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Short-term variation of oxygen isotopic composition of falling snow particles

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ABSTRACT

Oxygen isotopic composition, crystal types and the degree of riming of falling snow particles were simultaneously observed in order to determine the possible causes of short-term variation of the $\delta^{18}O$ value together with the formation process of snow in clouds. The results obtained are summarized as follows: (1) Whenever the type and/or degree or riming of snow crystals changed, the $\delta^{18}O$ value of falling snow changed. (2) Short-term variation of the $\delta^{18}O$ value in each case indicated that riming has two opposite effects on the $\delta^{18}O$ value of snow crystals, i.e., the $\delta^{18}O$ value increased (or decreased) by riming. (3) There was good correlation between the maximum precipitation intensity and the range of variation in the $\delta^{18}O$ value of snow particles from snow bands. (4) The short-term variations of the $\delta^{18}O$ values are not correlated to the surface air temperature and the precipitation intensity.

1. Introduction

Many researchers have observed the isotopic composition of rain water (for example, Epstein and Mayeda, 1953; Dansgaard, 1953, 1954; Epstein, 1956; Friedman and Woodcock, 1957; Ehhalt et al., 1963; Craig et al., 1963; Woodcock and Friedman, 1963). Dansgaard (1964) summarized their results and explained that the seasonal variations in the isotopic composition were caused by the temperature effect and/or the amount effect. Rozanski et al. (1982) stated that the isotopic composition of local precipitation is primarily controlled by the water vapour transport patterns into the continent, and by the average precipitation-evapotranspiration history of the air masses precipitating at a given place. Tsunogai et al. (1975) investigated the oxygen isotopic composition of falling snow along the coastline of the Sea of Japan during the winter monsoon season. They concluded that the oxygen isotopic composition of snow is not controlled directly by the temperature of the sea surface and the air where the snow is formed, but is controlled by the relation between water vapour contents in the Asian continental air, the air transported to the Pacific and the amount of water vapour evaporated from the Sea of Japan.

The above discussions are based on mean $\delta^{18}O$ values of samples collected during a rather prolonged time. However, the $\delta^{18}O$ value is known to vary dramatically within a very short time. Dansgaard (1953) tried to explain the ^{18}O-abundances in the precipitation from a warm front by considering the precipitation mechanism in clouds. However, his theory is only applicable to warm and layer clouds. It is well-known that most rain clouds contain ice particles in their upper regions. Therefore, it is necessary to clarify the relation between the stable isotopic composition of snow particles and their formation process in order to discuss the short-term variation of the $\delta^{18}O$ value of raindrops. Isono et al. (1966) and Miyake et al. (1968) observed that isotopic composition of snow particles by considering the crystal type of snow or the degree of riming. They speculated that variation of the isotopic composition is caused by differences in the formation process of snow particles in clouds. However, consistent process of snow particles have not been obtained because of the lack of supporting data.

The purpose of the present study is to discuss possible causes of short-term variation of the $\delta^{18}O$ value together with the formation process of snow in clouds on the basis of abundant data of both the $\delta^{18}O$ value of falling snow and crystal types and the degree of riming.

2. Method of observation and data obtained

Sampling of falling snow was carried out about every ten minutes, depending on precipitation intensity, on the roof of the Institute of Low Temperature Science (Hokkaido University) in February and March 1982. Crystal type of snow particle, degree of riming, size of snow particles and air temperatures were simultaneously observed. The water equivalent precipitation intensity was measured by weighing the total mass of snow particles which fell into a 56.5 cm × 40 cm pan. The $\delta^{18}O$ value was measured for each snow sample melted in a closed glass container by using a mass spectrometer located at the Water Research Institute (Nagoya University), according to the method of Epstein and Mayeda (1953). Accuracy of the $\delta^{18}O$ measurement is $\pm 0.2‰$.

Air temperature on the ground during the observations was in the range between -11 and $+3$°C. Maximum precipitation intensity was about 10 mm·h^{-1}. The $\delta^{18}O$ values of the snow samples were in the range between -7 and $-18‰$. The symbols for the snow crystals used in the following chapter, and the temperature and humidity conditions for the formation of snow crystals follow those of Nakaya (1951), Kobayashi (1961) and Magono and Lee (1966).

3. Observations

3.1. Case studies

3.1.1. Case I: February 23, 1982. Figs. 1–5 show the different recorded cases. Plotted are the average surface air temperature (T), the oxygen isotopic composition ($\delta^{18}O$), the precipitation intensity and snow morphology as a function of time. The vertical dotted lines marked distinct changes of the snow quality. The hatched areas indicate the periods when snow with a higher $\delta^{18}O$ value than the mean value fell during the day. The different symbols (l.r.), (r), (h.r.) and f denote lightly rimed, rimed, heavily rimed snow crystals and aggregates, respectively. Snow with a high $\delta^{18}O$ value fell before 21:25 JST (Japan Standard Time), and snow with a low $\delta^{18}O$ value fell afterwards. The magnitude and the variation with time of precipation intensity were almost the same before and after 21:25 JST . A distinct difference was observed in the degree of riming of crystals composing aggregates before and after 21:25 JST; i.e., aggregates were composed of heavily rimed dendritic crystals before 21:25 JST, and non-rimed dendritic crystals afterwards. If the $\delta^{18}O$ value of the dendritic crystals did not change largely before and after 21:25 JST, the $\delta^{18}O$ value of the cloud droplets collected by the snow crystals after 21:25 JST must be higher than that of the snow crystals.

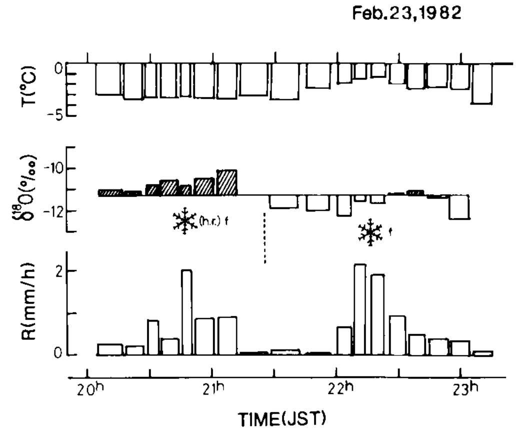

Fig. 1. Changes in surface air temperature (T) in °C, isotopic composition ($\delta^{18}O$) in ‰, precipitation intensity (R) in mm·hr^{-1} and crystal type of snow particles with time on February 23, 1982. Periods when snow with a higher $\delta^{18}O$ than the mean value are hatched.

3.1.2. Case II: February 18, 1982. Fig. 2 shows the observational results on February 18, 1982. Snow with a higher $\delta^{18}O$ value fell before 16:25 JST. Aggregates composed of heavily rimed dendritic and fernlike crystals were observed

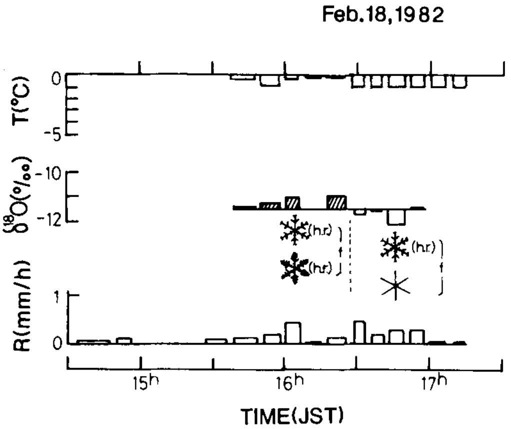

Fig. 2. As in Fig. 1 except for February 18, 1982.

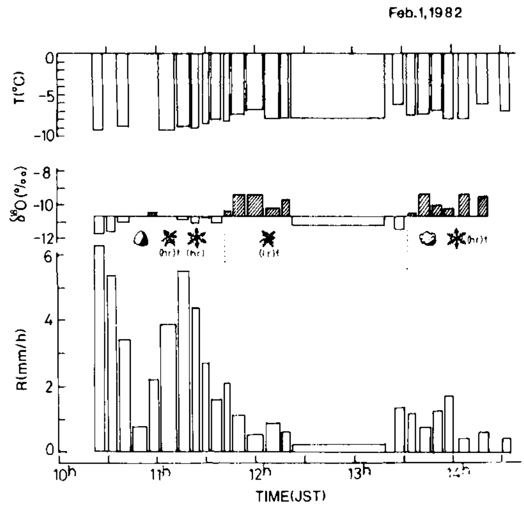

Fig. 3. As in Fig. 1 except for February 1, 1982.

before 16:25 JST, and those that fell after 16:25 JST were composed of heavily rimed dendritic and non-rimed stellar crystals. The stellar, dendritic and fernlike crystals were formed at almost the same temperature. However, the humidity conditions for formation of the three types of crystals differed from each other. Therefore, there might be the difference in the $\delta^{18}O$ values among the three types of snow crystals due to the kinetic effect in condensation. We will discuss this point later. If the kinetic effect modifies the $\delta^{18}O$ value only slightly, the $\delta^{18}O$ value of cloud droplets collected by fernlike crystals must be higher than that of the snow crystals.

3.1.3. Case III: February 1, 1982. Fig. 3 shows the observational results on February 1, 1982. An extremely high value of precipitation intensity appeared before 11:40 JST. The snow particles that fell during that time were graupel, aggregates composed of a heavily rimed radiating assemblage of dendrites and dendritic crystals. Aggregates of a lightly rimed radiating assemblage of dendrites fell from 11:40 to 13:30 JST. After 13:30 JST, graupels and heavily rimed dendritic crystals fell.

The $\delta^{18}O$ values of snow particles were not changed regardless of the dramatic variation of precipitation intensity, which means that the cloud was in a steady state and passed over the observational site while providing the same kind of snow particles. Despite the high degree of riming, snow with a lower $\delta^{18}O$ value fell before 11:40 JST as compared with that which fell after 11:40 JST, which differs from the results obtained on February 18 and 23. After 13:30 JST, falling snow had a higher $\delta^{18}O$ value than that which fell before 11:40 JST, and the value was almost as high as that observed from 11:40 to 12:20 JST, though the degree of riming was very high. The crystal type of snow in this period was dendrite, which is usually formed at higher temperatures (also at lower altitudes) than radiating assemblage of dendrites. Graupel also remained in dendritic shape.

3.1.4. Case IV: February 26, 1982. Fig. 4 shows the observational results on February 26, 1982. Aggregates of a heavily rimed assemblage of dendrites fell before 09:20 JST and during the period between 09:50 and 10:50 JST at different precipitation intensities. Almost the same $\delta^{18}O$ values were obtained for aggregates collected during the above two periods. During the period between 09:20 and 09:50 JST, aggregates of a rimed assemblage of dendrites and rimed dendritic crystals had a higher $\delta^{18}O$ value as compared with those of snow particles which fell before and after the period.

As shown by the results on February 1, a higher degree of riming produced snow particles with a lower $\delta^{18}O$ value in many of the cases investigated so far, whereas graupel, aggregates of heavily rimed radiating assemblage of dendrities and heavily rimed dendritic crystals, all of which had quite high $\delta^{18}O$ values, fell after 10:50 JST on the same day. The above result is

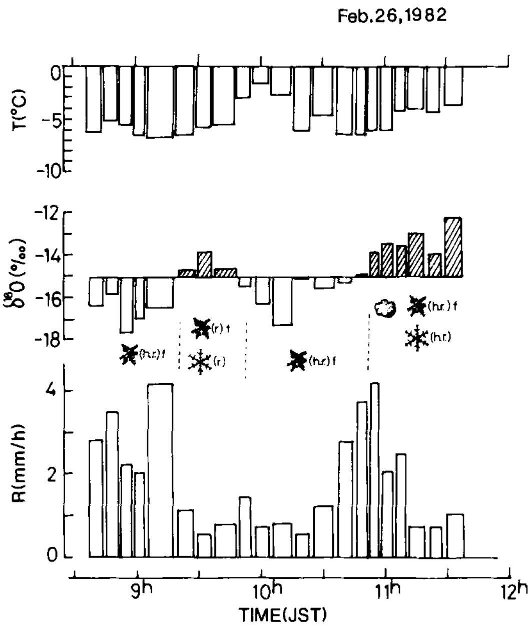

Fig. 4. As in Fig. 1 except for February 26, 1982.

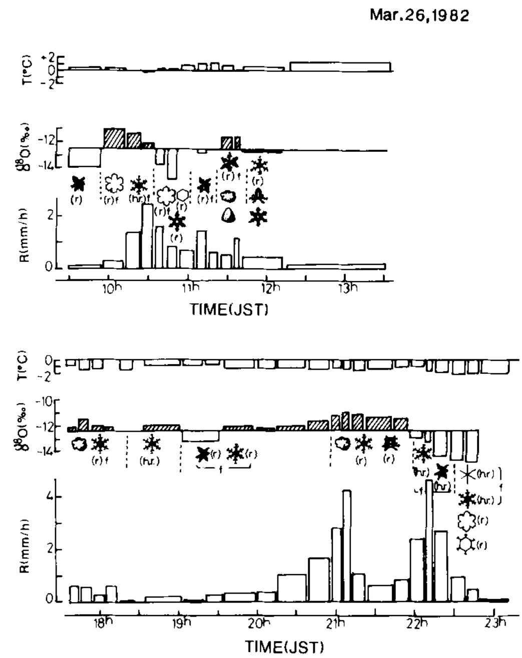

Fig. 5. As in Fig. 1 except for March 26, 1982.

consistent with those on February 18 and 23 and after 13:30 JST on February 1.

3.1.5. Case V: March 26, 1982. Fig. 5 shows the observational results on March 26, 1982. Higher $\delta^{18}O$ values were observed when aggregates of heavily rimed dendritic crystals (09:51 ~ 10.30 JST), aggregates of rimed fern-like crystals and grupaels (11:20 ~ 11:40 JST) were observed. This result is consistent with those on February 18 and 23 and after 10:50 JST on February 26. When the types of snow crystals were hexagonal plate, broad branches, plate with dendritic extensions, bullets with dendrites and radiating assemblage of dendrites, which are formed at a higher altitude (lower temperature) than that at which dendritic crystals are formed, their $\delta^{18}O$ values were low.

Before 22:00 JST and after 23:30 JST, a higher degree of riming produced snow particles with a higher $\delta^{18}O$ value, and the snow crystals that formed at a lower temperature (high altitude) appeared to be lower in $\delta^{18}O$ value. This trend was similar to that observed before 13:30 JST. However, aggregates with a lower $\delta^{18}O$ value fell during the period between 22:00 and 22:30 JST, and they were composed of heavily rimed dendritic crystals and a radiating assemblage of dendrites.

3.1.6. Case VI: February 20, 1982. All the examples shown so far were cases of falling snow derived from the snow band. Fig. 6a shows a typical example of vertical profiles of air temperature, relative humidity with respect to water, wind direction and wind speed in the above situation. Moist adiabatic temperature change occurred up to 2.7 km in altitude, and convective clouds formed under this altitude. Wind came from a northerly direction at any altitude.

Fig. 6b shows the result of radiosonde observations conducted on February 20 when snow fell under the climatic condition in which low pressure was approaching from the southern part of Hokkaido. Quite a different trend was observed in both temperature and humidity as compared with that observed on February 1. The air was relatively humid up to 5 km in altitude. Southerly wind was predominant and wind direction changed at a different altitude, which means that snow crystals and cloud droplets were possibly formed from water vapours derived from different origins.

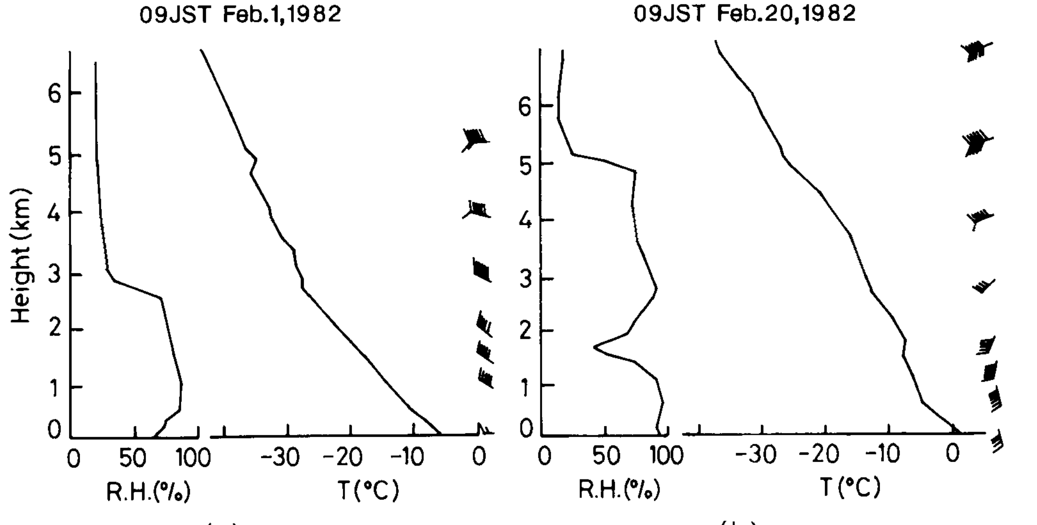

Fig. 6. Radiosonde data of air temperature, relative humidity with respect to water, wind direction and wind speed at Sapporo at 09:00 JST on February 1, 1982 (a) and at 09:00 JST on February 29, 1982 (b).

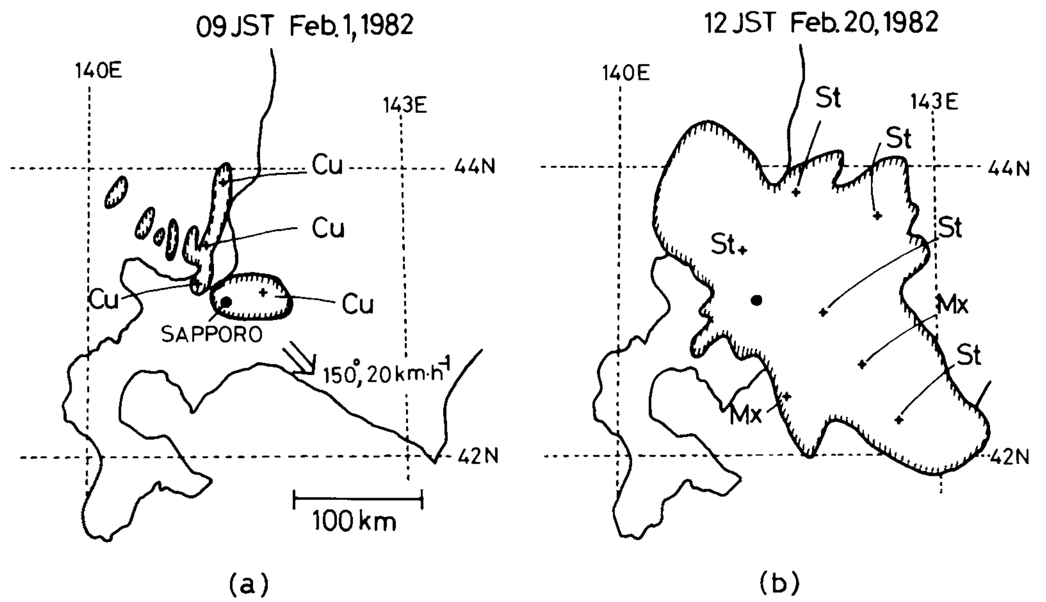

Fig. 7. Schematic patterns of radar echoes prepared by the Sapporo Meteorological Observatory at 09:00 JST on February 1, 1982 (a) and at 12:00 JST on February 20, 1982 (b). St, Cu and Mx mean stratified, convective and mixed echoes, respectively.

Fig. 7 shows the schematic patterns of radar echoes prepared by the Sapporo Meteorological Observatory. As shown in Fig. 7a, a small convective echo (Cu) moves with a northwesterly wind. The echo which appears with approaching low pressure (Fig. 7b) is a stratified echo (St).

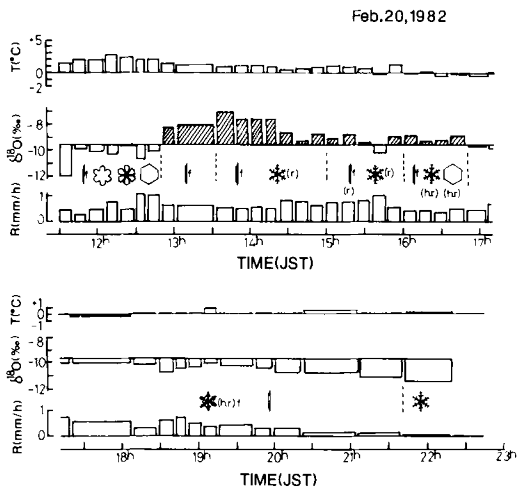

Fig. 8. As in Fig. 1 except for February 20, 1982.

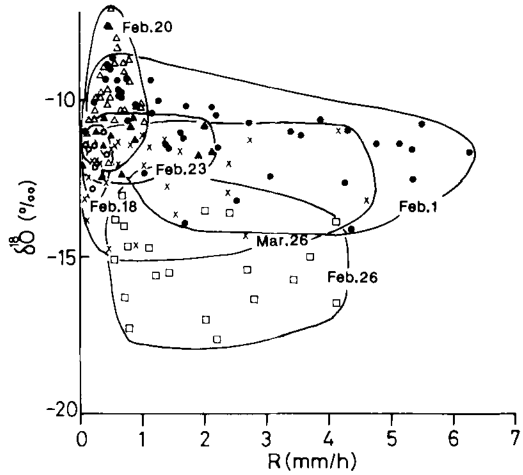

Fig. 9. The relation between precipitation intensity and the $\delta^{18}O$ value of snow. Feb. 1(●), Feb. 18(○), Feb. 20(△), Feb. 23(▲), Feb. 26 (□), Mar. 26(×).

Such an echo generally moves from the south to the north, which is not obvious as compared with the echo movement of a snow band.

Fig. 8 shows the observational results on February 20, 1982. Precipitation intensity scarcely changed with time. Aggregates with a higher $\delta^{18}O$ value fell during the period between 12:50 and 16:50 JST and they were the needle type, having been formed at a warmer temperature than dendritic crystals. Aggregates of heavily rimed fernlike crystals fell predominantly during the period between 16:50 and 21:40 JST. After this time, aggregates with a lower $\delta^{18}O$ value of non-rimed dendritic crystals than that of the needle type crystals were observed.

The predominant type of snow crystals composing the aggregates that fell before 12:50 JST was needle. The crystals were mixed with sector, broad branches and hexagonal plate, which were formed at a lower temperature than the needle type. Their $\delta^{18}O$ values were low.

3.2. Precipitation intensity and oxygen isotopic composition

Fig. 9 represents the relation between precipitation intensity and the $\delta^{18}O$ value of falling snow. Tsunogai et al. (1975) reported that an inverse relationship exists between them; this however, could not be verified with our measurements. If there is any relationship between the precipitation intensity and the $\delta^{18}O$ value, it should be elucidated by using radar and by taking cloud movements all around the area under consideration, since the $\delta^{18}O$ value of snow is different if the observation is carried out at the edge or at the central part of a cloud, even though the sample is taken under the condition in which the precipitation intensity is the same.

3.3. Maximum precipitation intensity and range of variation in oxygen isotopic composition

In Fig. 10 the abscissa represents the maximum value of precipitation intensity (R_{max}) observed in each case, and the ordinate means the difference between the maximum and the minimum $\delta^{18}O$ value (range of variation in $\delta^{18}O$) in each case. Good correlation exists between R_{max} and $\Delta\delta^{18}O$ in the snowfall from the snow band. The coefficient of correlation is 0.96. Only the snow that fell on February 20 occurred under a different climatic condition from the snow that fell on other days, as stated in 3.1.6.

It should be noted that the maximum precipitation intensity did not always produce snow particles with the maximum $\delta^{18}O$ value, and vice versa. The result in Fig. 10 indicates that a cloud capable of strong precipitation intensity produces falling snow with an $\delta^{18}O$ value which varies dramatically under the common condition that the cloud is a snow band and that the wind comes from a northwestern direction.

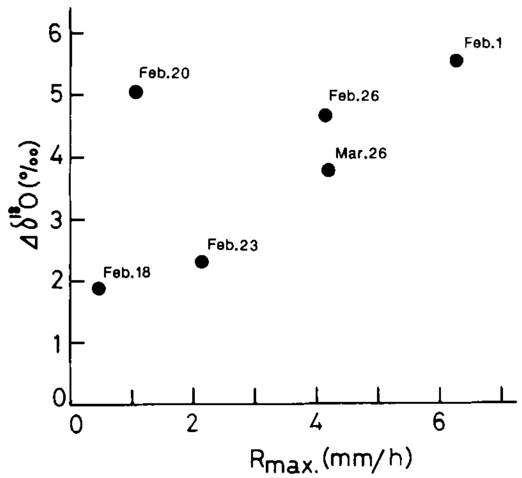

Fig. 10. The relation between the maximum precipitation intensity (R_{max}) observed in each case and the range of variation in oxyen isotopic composition ($\Delta\delta^{18}$; ‰).

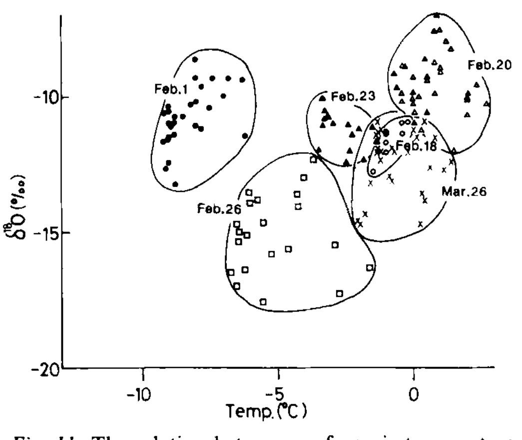

Fig. 11. The relation between surface air temperature and the $\delta^{18}O$ value of snow. Feb. 1(●), Feb. 18(○), Feb. 20(△), Feb. 23(▲), Feb. 26(□), Mar. 26(×).

3.4. Surface air temperature and oxygen isotopic composition

Fig. 11 shows the relationship between $\delta^{18}O$ values of snow samples and the surface air temperature for the different cases A consistent relationship between them was not obtained. One reason is that the heights of cloud top and cloud base differed for each case and even changed during one event.

4. Discussion and summary

The results obtained in the present observational study are summarized as follows:

1) Whenever the type and/or degree of riming of snow crystals changed, the $\delta^{18}O$ value of falling snow changed.

2) Short-term variation of the $\delta^{18}O$ value in each case indicates that riming has two opposite effects on the $\delta^{18}O$ value of snow crystals, i.e., the $\delta^{18}O$ value increased (or decreased) by riming.

3) There was good correlation between the maximum precipitation intensity and the range of variation in the $\delta^{18}O$ value of snow particles from snow bands.

4) The short-term variations of the $\delta^{18}O$ values are not correlated to the surface air temperature and the precipitation intensity.

The $\delta^{18}O$ value changed to some extent with time even when the predominant type of snow crystals comprising an aggregate did not change. The atmospheric factors determining snow crystal types are temperature and degree of supersaturation with respect to ice. If the snow crystal types such as stellar, dendritic and fern-like change only as the result of the difference in the degree of supersaturation, then the $\delta^{18}O$ values of the three types of snow crystals are possibly different from each other due to kinetic and vapor pressure effects. Jouzel and Merlivat (1984) stressed the kinetic effect. At present, the effect cannot be elucidated in greater detail because a possible means of assessing the kinetic effect is to measure the deuterium content, which was not done in our study. Additionally there are no quantitative data on the degree of supersaturation under which these three types of snow crystals are formed.

When the degree of riming was the same among the snow crystals, the $\delta^{18}O$ value showed such a short-term variation that the $\delta^{18}O$ value of snow crystals formed at a higher temperature was higher than that formed at a lower temperature. This fact suggests that the $\delta^{18}O$ value of snow crystals becomes lower with increasing altitude, in the same way as the $\delta^{18}O$ value of cloud droplets.

During the riming process, fractionation does not occur, since the freezing time of cloud droplets is so short that isotopic exchange does not take place (Federer et al., 1982). From many theoretical calculations (for example, Dansgaard, 1953, 1954; Federer et al., 1982), the $\delta^{18}O$ values of cloud droplets in a convective cloud decrease with increasing altitude (or decreasing temperature). Federer et al. (1982) also show that the $\delta^{18}O$ value of snow crystals is not lower than that of cloud droplets. Snow crystals collect cloud droplets during both their ascending and descending motion. If the theoretical results are applicable to the clouds observed, the $\delta^{18}O$ value of rimed snow crystals would be lower (or higher) than that of non-rimed snow crystals when the total mass of cloud droplets collected above the altitude at which snow crystals are formed is larger (or smaller) than that collected before that altitude.

The mass ratio of snow crystals and collected cloud droplets is an important value in the study of the $\delta^{18}O$ value of rimed snow crystals, because the $\delta^{18}O$ value of snow crystals is possibly different from that of collected cloud droplets. However, at present there is no established method to measure their masses individually. From the simple calculation presented in the Appendix, the rough estimate of the mass ratios of collected cloud droplets to snow crystals are shown in Table 2.

Table 1 list mean $\delta^{18}O$ values for each type of snow particle and their standard deviation. Only the data in which the predominant type of snow crystals did not change during each sampling time were included in the above investigation. An aggregate is generally composed of snow crystals with a different degree of riming and different types (Fujiyoshi and Wakahama, 1985). In order to investigate the oxygen isotopic composition of each type of snow crystal in detail, the $\delta^{18}O$ value should be measured in each snow particle after each one is separated from the parent aggregate. As this procedure is very complicated and time consuming to carry out practically, the $\delta^{18}O$ value of a pertinent aggregate was considered in this study as the predominant snow crystal composing the aggregate.

Table 1. *Mean values of $\delta^{18}O$ of each snow crystal, their standard deviation and the number of samples*

Crystal Type	Number	Mean (‰)	Standard Deviation
Needle (rimed)	8	−8.9	0.9
Needle (non-rimed)	16	−9.4	1.2
Dendrite (heavily rimed)	36	−11.0	2.1
Dendrite (rimed)	31	−11.0	0.8
Dendrite (non-rimed)	5	−12.0	0.5
Radiating assemblage of dendrites (heavily rimed)	20	−14.2	1.7
Graupel*	17	−11.1	0.8
Graupel**	3	−15.4	1.9

The symbol * (or **) means that aggregates composed of dendrites (or radiating assemblage of dendrites) predominantly fell before and after graupel falling.

The $\delta^{18}O$ value appeared to decrease in the following order: needle, dendrite and heavily rimed radiating assemblage of dendrites. The $\delta^{18}O$ values of rimed snow crystals (both needle and dendrite) tend to be higher than those of non-rimed crystals. This result indicates that the cloud droplets collected by snow crystals at the lower altitude at which snow crystals were formed are larger in mass than those collected at a higher altitude, as is seen from the average of all the cases obtained. It seems meaningless to calculate the mean $\delta^{18}O$ value of graupel in all the graupel collected samples since, they were formed at various temperatures. As expressed in Table 1, the $\delta^{18}O$ value of graupel differed with the type of snow crystal, such as dendrite and radiating assemblage of dendrites, which fell predominantly before and after the graupel falling.

Dansgaard (1964), Miyake et al. (1968), Tsunogai et al. (1975), Kato (1979), Rozenanski et al. (1982) and Higuchi et al. (1985) indicated that the $\delta^{18}O$ value of falling snow is likely to be changed dramatically depending on its transportation process to the observational site. Any clouds formed at sea surface probably produce falling snow with almost the same intensity, and the places of their origin in the sea are different from each other. Even if clouds are formed in the same place, the time necessary for snow to fall to the ground may differ among the clouds. If this is true, a cloud with a lower R than R_{max} may show one of the following characters: one is that the cloud has already produced much snow before arriving at the observational site (decaying stage); and the other is that the cloud will begin to release snow in time (growing stage). It may well be considered that a cloud whose snowfall intensity is equal to R_{max} is just passing over the observational site during its most active period (mature stage). Precipitation intensity with the same value is derived from either a growing cloud or a decaying one. It is therefore reasonable that no good correlation exists directly between R and $\delta^{18}O$. The idea given above can be summarized as follows: the cloud has a capability to change the $\delta^{18}O$ value dramatically during its movement on the day when the maximum precipitation intensity (R_{max}) is large. Thus R_{max} and $\Delta\delta^{18}O$ value have good correlation.

In the present study, the authors focused on the range of $\delta^{18}O$ variation instead of the absolute value of $\delta^{18}O$. This direction of attention revealed that the short-term variation of $\delta^{18}O$ in falling snow resulted from the change in the type of falling snow crystals and/or the degree of riming. However, a different $\delta^{18}O$ value was sometimes obtained in snow particles which fell on the same day, in spite of their having the same crystal type and the same degree of riming. The range of $\delta^{18}O$ variation is suggested to be proportional to the amount of falling snow which is produced from the cloud before reaching the observational site. The process shown above is a kind of Rayleigh process (Dansgaard, 1964).

Higuchi et al. (1985) found that a time variation of 6 hours running mean of the surface air temperature showed a good correlation with the variation of the $\delta^{18}O$ value of falling snow. In our study, however, we measured the surface air temperature only during the periods of snowfall; therefore, we were unable to confirm the result. From result (4), we can safely say that the short-term variation of $\delta^{18}O$ value of snow particles does not correlate with that of surface air temperature.

The authors have ignored the exchange of water vapour between a cloud and the surrounding atmosphere to simplify the whole discussion. In order to verify the points made in the present discussion, the following data are needed through the whole life history of a cloud: $\delta^{18}O$ and δD values of water vapour both in and out the cloud, vertical distribution of air temperature and relative humidity in the cloud, vertical distribution of $\delta^{18}O$ and δD values of precipitation particles and cloud droplets, trajectory of motion of precipitation particles in the cloud, and $\delta^{18}O$ and δD values of falling snow sampled on the ground along the trajectory of motion of the cloud. Furthermore, we must improve the technique which enables us to analyse smaller quantities of sample than those currently required.

5. Acknowledgements

The authors wish to express their appreciation to Prof. K. Higuchi, Water Research Institute, Nagoya University, for the use of certain laboratory facilities. Thanks are also due to Messrs. S. Irikawa and H. Konishi for their aid in collecting samples.

6. Appendix

Mass ratio of snow crystals to cloud droplets collected by them

We have roughly classified the degree of riming of snow crystals into four categories: lightly rimed, rimed, heavily rimed or graupel-like. However, these are rather qualitative expressions and are not directly related to the mass ratio (MR) of collected cloud droplets to snow crystals. For this reason, simple calculations were carried out to elucidate the relation between MR and the degree of riming. We assume that the radius of collected cloud droplets (r_d) is constant and that they freeze instantaneously when they collide with a snow crystal. We ignore the change in volume and shape during their freezing. The types of snow crystals considered are plates, sectors, stellars, dendrites and needles.

The thickness (T; cm), surface area (A; cm²), density (ρ; kg·m⁻³) and volume (V; cm³) of a snow crystal are calculated as a function of its maximum diameter (D; cm) through the following equations (Pruppacher and Klett, 1978).

Plate	$T = 1.41 \times 10^{-2} \cdot D^{0.474}$	$A = 0.65 \cdot D^2$
Sector	$T = 1.05 \times 10^{-2} \cdot D^{0.423}$	$A = 0.55 \cdot D^{1.97}$
Stellar	$T = 9.96 \times 10^{-3} \cdot D^{0.415}$	$A = 0.11 \cdot D^{1.63}$
Dendrite	$T = 9.96 \times 10^{-3} \cdot D^{0.415}$	$A = 0.21 \cdot D^{1.76}$

$V = 9.17 \times 10^{-3} \cdot D^{2.475}$	$\rho = 0.9 \times 10^3$
$V = 7.37 \times 10^{-3} \cdot D^{2.42}$	$\rho = 0.9 \times 10^3$
$V = 1.096 \times 10^{-3} \cdot D^{2.045}$	$\rho = 0.46 \cdot D^{-0.482} \times 10^3$
$V = 2.09 \times 10^{-3} \cdot D^{2.175}$	$\rho = 0.588 \cdot D^{-0.377} \times 10^3$

The shape of needle crystal is assumed to be columnar, and its diameter (d; cm) is calculated as a function of its length (D; cm).

$$d = 3.0487 \times 10^{-2} \cdot D^{0.61078}, \quad \rho = 0.3 \times 10^3$$

When N cloud droplets are collected by a snow crystal,

$$\mathrm{MR} = \tfrac{4}{3}\pi \cdot r_d^3 \cdot \rho_0 \cdot N/\rho V.$$

Here, ρ_0 is a density of ice ($= 0.9 \times 10^3$ kg $\cdot$m^{-3}). The total cross section (A_d) of collected cloud droplets is,

$$A_d = \pi r_d^2 \cdot N.$$

Then, the ratio of surface area (RA) of a snow crystal to total cross section of collected cloud droplets is,

$$\mathrm{RA} = A_d/A = 3\rho V \cdot (\mathrm{M.R.})/4\rho_0 r_d.$$

Fig. 12 shows the change of RA with D(0.1 ~ 3 mm) when $r_d = 5$ μm and MR = 1. A snow crys'al is covered with more than 3.5 (stellar, sector and dendrite), more than 1.0 (plate) and less than 0.5 (needle) layers of collected cloud droplets. Conversely, MR is less than 1/3.5 = 0.29 (stellar, sector and dendrite), less than 1/1 = 1 (plate) and more than 1/0.5 = 2 (needle) when all surfaces of a snow crystal are covered by cloud droplets (RA = 1). This simple calculation indicates the difficulty of defining the relation between the MR and the degree of riming uniquely for all types and sizes of snow crystals.

If we define RA ≦ 0.5 as lightly rimed, 0.5 < RA ≦ 2 as rimed, 2 < RA ≦ 5 as heavily rimed and RA > 5 as graupel-like, MR has values such as shown in Table 2 for each type of snow crystal with a maximum dimension of 1 mm. This definition is rather arbitrary, and requires further improvement.

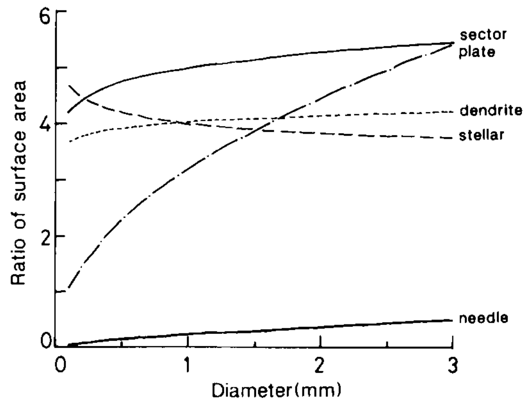

Fig. 12. Change of ratio of surface area with diameter (D; mm) of snow crystal.

Table 2. *Values of mass ratio for each type of snow crystal with different degree of riming*

	Lightly rimed	Rimed		Heavily rimed		Graupel-like
Plate	≦0.15	0.15<	≦0.6	0.6<	≦1.5	1.5<
Sector	≦0.10	0.10<	≦0.4	0.4<	≦1.0	1.0<
Stellar	≦0.13	0.13<	≦0.5	0.5<	≦1.3	1.3<
Dendrite	≦0.13	0.13<	≦0.5	0.5<	≦1.3	1.3<
Needle	≦2	2<	≦8	8<	≦20	20<

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