

CHEMICAL STUDIES OF SNOW IN JAPAN

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ABSTRACT

The winter monsoon blowing from Siberia to Japan plays an important role in constructing the climate of Japan in Winter. About 20 million people lives in the Japan Sea side area of Japanese Islands where the mean annual maximum depth of snow cover is more than 50 cm. The Japan Sea side area of Japanese Islands is the only area in the world which contains such a high population under this type of snow conditions.

Chemical studies of the snowfall and the snow cover in Sapporo were undertaken in 1981. The weight-averaged pH of snow was 4.63. Sodium, chloride and magnesium in the snow samples originated from sea water. The concentrations of chemical constituents of sea salt in snow is thus explained by the type of snow clouds, the height of convective mixing layer and the duration of the convective mixing of air. Chloride and excess sulfate in the snow cover have different deposition patterns, because of different sources.

A chemical condition of snowmelt runoff was investigated in a small forested watershed, and the mechanism of snowmelt runoff generation was discussed with separation of runoff components by using the method of mass balance relations.

1. Climatic conditions of winter in Japan

About 20 million people lives in the Japan Sea side area of Japanese Islands where the mean annual maximum depth of snow cover is more than 50 cm. The Japan Sea side area of Japanese Islands is the only area in the world which contains such a high population under this type of snow conditions. The seasonal wind i.e. the winter monsoon that blows from Siberia plays an important role in the control of the weather of Japan in winter.

When there is an intense development of the Siberian High, the winter monsoon blows strongly and cold air spreads over Japan. The winter monsoon is originally made up of dry cold air. However, as this monsoon blows over the warm surface of the Japan Sea, it picks

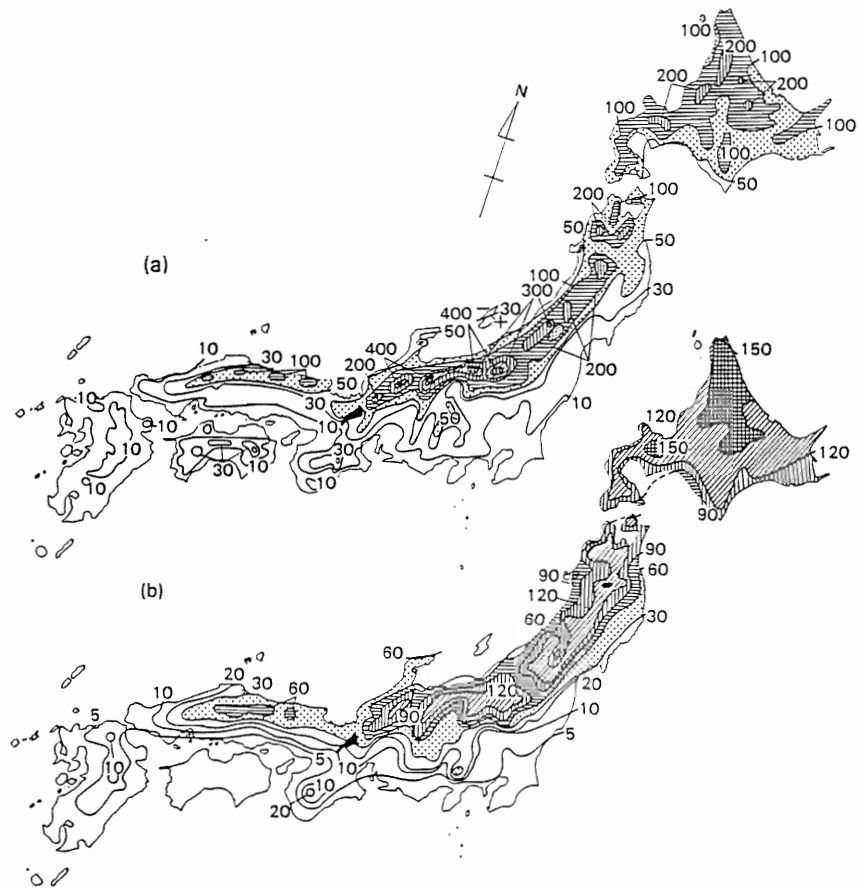


Figure 1. Mean annual maximum depth of snow cover (a), and the mean annual number of days with snow cover (b). (Arai, 1977)

up abundant water vapor. As a result, air convection becomes active and a large number of convective clouds are formed over the Japan Sea. These clouds, include voluminous amount of vapor and precipitate a lot of snow on the Japan Sea side area of the Japanese Islands through orographic effects.

The geographical distribution of the mean annual maximum depth of snow cover and the mean annual number of days with snow cover of Japan are shown in Figure 1 (Arai, 1977). There are regions of heavy snowfall where mean maximum depth of snow cover exceed 4 m. Densely snow covered regions extend from Hokkaido to the south-west district along the mountain ranges that border the Japan Sea coast. About 20 million people live in these regions. The annual number of days with snow cover reaches 120 days in many parts of the snowy region and exceeds 150 days in the northern areas.

Snow cover is a natural reservoir of water. Snow cover plays an important role as a water resource. It is usual to divide the annual runoff patterns of Japanese rivers into three types (Arai, 1977).

- A: peak in summer or autumn, low flow in winter
- B: peaks in spring and summer, low flow in winter
- C: peak in spring, strongly affected by the snowmelt

Also, snow offers the opportunity of leisure as a skiing area. There are ski stations in the area where the mean annual maximum depth of snow cover reaches more than 1m. The population that enjoys skiing is increasing year by year. Skiing is the most popular sport in winter in Japan.

2. A chemical study of snow in Sapporo

Samples of daily snowfall are collected at the campus of Hokkaido University, Sapporo during a period from December 1980 to March 1981 (Suzuki, 1983). Samples are collected in plastic box having a cross-sectional area of 2,800 cm². About two-thirds of the snow samples show acidity (pH<5.6), and the weight-averaged pH is 4.69. The snow in Sapporo is considerably acidic. Relatively pure snow of very low conductivity dose, however, sometimes fall in Sapporo. The ratios of Cl/Na concentration in the snow samples are nearly equal to that in the sea water. The ratios of Mg/Na concentration in the snow samples are larger than that in the sea water, but the ratios of Mg/Na concentration of all samples have small variability. These results suggest that sodium, chloride and magnesium in the snow samples originate from sea water.

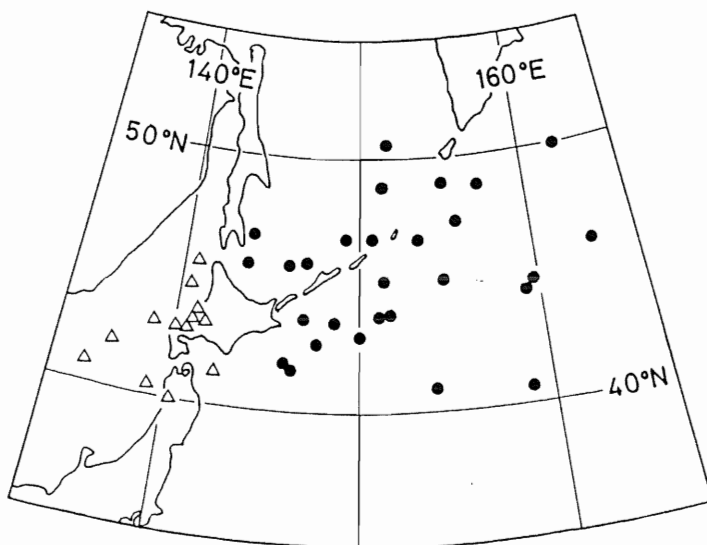


Figure 2. Location of cyclones which carry the snow

△ : Na concentration \leq 1mg/l

● : Na concentration $>$ 1mg/l

The locations of cyclones which carry the snow are shown in Figure 2. The locations of the snow-bearing cyclones correlate with the sodium concentrations in snow. The sodium concentration in the snow due to cyclones located south or west of Hokkaido is smaller than for cyclones located east of Hokkaido. The stratiform clouds which spread over the front of the former type of cyclone produce relatively unpolluted snow. The lowest sodium concentration in the samples is 0.20 mg/l in the snow which fell on the 2nd of January, 1981. The conductivity of this snow is 4.9 μ S/cm which is the lowest value of all the samples. The surface weather chart at 2100 JST on the 2nd of January is shown in Figure 3-a. Three cyclones are located west and south of Hokkaido, and snowfalls occurred over

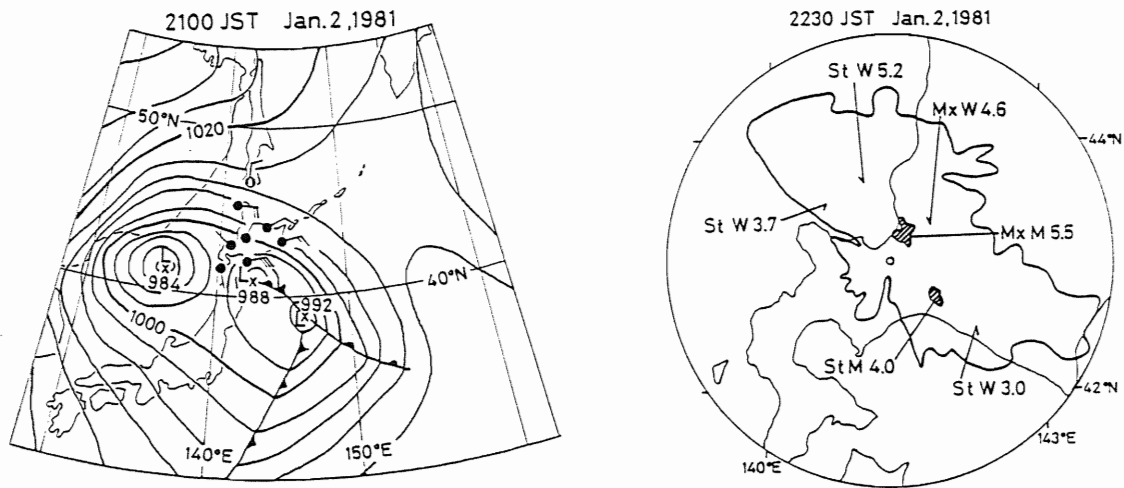


Figure 3. Surface weather chart (a), and a sketch of the radar echo (b) at 2100 JST on the 2nd of January, 1981.

the whole area of Hokkaido. Figure 3-b is a sketch of the radar echo of this case. Stratiform clouds spread broadly, and mixed echoes indicating stratiform clouds and convective clouds occupies a partial area.

On the other hand, when a cyclone is located east of Hokkaido, sodium concentration in the snow is higher. Figure 4 shows the surface weather chart and a sketch of the radar echo at 2100 JST on the 16th of March, 1981. A cyclone is located east of Hokkaido, and the snow is produced from cumuliform clouds. The sodium concentration in the snow is 3.37 mg/l. The concentration of the chemical constituents originating from sea water in snowfall from convective clouds can be explained by the height of convective mixing layer. The vertical profiles of potential temperature in the previous two cases are illustrated in Figure 5. The difference between the two cases is clearly pronounced. In the former case, the convective mixing of air takes place from the surface to about 900mb. On the other hand, in the latter case, the convective mixing of air is observed

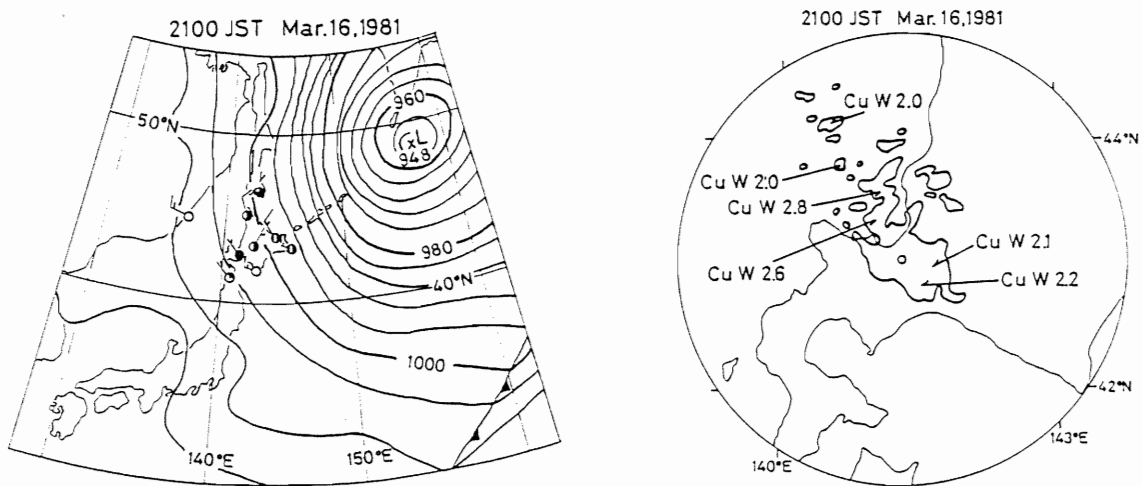


Figure 4. Surface weather chart (a), and a sketch of the radar echo (b) at 2100 JST on the 16th of March, 1981.

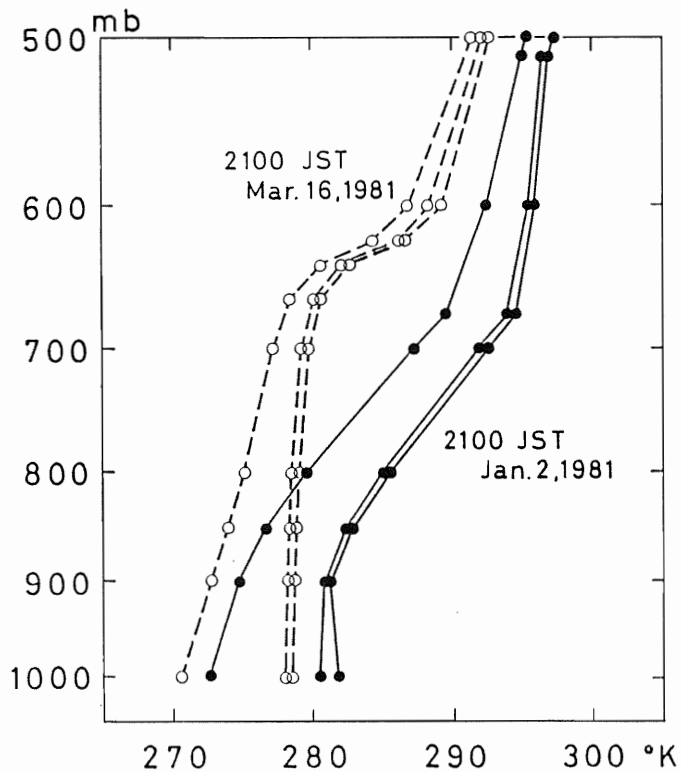


Figure 5. Vertical profiles of potential temperature, equivalent potential temperature and saturated equivalent potential temperature at 2100 JST on the 2nd of January, 1981 and the 16th of March, 1981 at Sapporo

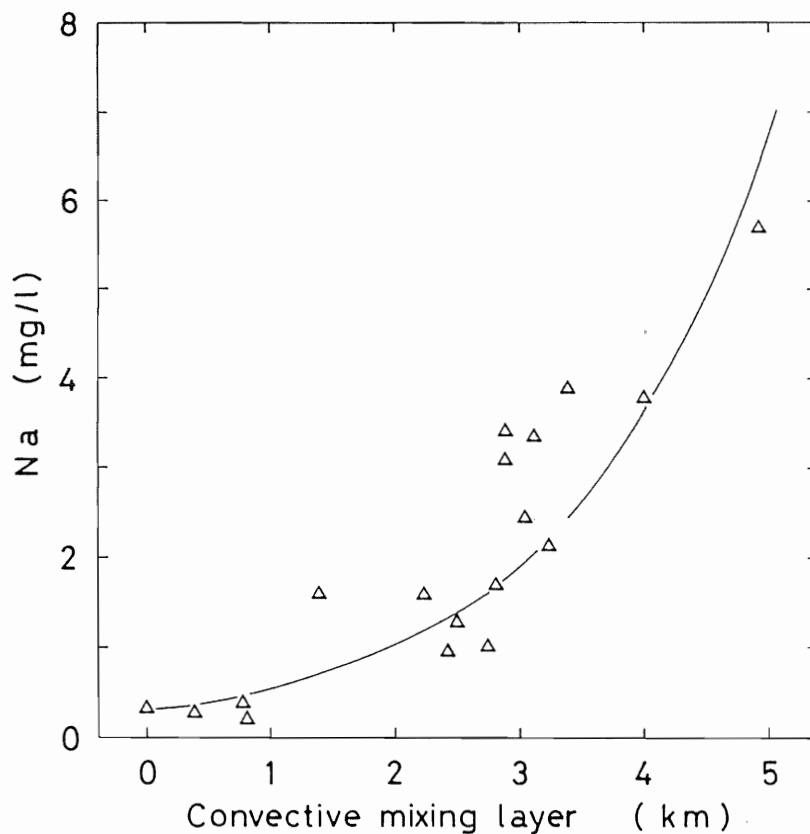


Figure 6. Relation between the height of convective mixing layer and sodium concentration

from the surface to about 650mb. This result suggests that the height of the convective mixing layer is related to the sodium concentration of the snow. The relation between the height of the convective mixing layer and sodium concentration is shown in Figure 6. Sea salt particles are collected by snow crystals through the rain-out process. The higher the convective mixing layer reaches, the larger the rate of collection of the sea salt particles by the snow crystals. The concentrations of chemical constituents of sea salt in snow is thus explained by the type of snow clouds, the height of convective mixing layer and the duration of the convective mixing of air.

3. Spatial distribution of chloride and sulfate in the snow cover in Sapporo

A chemical study of the snow cover in Sapporo is undertaken in February 1981 to assess different deposition patterns of ions of different origins (Suzuki, 1987).

Chemical constituents are retained in the snow cover during cold periods in Sapporo. The concentrations of chemical constituents in the snow cover correspond to the weighted mean concentrations of the chemical constituents in the total snowfall in the winter season. Samples of total snow cover were collected at 20 sites in Sapporo area on the 12th and 15th of February, 1981. Sapporo city has a population of about 1.5 million, and a large amount of sulfur is released to the atmosphere from house heating in winter and automobile exhausts. Chloride bearing salt is not used on roads for de-icing in Sapporo.

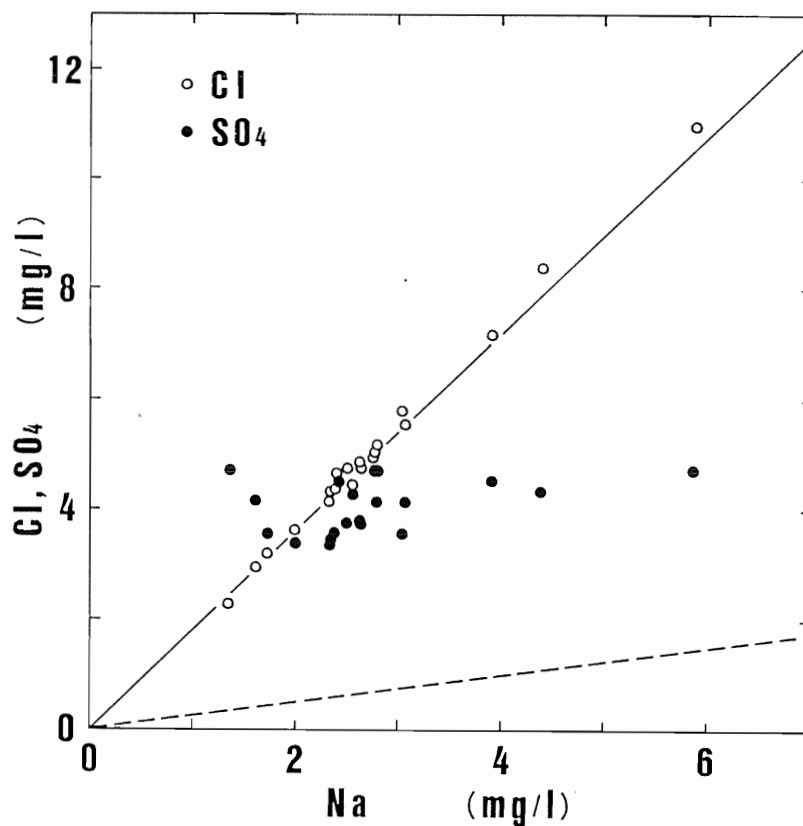


Figure 7. Relationships between the concentrations of chloride, sulfate and sodium in the snow cover. The solid line and the broken line show the ratio of Cl/Na and SO₄/Na in the sea water, respectively. (Suzuki, 1987)

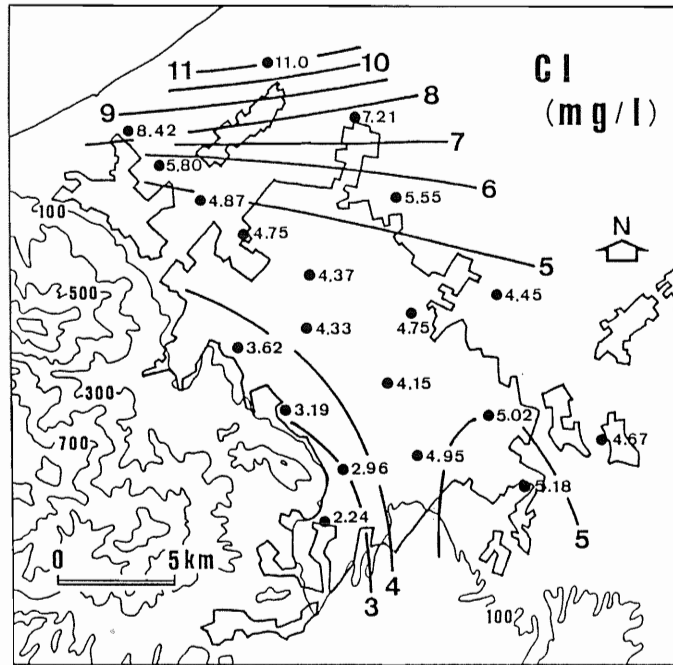


Figure 8. Distribution of chloride concentration in the snow cover (Suzuki, 1987)

The relationships between the concentrations of chloride, sulfate and sodium in the snow cover are shown in Figure 7. The ratios of Cl/Na at all sampling sites are nearly equal to that of sea water, and are considered to come from sea water. Sulfate concentration at all sampling sites is greater than that of sea water. In Sapporo, only a small part of sulfate in the snow cover comes from sea water, and anthropogenic emissions are considered to play an important role. Figure 8 shows the distribution of chloride concentration in the snow cover. Chloride concentrations near the seashore are greater

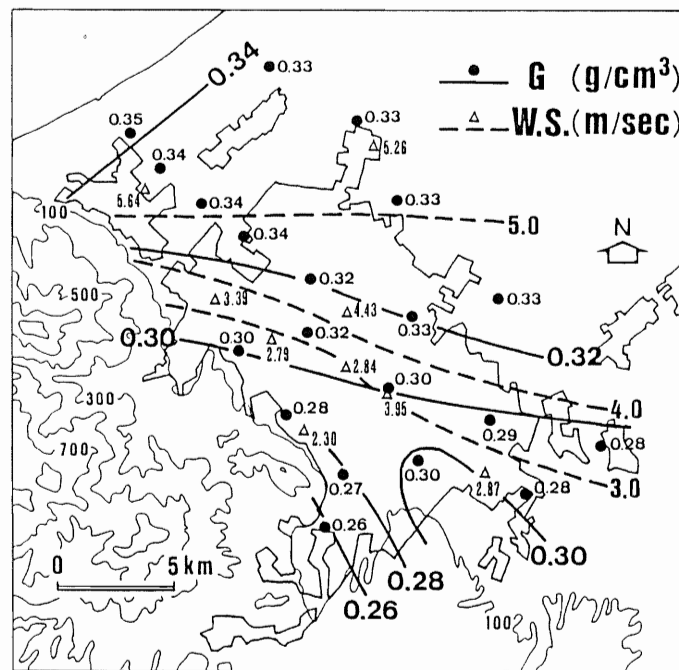


Figure 9. Distribution of density (G) of the snow cover and the mean wind speed (WS) of a WSW-NW direction (Suzuki, 1987)

than those inland. Snow particles are first generated over the Japan Sea; the snow crystals then collect cloud droplets containing sea salt particles over the Japan Sea, and the concentration of chemical constituents in the snow increases. In order to transport the hail and rimed crystals inland, sufficient wind force is required. Figure 9 shows the distribution of density of the snow cover and the mean wind speed of a WSW-NW direction. Snow densities near the seashore are higher than those of the inland area, and isoplethes of density show a trend similar to those of chloride concentrations. Figure 9 also shows that the mean wind speed of the prevailing wind direction for snowfall exhibits a trend similar to snow density and chloride concentration. These results confirm that the north-west wind transports hail and rimed crystals inland. The wind pattern causes the pattern of chloride concentration and density of snow cover.

Spatial distribution of excess sulfate concentration in the snow cover is shown in Figure 10. Chloride and sulfate have different deposition patterns, because of different sources. The source of chloride in snow cover in the Sapporo area is sea water. On the other hand, a large portion of measured sulfate is released to the atmosphere by anthropogenic emissions. Because sulfur concentration in the atmosphere is highest in the city center of Sapporo, sulfur is considered to be released to the atmosphere by combustion of fossil fuels for house heating and automobile exhausts. However, the concentration of excess sulfate in the snow cover is lowest in the city center, and a high concentration band of excess sulfate is located in the area south-east of the city center. This distribution is caused both by a urban heat island effect which causes sulfate to rise, and by a snow deposition pattern. North-west winds bring a large amount of snow, and sulfate is scavenged below the clouds by the snow flakes. An urban heat island effect and a snow deposition pattern thus cause this type of distribution of excess sulfate concentration in snow cover.

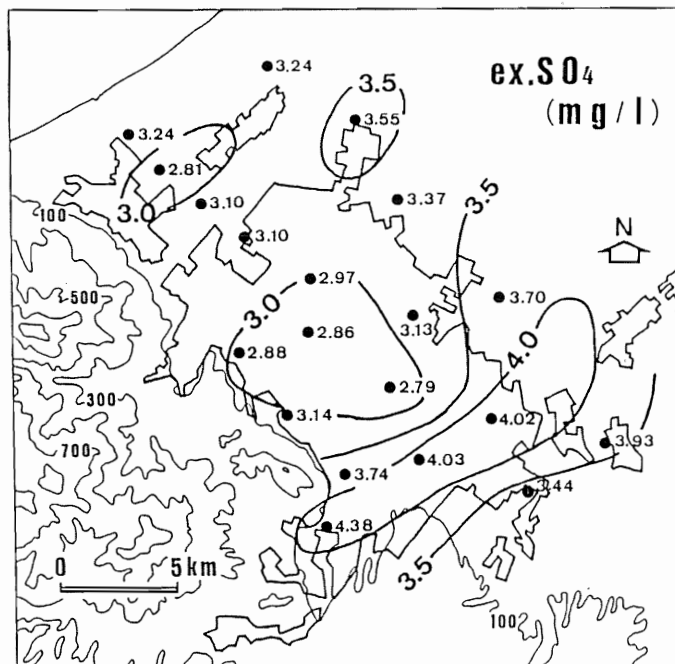


Figure 10. Distribution of excess sulfate concentration in the snow cover (Suzuki, 1987)

Chloride concentration in the snow cover near the seashore is larger than that inland, and excess sulfate is lowest in the city center. The wind speeds are high along the seashore. The distributions of chloride concentration and density of snow cover can be explained by the pattern of mean wind speed. The excess sulfate concentration in the snow cover is lowest in the city center, and a high concentration band of excess sulfur is located in the area south-west of the city center. North-west winds bring a large amount of snow, and sulfate is scavenged below cloud by these snow particles.

4. A chemical study of snowmelt water

Snowmelt water is measured by using the large lysimeter=3.6m square. The amount of meltwater is recorded automatically. Figure 11 shows the amount of meltwater, depth of snow cover, air temperature and precipitation. Diurnal variation of snowmelt can be clearly recognized. These peaks correspond with rainfall. The reductions of ion load of the snow cover are equivalent to the ion load in the outflow of meltwater from the snow cover. Snowmelt water was collected manually during 3 days. The amount of meltwater and anion concentrations in meltwater are shown in Figure 12. On the morning of the 27th of April, it rained; meltwater was collected after this rain. The high concentrations of sulfate and nitrate are considered to reflect the chemical composition of the rain. Anion concentrations of meltwater show a diurnal variation.

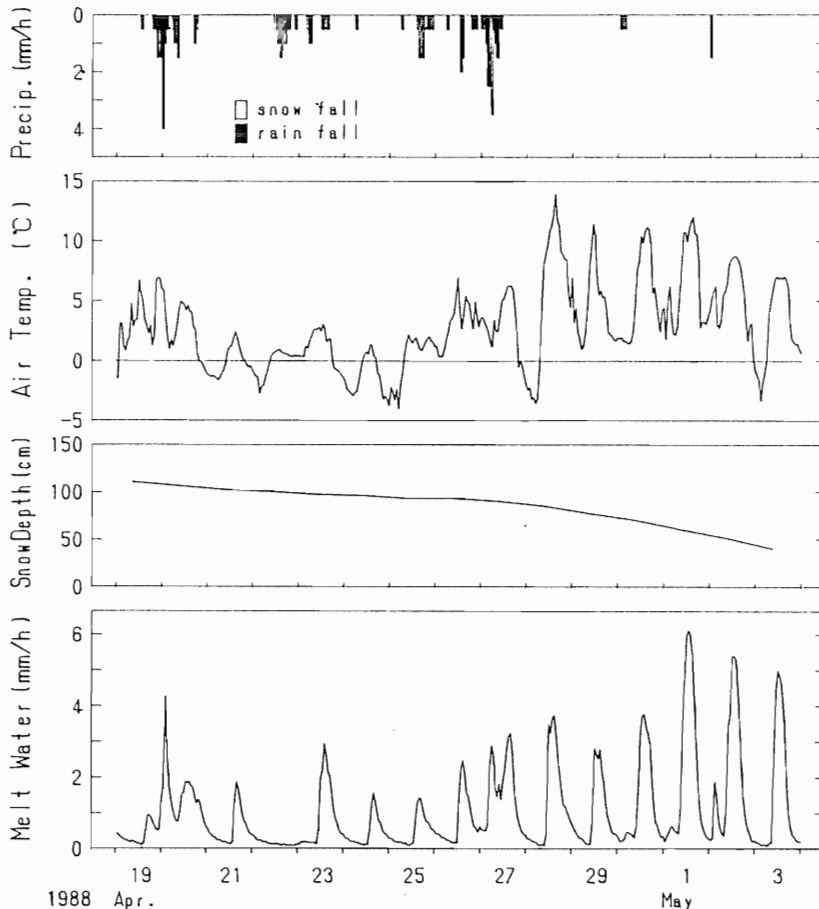


Figure 11. Amount of meltwater, depth of snow cover, air temperature and precipitation

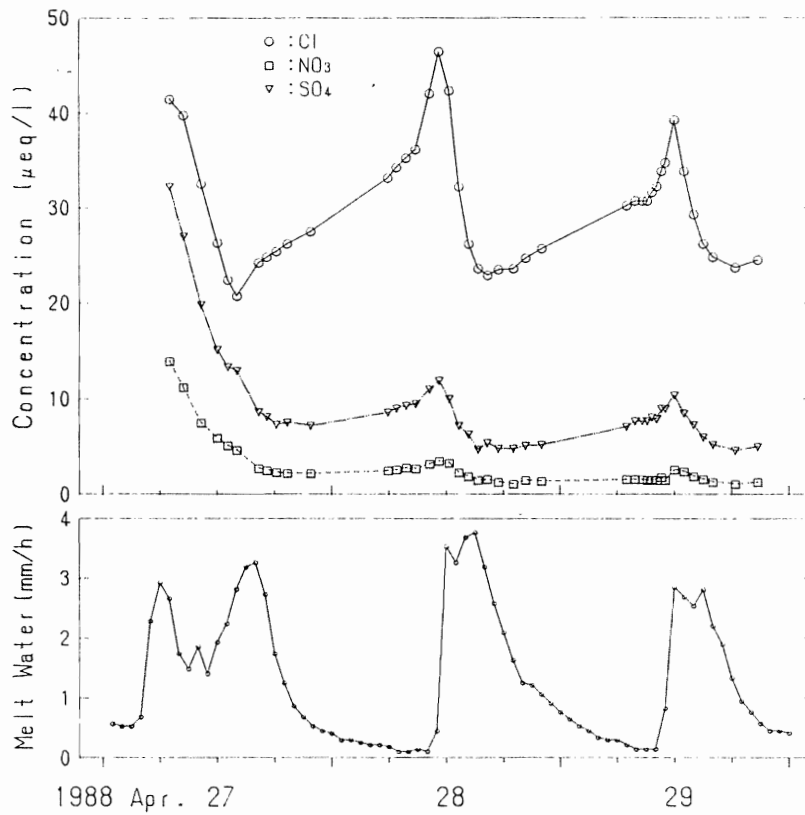


Figure 12. Amount of meltwater and anion concentrations in meltwater

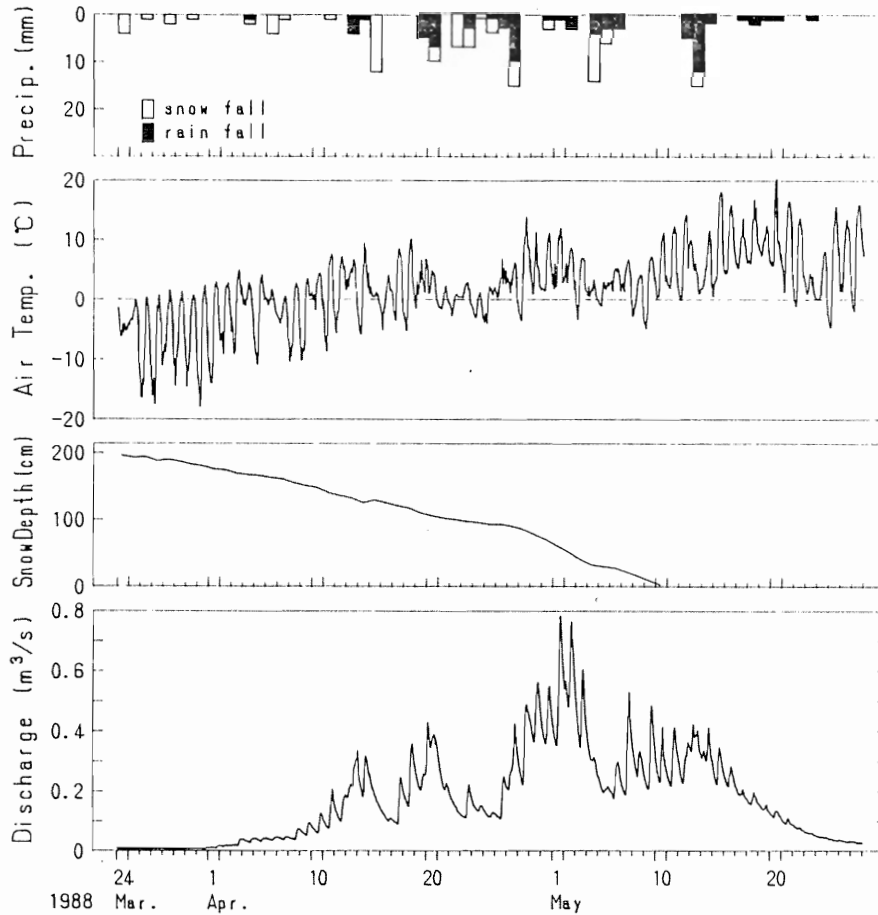


Figure 13. Stream discharge, depth of snow cover, air temperature and daily precipitation

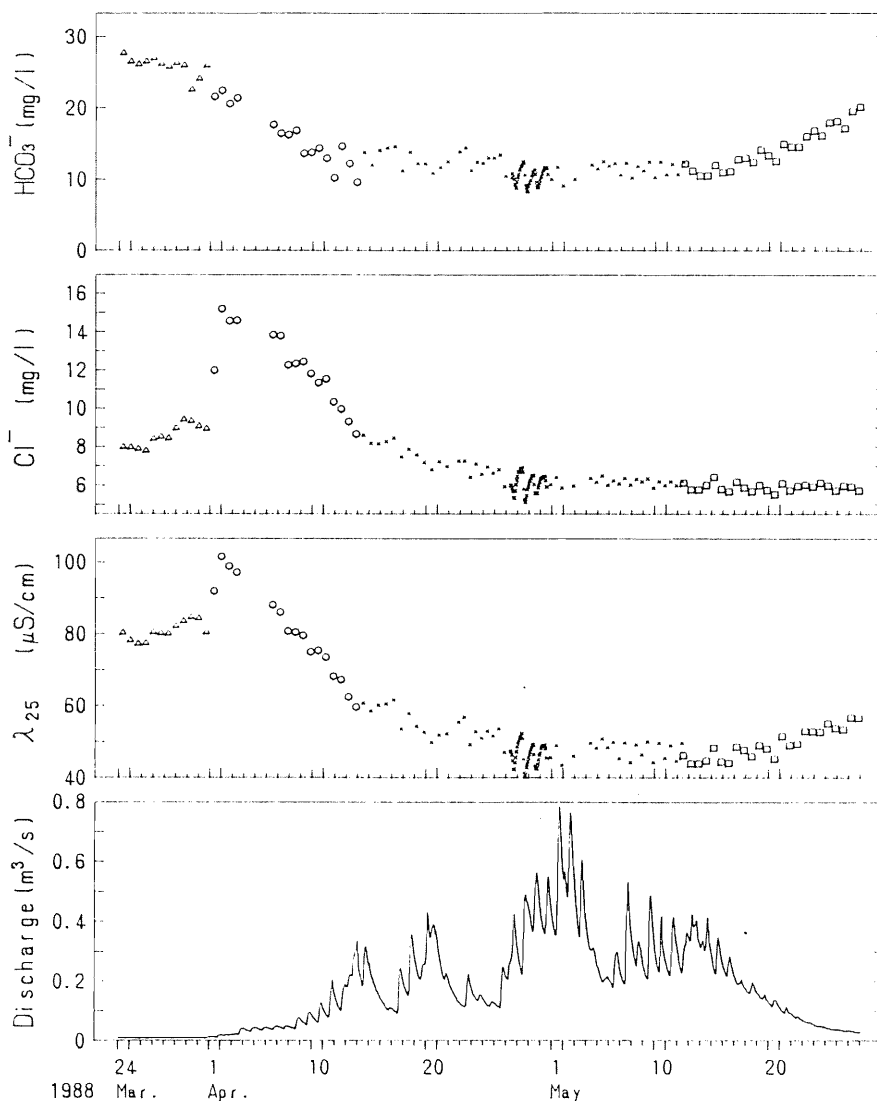


Figure 14. Stream discharge, conductivity (λ_{25}), chloride and bicarbonate concentration

5. Snowmelt runoff generation in a small forested watershed

The experimental watershed is located in northern Hokkaido, and has an area of 1.28 km². The bedrock of the watershed consists of tuff breccia. The watershed is one of the tributaries of Lake Shumarinai. The watershed is entirely covered with mixed forest vegetation dominated by *Picea jezoensis*, *Quercus mongolica* and *Acer mono*.

A chemical condition of snowmelt runoff is investigated in a small forested watershed, and the mechanism of snowmelt runoff generation is discussed with separation of runoff components by using the method of mass balance relations.

Figure 13 shows stream discharge, depth of snow cover, air temperature and daily precipitation during the snowmelt season in 1988. Stream discharge is constant until the end of March. This discharge is equivalent to the baseflow for the winter. The snowmelt runoff began on the first of April, and the peak discharge was observed on the first of May. The diurnal variation of stream discharge is clearly observed. The chemical composition of stream water is illustrated in Figure 14. Chloride concentrations are

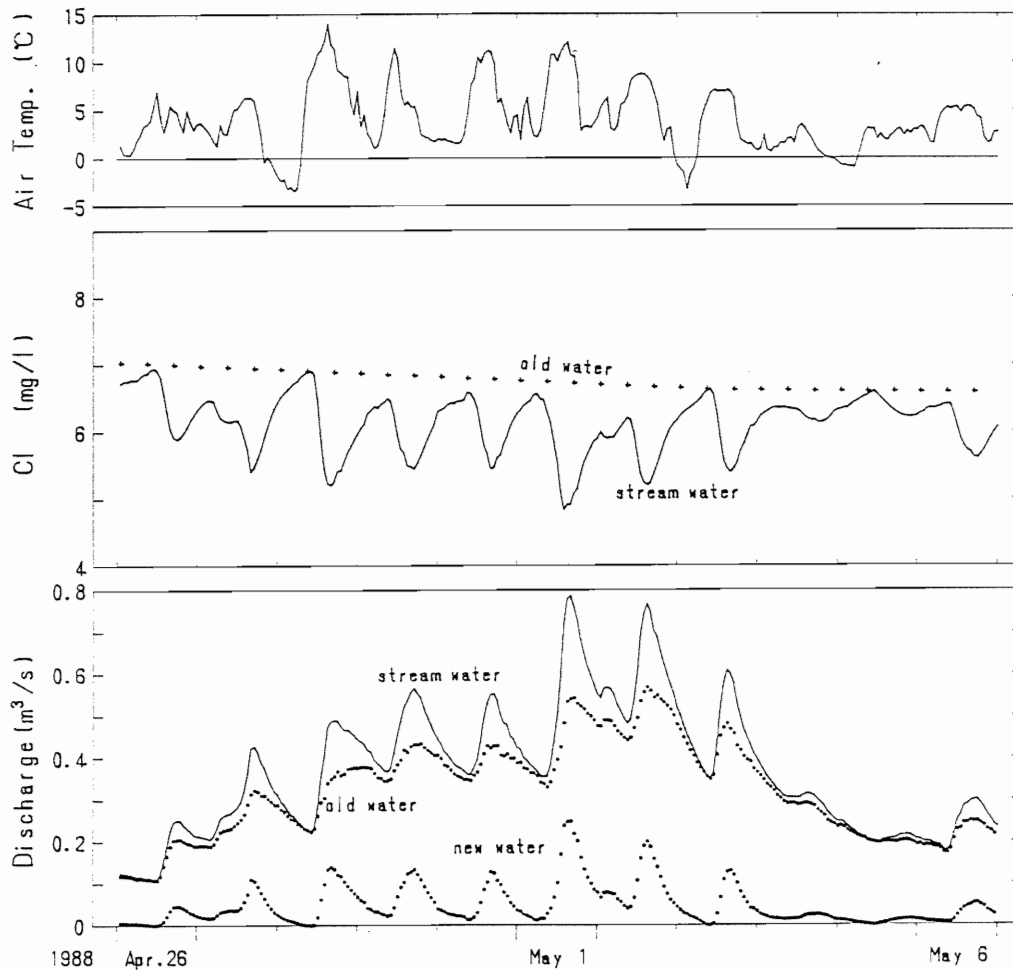


Figure 15. Air temperature and chloride concentrations in stream water and "old water" calculated from conductivity; and hydrograph separation

higher in the early period of snowmelt than before melt and in the middle of snowmelt. Only a small amount of chloride is released from rock and soil, and the predominant source of chloride in the stream water is snowmelt water. The early snowmelt waters contain extremely large amount of chloride. Therefore, chloride concentration is higher in the early period of snowmelt season, and decreases as the snowmelt progressed. Bicarbonate concentration of stream water is diluted by snowmelt water containing lower bicarbonate concentration during the melt season. The ionic composition of stream water is variable according to the stage of snowmelt. Bicarbonate is the major anion in the pre-snowmelt season, and the ratio of chloride is higher in the early period of snowmelt. In the post-snowmelt season, bicarbonate becomes the major anion again.

Chloride concentration of stream water is mutually related with conductivity of stream water during the middle of snowmelt. Correlation coefficient is 0.96. Therefore, it is possible to calculate chloride concentration of the stream water from the recorded conductivity. Figure 15 shows variations of air temperature and chloride concentrations calculated from conductivity in stream water during the middle of snowmelt. The daily peak values of chloride concentration of stream water gradually decrease as snowmelt

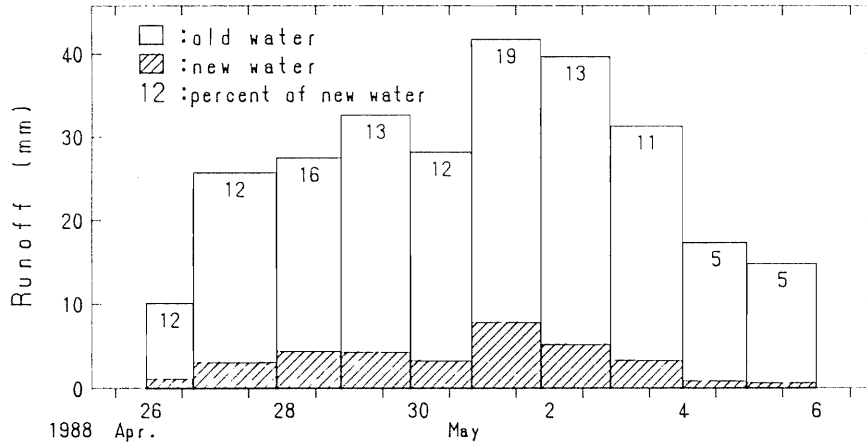


Figure 16. Amounts of daily runoff and ratio of "new water"

progresses. After air temperature falls below zero, the peak of chloride concentration attains a relatively high value. The line that joins the peak values in cold periods can be considered as the chloride concentration of "old water". Components of snowmelt runoff are separated from the mass balance equations of chloride and water. The result of the hydrograph separation is shown in Figure 15. The separated "old water" is the major component of snowmelt runoff, being more than 60% of the peak discharge. Figure 16 shows amounts of daily runoff and ratio of "new water". "New water" contributes to only 20% of the daily runoff.

References

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