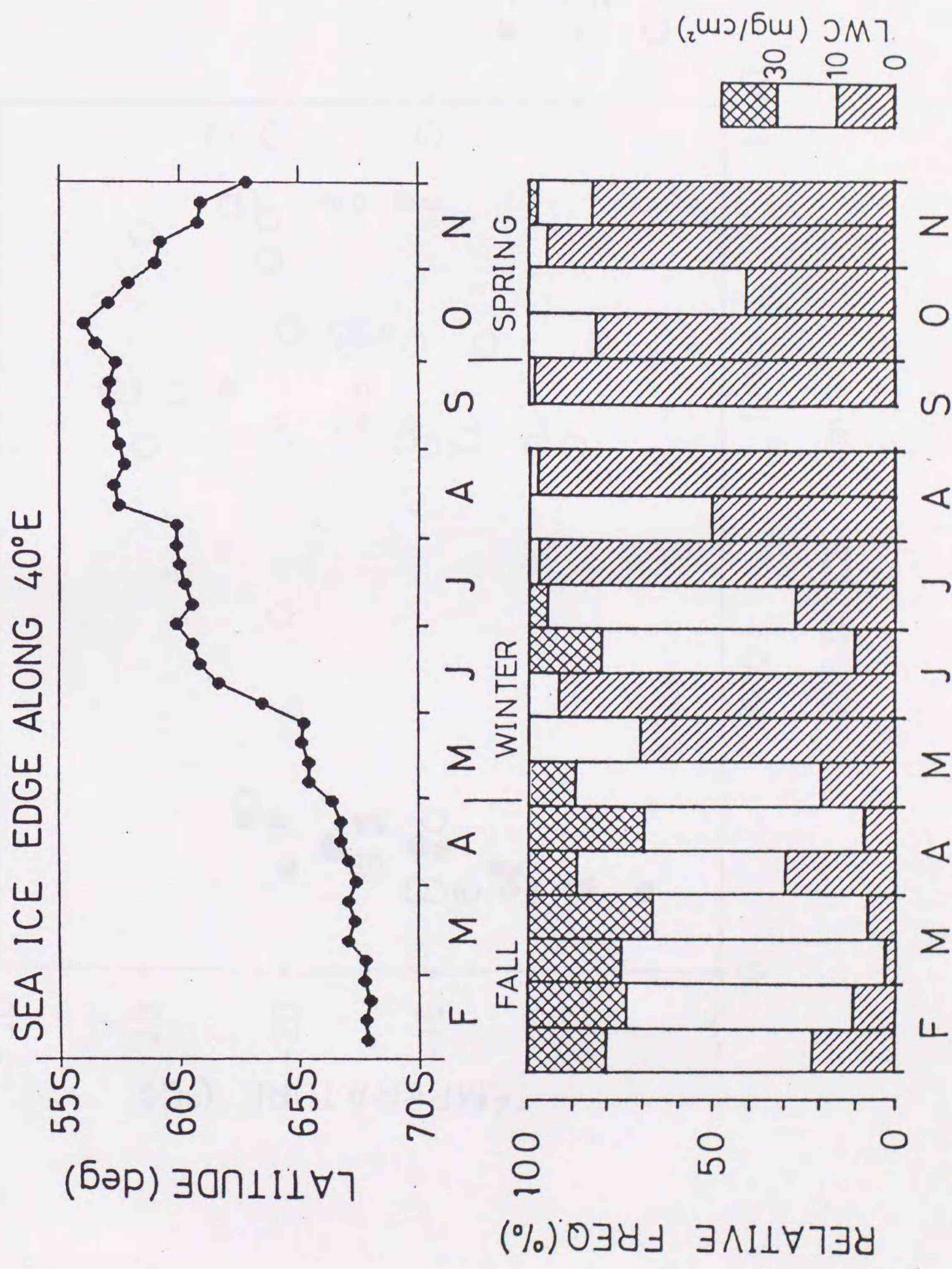


Figure 5-6. Seasonal variation of the sea ice limit along 40°E and liquid water content. The lower part of the figure shows the occurrence frequency of solid-phase clouds and mixed-phase clouds. Double hatched and hatched columns show the relative frequencies of mixed-phase clouds and solid-phase clouds respectively. Open columns show the intermediate clouds between them.

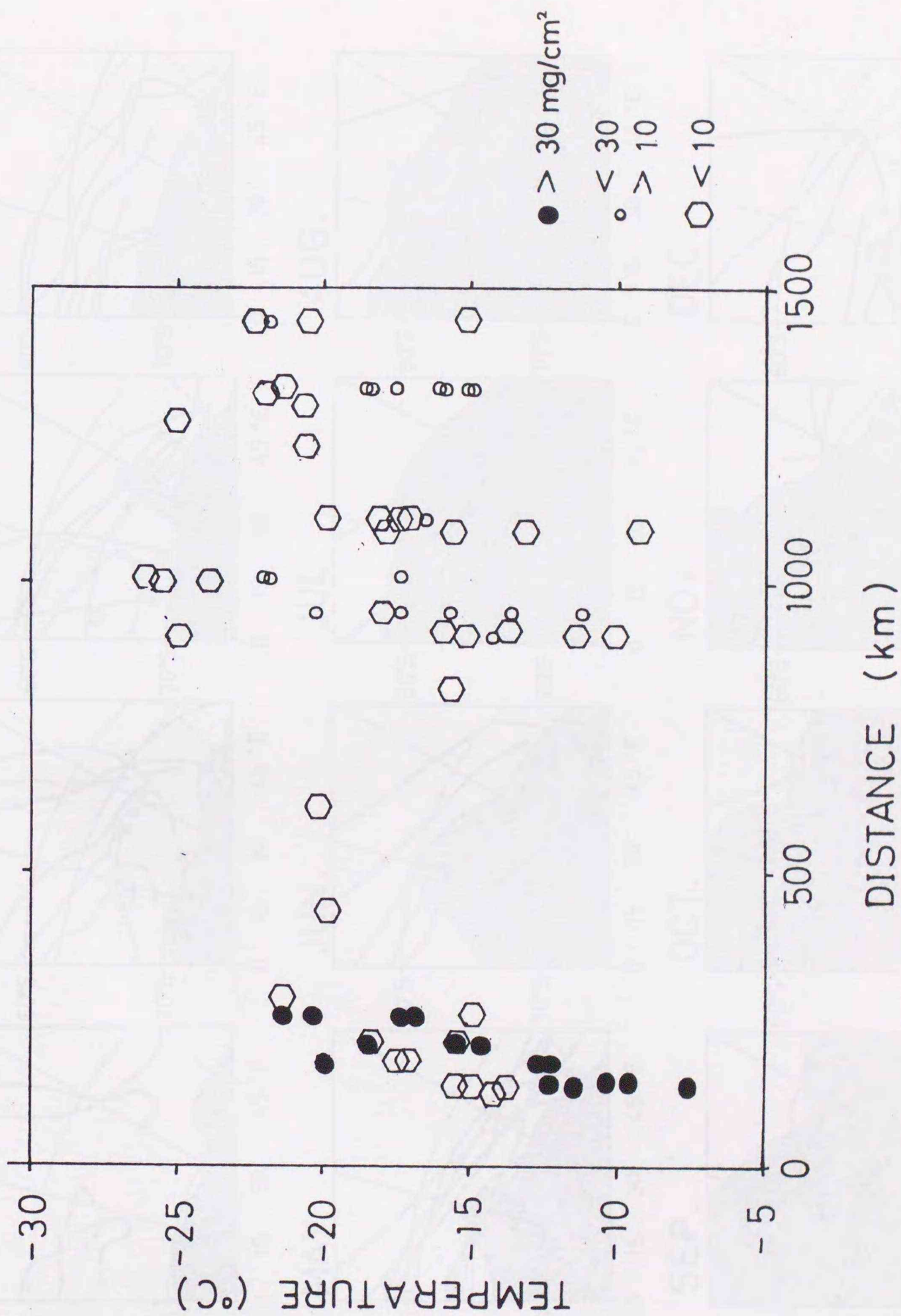


Figure 5-7. Relation between air temperature at 2 km height and distance from Syowa Station to sea ice edge for each cloud. The hexagonal mark represents solid-phase clouds, the solid circle represents mixed-phase clouds and the open circle represents the intermediate clouds between them.

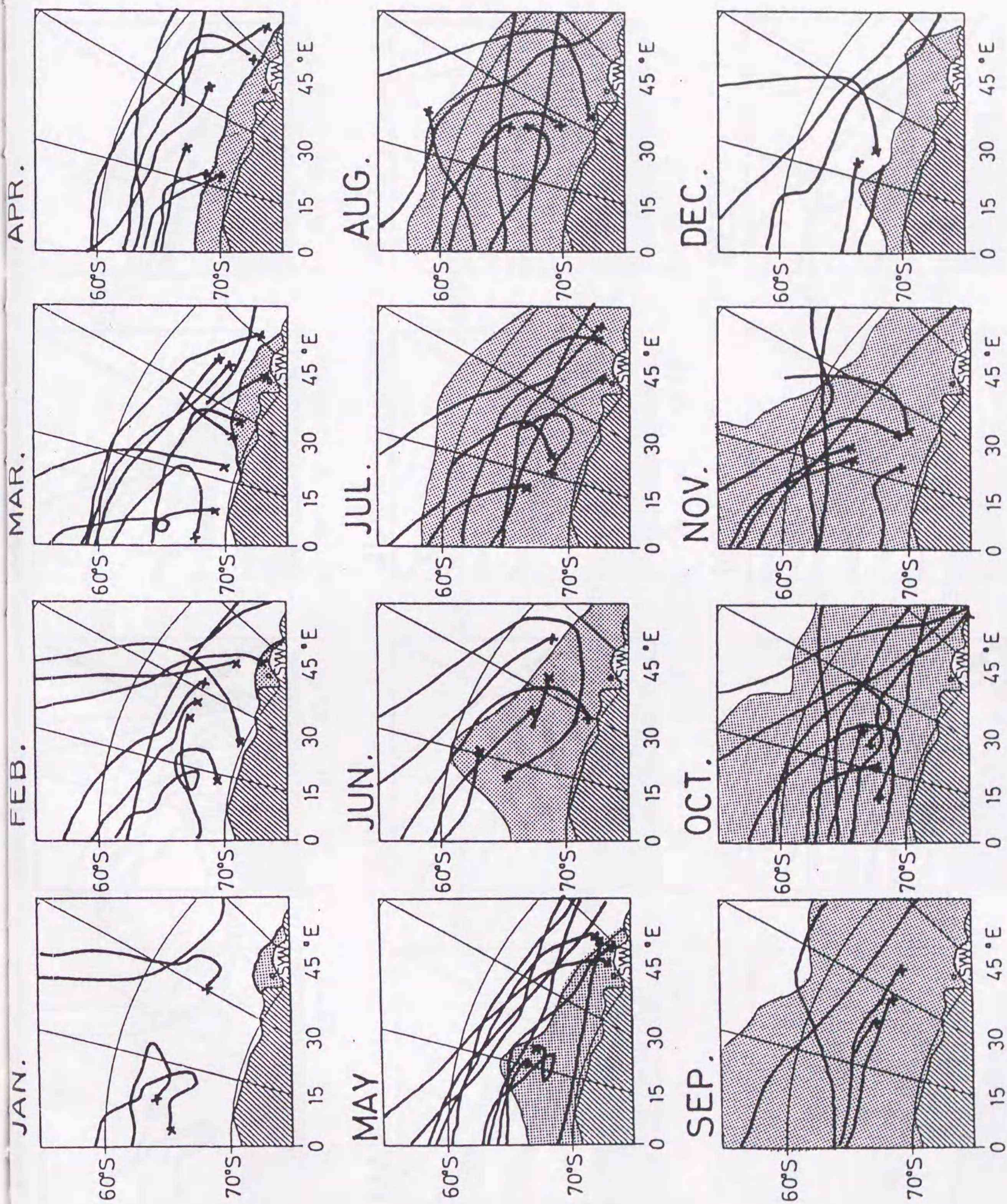


Figure 5-8. Trajectory of low pressure center south of latitude 60°S. The cross marks show where the low pressure center dissipated. The hatched region shows the Antarctica and shaded area shows the sea ice extent at the beginning of each month.

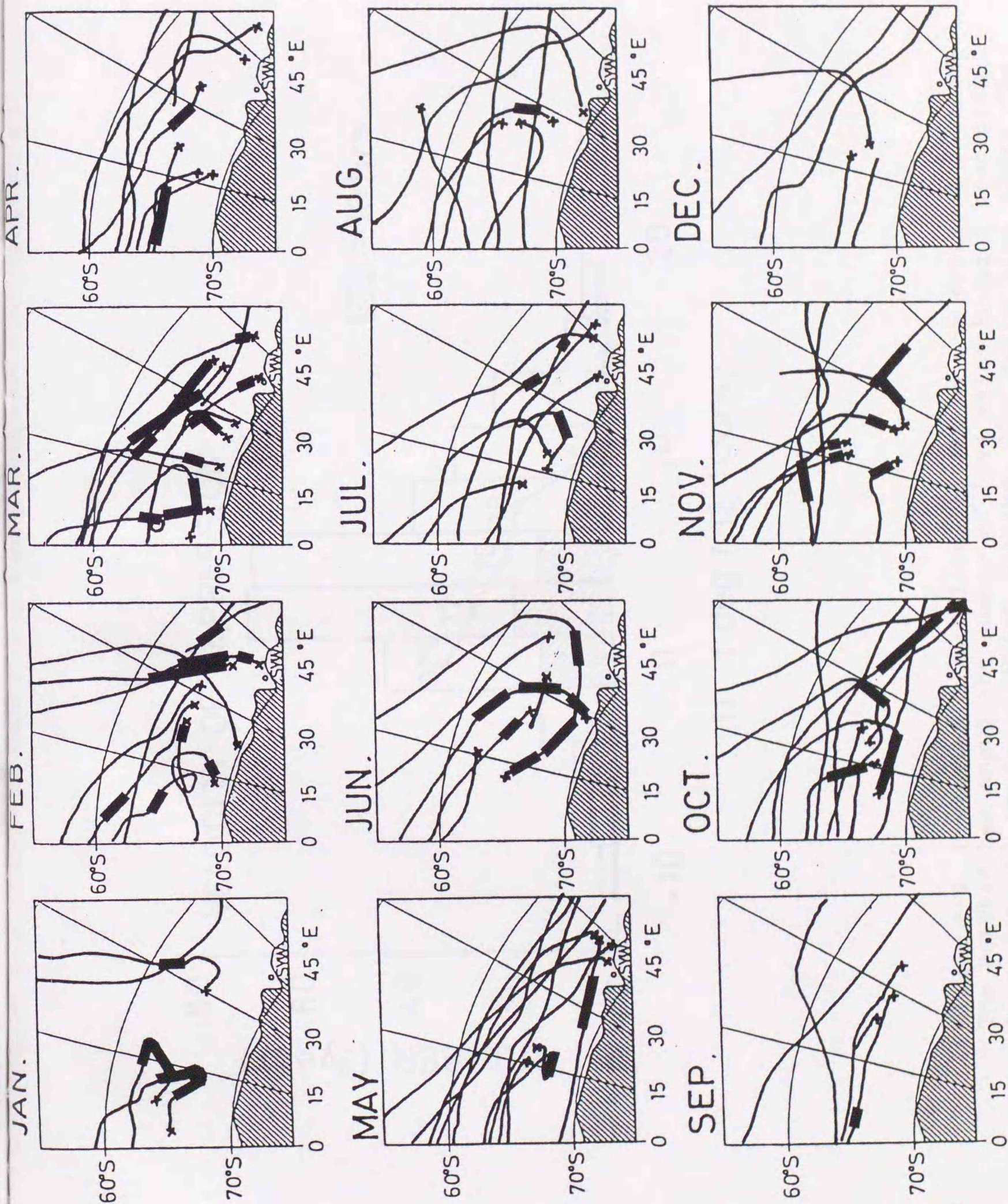


Figure 6-1. Trajectory of low pressure center as shown in figure 5-8. The thick solid line shows the duration of the low pressure center when the precipitating echo was from directly over Syowa Station for more than 10 hours.

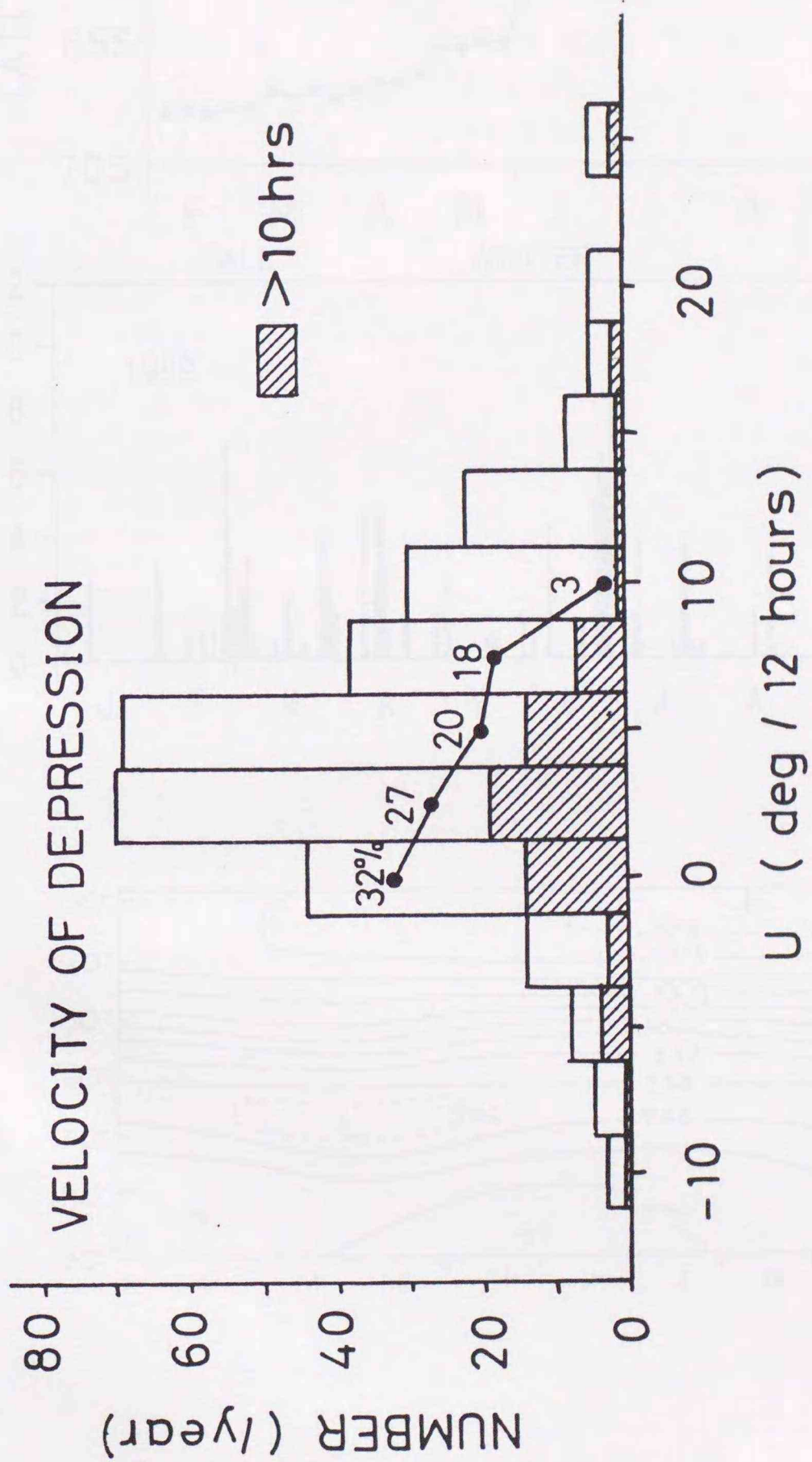


Figure 6-2. Histogram of zonal velocities of low pressure center. The hatched bar shows the number of lows which brought precipitation for >10 hours at Syowa Station. The solid line shows the percentage of long duration precipitation for each velocity.

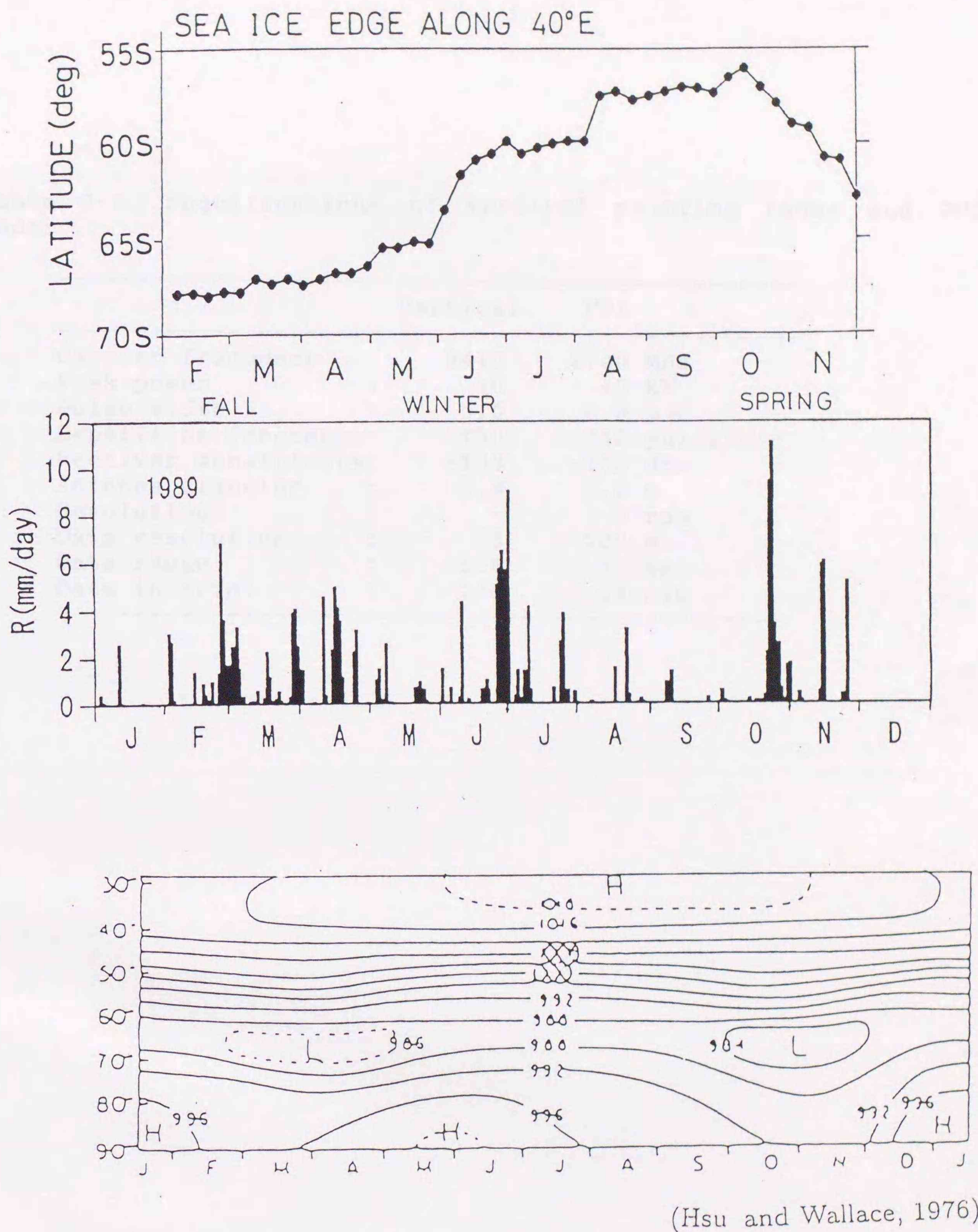


Figure 6-3. Seasonal variation of snowfall. The upper figure shows the sea ice edge along 40°E. The middle figure shows the daily snowfall rate at Syowa Station. The lower figure shows the zonal mean sea surface pressure after Hsu and Wallace (1976).

Table 2-1. Specifications of vertical pointing radar and PPI radar

	Vertical	PPI
Carrier frequency :	9410	9740 MHz
Peak power :	40	40 kW
Pulse width :	0.5	0.5 μ s
Repetition frequency:	750	750 pulse/sec
Receiver sensitivity:	-103	-105 dBm
Antenna diameter :	2.4	1.2 m
Revolution :	-	2 rpm
Data resolution :	50	500 m
Data range :	6.4	64 km
Data interval :	1/6	18 min

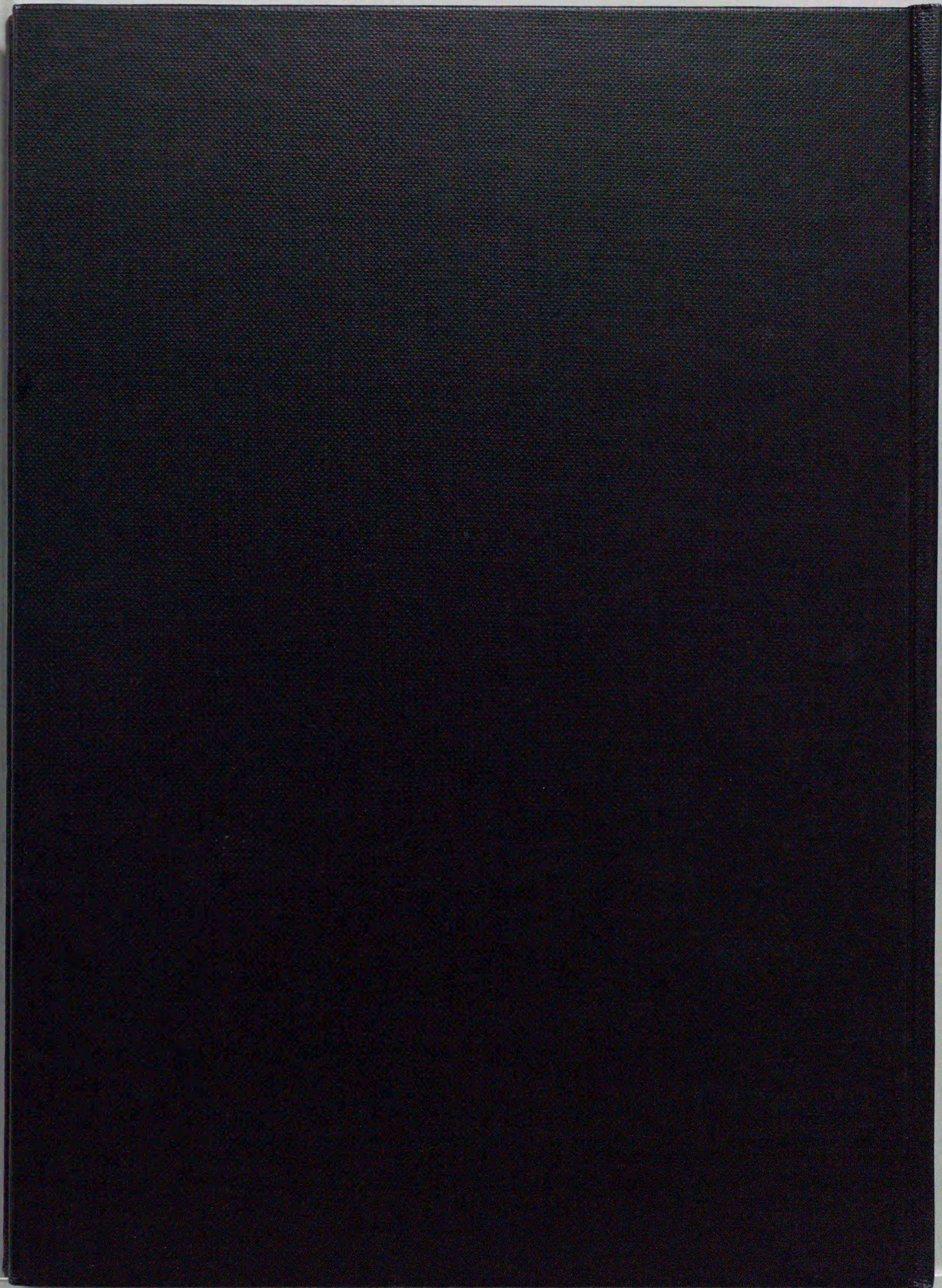
Table 3-1. Coefficient B and β in Z-R relation for 14 snowfalls observed at Syowa Station in 1989.

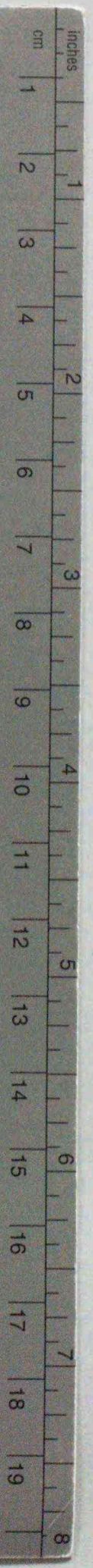
DATE 1989	Coefficient		Daily mean temperature (°C)	Type of crystals
	B	β		
28 FEB.	61.6	1.21	-1.4	aggregates of dendrites
02 MAR.	62.3	1.32	-3.8	aggregates of dendrites
13 MAR.	17.1	1.26	-7.2	graupel
07 MAY	26.3	1.27	-18.0	column
21 MAY	11.0	1.28	-16.9	graupel
19 JUN.	17.0	1.15	-21.6	column, thick plate
21 JUN.	7.6	1.31	-14.6	combination of bullets
01 JUL.	45.7	1.02	-10.5	aggregates of dendrites
24 JUL.	16.4	1.29	-22.9	combination of bullets
02 OCT.	16.5	1.30	-12.6	graupel-like
03 OCT.	22.0	1.29	-16.0	graupel-like
24 OCT.	63.0	1.52	-2.5	aggregates of crossed plates
25 OCT.	46.7	1.40	-5.3	aggregates of dendrites
31 OCT.	40.4	1.21	-10.0	aggregates of dendrites

Table 5-1. Number of low pressure (0-30°E and 60-70°S).

1989	Type of low				Total	Echo type	
	Dissipating		Passing			Type-A	Type-B
Feb.	7(7)		2(1)				
Mar.	9(9)	22(18)	1	5(1)	27	10	5
Apr.	6(2)		2				
May	6(1)		4				
Jun.	6(3)		0				
Jul.	6(3)	26 (9)	1	10(0)	36	5	1
Aug.	5(1)		3				
Sep.	3(1)		2				
Oct.	5(4)	11 (9)	5(1)	8(3)	19	5	4
Nov.	6(5)		3(2)				
Dec.	2	5 (3)	3	4	9	1	1
Jan.	3(3)		1				

(): Number of low pressure causing precipitation for long duration (>10 hours) at Syowa Station

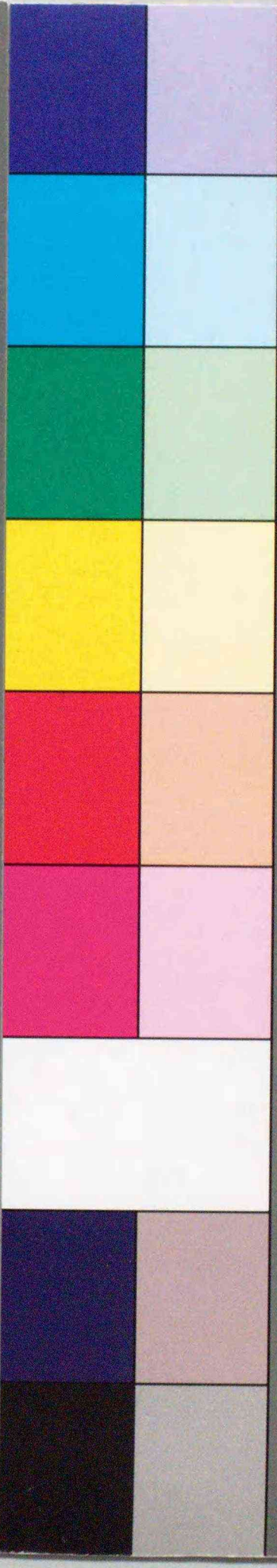




Kodak Color Control Patches

Blue Cyan Green Yellow Red Magenta White 3/Color Black

© Kodak, 2007 TM: Kodak



Kodak Gray Scale



© Kodak, 2007 TM: Kodak

A 1 2 3 4 5 6 M 8 9 10 11 12 13 14 15 B 17 18 19

