

Winter precipitation chemistry at a high elevation site of Japan Northern Alps

Motoki TANAKA¹ and Keisuke SUZUKI^{2,3}

¹ Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Central 7, Tsukuba, 305–8567, Japan

² Department of Environmental Sciences, Faculty of Science, Shinshu University, Matsumoto, 390–8621, Japan

³ Institute of Mountain Science, Shinshu University, Matsumoto, 390–8621, Japan

(Received March 29, 2010; Revised manuscript accepted July 16, 2010)

Abstract

Spatial variability of the chemical constituents of winter precipitation on the eastern-western slopes of Mt. Norikura (alt. 3025 m) of Japan Northern Alps was examined to clarify the transport process of aerosol that flows over the mountain barrier. The concentrations of chemical constituents in the snow recorded at the upper part of the mountain (above alt. 2420 m) make a little difference. However, at the lower part of the mountain (below alt. 2420 m), Cl^- concentration in the snow on the eastern slope was lower than that on the western slope; non-sea-salt SO_4^{2-} (nss SO_4^{2-}), NO_3^- , nss Ca^{2+} , nss Mg^{2+} and NH_4^+ concentrations on the eastern slope was higher than that on the western slope. The prevailing westerlies raged at the western and alpine parts of the mountain. On the eastern part of the mountain, the easterlies were predominant. We infer that the snow below an altitude of 2420 m, in comparison to the other parts of mountain, is under relatively greater influence of the local emission of the chemical constituents.

Key words: Japan Northern Alps, winter precipitation, chemical constituents, mountain barrier

1. Introduction

Snowpack retains chemical constituents in the same state as they were during snowfall and before snow melt season (Suzuki, 1984; Watanabe, 1986). The chemical constituents in the winter precipitation in high mountainous areas with regards to free troposphere reflect more lithometeor without the influence of local emission of the chemical constituents than that in the lowlands (Kido *et al.*, 1997; Osada *et al.*, 2004). In other words, mountain snowpack without snowmelt retains the useful information to guess the lithometeor in the high elevation and/or precipitation in the mountainous area (Suzuki, 2000). However, only few studies have been reported on mountain snowpack chemistry and/or precipitation due to the difficulty in getting access to high mountainous areas.

The spatial variability of the emission source of chemical constituents affects the spatial variability of concentrations of chemical constituents in the winter precipitation (Suzuki, 1987). For example, Suzuki (1984) conducted a research on the spatial variability of concentrations of chemical constituents in precipitation particles, from the shore of the Japan Sea to the inland in Hokkaido, Japan and reported that, the con-

centrations of sea salt substances in the snow decreases exponentially with increasing distance from the seashore. On the other hand, Ueno (1993) performed a similar study in Honshu of Japan and indicated that, both the spatial variability of the emission source of chemical constituents and local atmospheric circulation affected the spatial variability of concentrations of chemical constituents in the precipitation on the basis of uneven spatial distribution of NO_3^- in the precipitation particles.

It is well known that, the concentration of chemical constituents in the winter precipitation in mountainous area is high on the windward slope and low on the leeward side (Inoue *et al.*, 1985). Tanaka and Suzuki (2007) showed that, in Mt. Koma of Japan Central Alps, $\text{NO}_3^-/\text{nssSO}_4^{2-}$ ratio in the snowpack on the eastern ridge (leeward) was higher value than that on the western ridge (windward). And they inferred that winter precipitation on the eastern ridge as compared to that on the western one is under greater influence of the local emission of the chemical constituents.

It is important to elucidate the transport process of aerosol to clarify the spatial variability of chemical constituents in snowpack in high mountainous areas during the winter period. However, in winter, the air mass from the Asian Continent entering the Japanese

Islands via the Japan Sea passes over the high mountainous areas in Japan. The movement of air mass that flows over the high mountainous areas is complicated. Then the aerosol of Asian Continent origin mixes with that of the Japan Inlands origin. However, the mixing mechanism of the aerosols has not been clarified. The emission source of the chemical constituents of mountain snowpack is therefore not yet clear. For effective clarification of the mixture process, it is necessary to clarify first the general behavior of aerosol as one air mass flows over a mountain barrier.

The objective of this study is to investigate the spatial variability of chemical constituents of the snow produced by Asian winter monsoon on the windward-leeward (western-eastern) slope in Mt. Norikura of Japan Northern Alps; and to clarify the transport process of aerosol that flows over the mountain barrier. The explanations presented in this study will provide basic knowledge for the transport process of aerosol in mountainous areas.

2. Methods

2.1 Site description

The study area in this research is located above 1810 m on Mt. Norikura (3025 m), which is in the southern part of the Japan Northern Alps in central Japan (Fig. 1). Urban areas such as Matsumoto City and Takayama City lie approximately 30 km to the east-west of Mt. Norikura. The timberline of Mt. Norikura is located at an altitude of approximately 2450 m. A major portion of Mt. Norikura below the timberline is covered with deciduous and coniferous forest. Mt. Norikura is a volcanic mountain. The foot of the mountain emits hydrogen sulfide, although the accuracy emission source cannot be located.

The westerlies blow throughout the winter period at higher altitude in the Japan Northern Alps. Snow-

fall is primarily caused by low pressure passing along the southern and/or northern coast of Japan and by snow clouds formed along the northern coast of Japan during the Asian winter monsoon.

2.2 Data collection

Snow pit sampling was conducted during the period of January 5–6, 2008 at three sampling sites located at altitudes of 1950 m, 2230 m and 2440 m on the western slope (wind ward) of main ridge of Mt. Norikura. Sampling was again performed on January 7, 2008 at four sites located at an altitude of 1810 m, 1990 m, 2240 and 2420 m on the eastern slope (leeward) of main ridge of the same mountain (Fig. 1). For convenience, the sites investigated were named according to the elevation and direction from main ridge of the Mt. Norikura. For example, the 2440 m-site on the western slope was referred to as W2440. In addition, on December 29, 2007, net (PE, 180 cm × 90 cm) was used as time marker to set up on snow surface at each of E1990 and E1810.

Snow pit samplings were conducted on flat and open spaces, which were selected by terrain evaluation. Pits were dug through the entire snowpack at E1810 and E1990. At other locations, snow pits were dug to melt forms layer near the snow surface as will be discussed in detail in Section 3.3. The physical stratigraphy on snow pit wall was observed, and the snow temperature measured at every 3 cm depth interval. The density (100 cm^3) was also recorded and the snow samples collected for every 3 cm interval.

The samples were placed in vinyl bags (WHIRLPAK) and allowed to melt in a clean room. The pH (DKK-TOA: GST-5420C) and electrical conductivity (EC) (DKK-TOA: CT-84101B) were measured after filtration through a PTFE membrane filter with pore sizes of $0.45 \mu\text{m}$. The concentrations of the dissolved substances (Na^+ , NH_4^+ , K^+ , Mg^{2+} , Ca^{2+} , Cl^- , NO_3^- , SO_4^{2-}) were measured by the suppression method using an

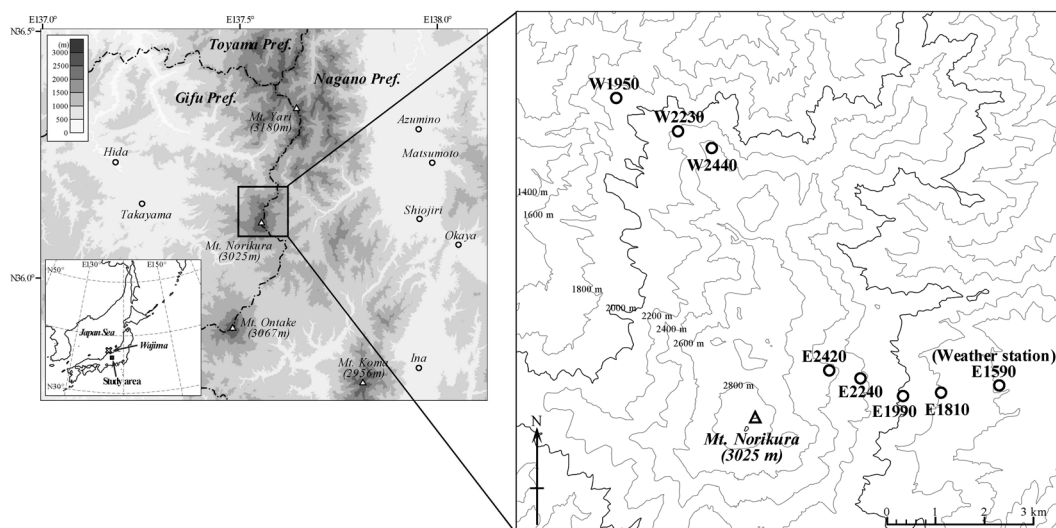


Figure 1 Study area.

ion chromatograph (DIONEX: DX-500).

A weather observation station was set up at E1590 for automatic measurements (KONA System: KADEC-Me-N). Air temperature was measured by a ventilated-type temperature sensor; wind speed and wind direction by a combined wind vane and fan anemograph. This study used the radiosonde upper-air data at Wajima observed by the Japan Meteorological Agency (Fig. 1).

3. Results and Discussion

3.1 Physical stratigraphy and vertical profile of pH and EC in the snowpack in E1810 and E1990

In order to clarify the spatial variability of winter precipitation chemistry, it is necessary to collect the sample of precipitation that fall during the same period at all the sites. It was for that purpose that we abstracted simultaneous precipitation from snowpack using time marker in the snow pack such as vertical profile of the chemical concentration, physical stratigraphy, and the net.

Figure 2 shows the vertical profiles of the pH and EC in the snow layers and the snow stratigraphy at E1810 and E1990 on January 7. The snow depth at E1990 and E1810 was recorded as 135 cm and 137 cm respectively. At E1810, the snowpack below a depth of 71 cm was made up of melt forms with ice formations, and the snowpack above a depth of 71 cm was precipitation particles, decomposing and fragmented precipitation particles and rounded grains: the boundary between melt forms and rounded grains was formed at a depth of 71 cm. At E1990, the snowpack above a depth of 82 cm consisted of precipitation particles, decomposing and fragmented precipitation particles, and rounded grains, and the boundary between melt forms and rounded grains was formed at a depth of 82 cm. The air temperature at E1590 from December 29 0:00 to 18:00 was recorded as 0–3.86°C and that from December 29 19:00 to January 6 11:00 was observed to be below 0°C. It is conceivable that grain shape boundary at depth of 71 cm at E1810 and depth of 82 cm at E1990 was formed by temperature rise with low pressure passing along the southern coast of Japan and temperature fall with Asian winter monsoon. The burial depths of the net that were set up on December 29 at E1810 and E1990 were 68 cm and 81 cm respectively. These burial depths were around the boundary between melt forms and rounded grains (depth of 71 cm at E1810 and depth of 82 cm at E1990). The shape of the vertical profiles of the pH and EC in the snow layers above this boundary at E1810 was almost same as that at E1990. In other words, it is conceivable that time marker of December 30 can be made use of boundary between melt forms and rounded grains that is nearest to the snow surface.

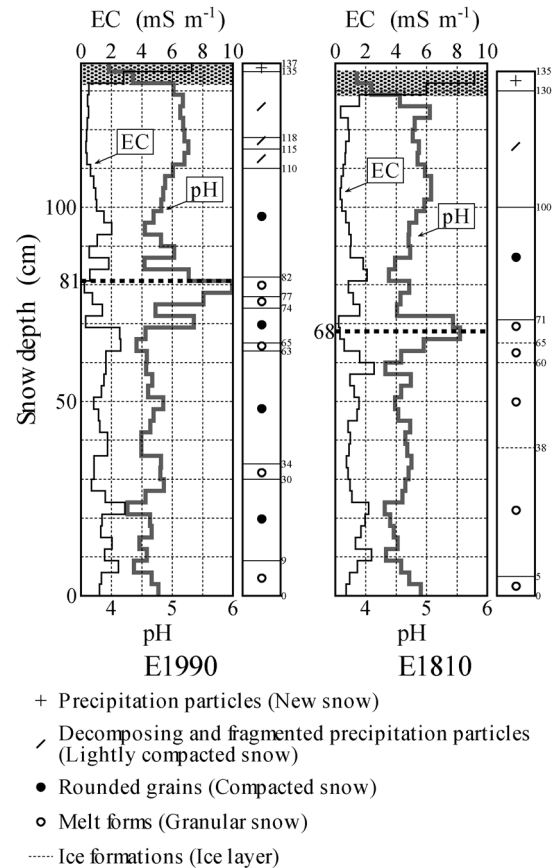


Figure 2 Vertical profile of pH and EC in the snow layers and physical stratigraphy at E1990 and E1810. Wide dotted line shows the burial depth of nets that were set up on December 29, 2007. Hatched depth shows the L snow layer that was formed by snowfall during the period of January 5–7, 2008. Non-hatched depth shows the snow layer that was formed before Jan. 4, 2008. The snow classification is expressed using grain shape classification given in Fierz *et al.* (2009). It can also be expressed by snow type classification shown in parenthesis.

3.2 Origin of chemical constituents in snowpack

Figure 3 shows the relationship between the pH and the EC in the snow layers. The percentage of acid snow (less than 5.62) in all the samples was 98.5%, and the weighted mean pH was 4.87. There is a clear relationship between falling pH and rising EC. In other words, H^+ concentration is good correlated with the EC ($r^2=0.96$, $P\leq 0.001$). This implies that not alkali substances of dust origin, the acidic substances of anthropogenic and volcanic origin control the EC. Kurita and Ueda (2006) reported that the pH of the precipitation in urban areas in Nagano prefecture that Mt. Norikura is located during 1972–2003 was approximately 5.0. The pH in the snow layers in the study area differed little from that in the urban areas.

Figure 4 shows the relationship between the Na^+ concentration and the concentrations of the other ions (Ca^{2+} , Cl^- and SO_4^{2-}) in all the snow samples collected in this study. The origin of Na^+ is the sea water and/or soil dust that is transported from Asia continent.

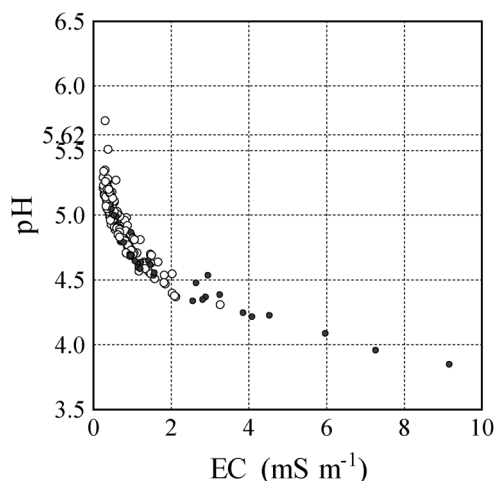


Figure 3 Relationship between pH and EC in snow layers. Solid circles indicate L snow layer that was formed by snowfall from January 5 to 7, 2008. Open circles indicate snow layers that was formed before January 4, 2008.

There is a little Na^+ of the soil dust (Inoue and Yoshida, 1978), but little silicate minerals containing Na in the soil dust dissolves water (Osada, 2001). Therefore, the origin of Na^+ in the precipitation is considered to be sea water in many studies (Suzuki and Endo, 1994; Suzuki, 1997). The relationship between Na^+ and Cl^- is nearly equal to that in sea water, suggesting that the origin other than sea water can be considered to be slight contributions. Thus, it was concluded that sea water was the predominant origin of Na^+ and Cl^- in the snow. However, the snow samples with high Cl^- concentrations are plotted slightly above the seawater line. This suggests that such snow samples also contain small amounts of Cl^- of non sea-salt origin. Toyama *et al.* (2007) also reported that winter precipitation contains non sea salt Cl^- in the Japan Northern Alps. It is also reported that Cl^- produced by anthropogenic activities or volcanic events occurs in the atmosphere (Okita *et al.*, 1974). Anthropogenic Cl^- is exhausted from inclination facilities for household and industrial wastes in the form of HCl (Tsuruta, 1989). This study has not got concrete evidence as to whether the nssCl^- was of anthropogenic or volcanic origin.

The SO_4^{2-} and Ca^{2+} are plotted remarkable above the seawater line, suggesting that SO_4^{2-} and Ca^{2+} have sea salt and non-sea salt origin. The nssSO_4^{2-} originates mainly from anthropogenic and volcanic, and the nssCa^{2+} is mainly dust. The nssSO_4^{2-} and the anthropogenic NO_3^- contributes to the acidic anion load (Suzuki, 1997).

3.3 Vertical profile of chemical concentration in snowpack from December 30 onward

From now on, snow depth 0 cm defined the boundary between melt forms and rounded grains that is the

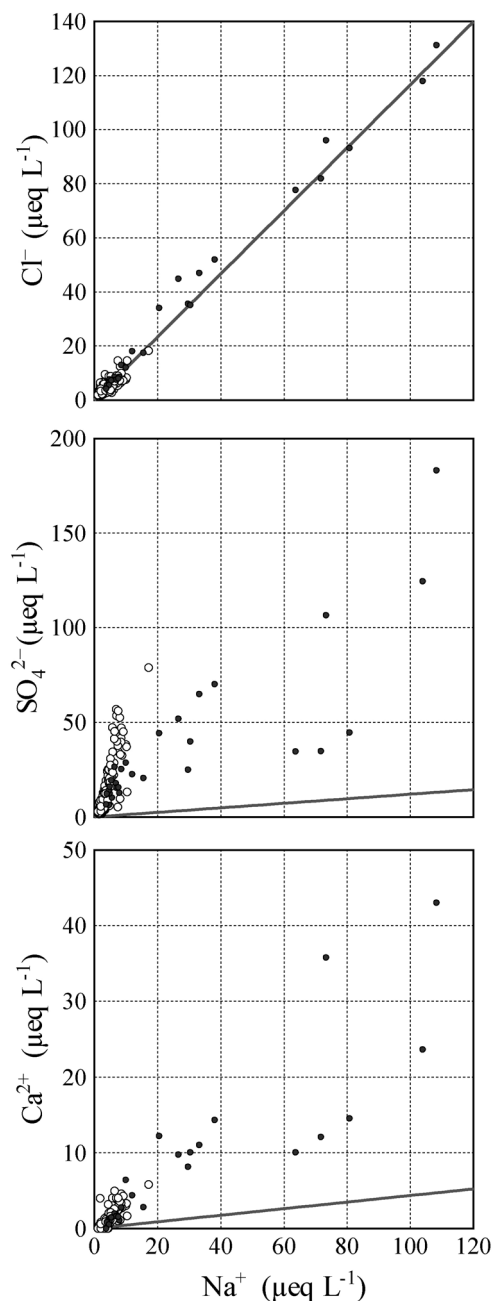


Figure 4 Relationship between the concentrations of SO_4^{2-} , Cl^- , Ca^{2+} , and Na^+ in all of the snow samples collected in this study. The lines represent the ratio for sea salt (Hanya *et al.*, 1999). Solid circles indicate the L snow layer that was formed by snowfall of weak low pressure system from January 5 to 7, 2008. Open circles indicate snow layers that was formed before January 4, 2008.

nearest to the snow surface (i.e. boundary-layer between December 30 and December 29). At all the sites, the snowpack above a depth of 0 cm was composed of precipitation particles, decomposing and fragmented precipitation particles, and rounded grains. The temperature in these snow layers ranged between -2.3 to -13.4°C . These facts indicated that none of the snow layers above the depth of 0 cm had melted. In other words, the snow retained the chemical substances present during precipitation in almost the

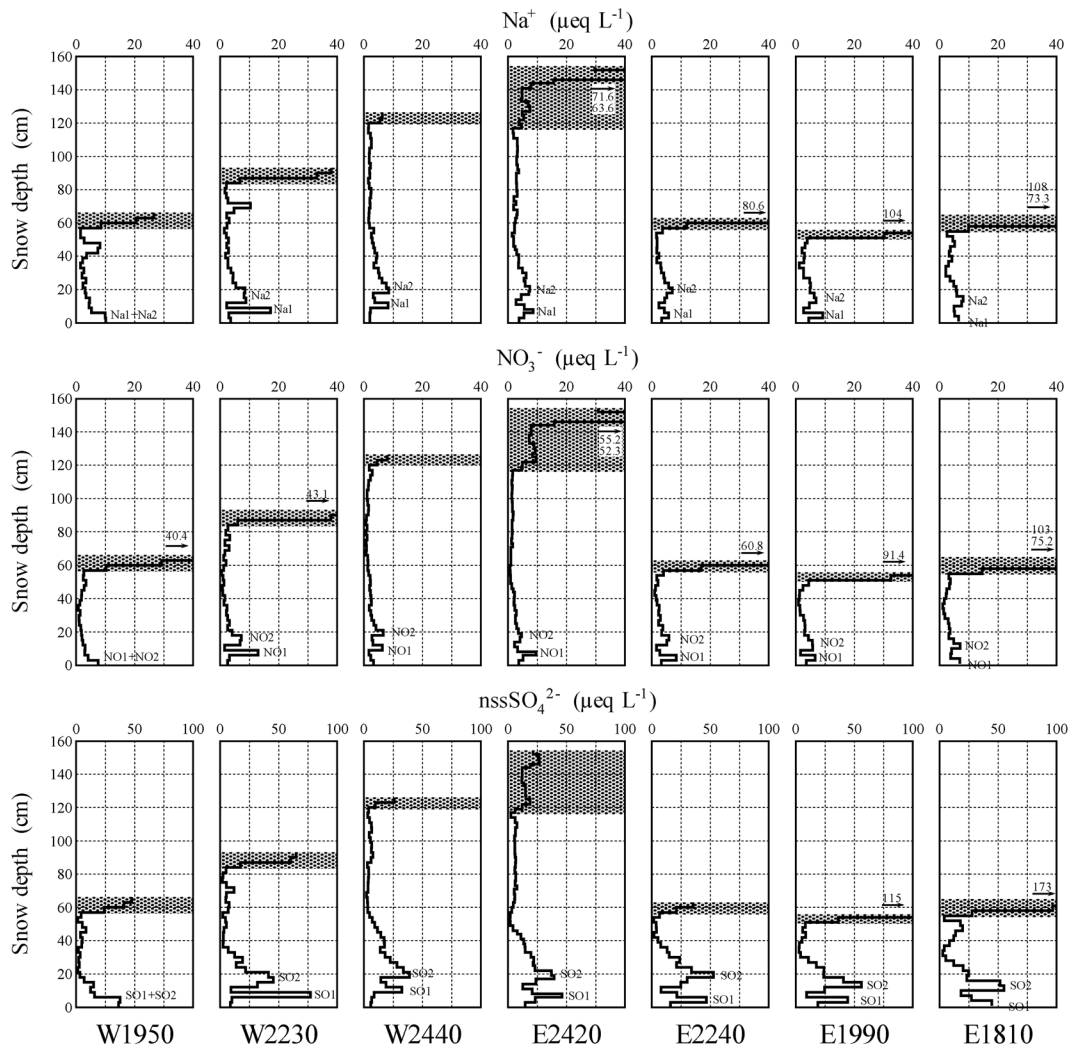


Figure 5 Vertical profile of nssSO_4^{2-} , NO_3^- , and Na^+ concentrations in the snow layers at the all study sites. The snow layers with remarkably high Na^+ , NO_3^- and SO_4^{2-} concentrations are labeled Na1-Na2, NO1-NO2, and SO1-SO2, respectively. Hatched depth shows the L snow layer that was formed by snowfall during the period of January 5–7, 2008. Non-hatched depth shows the W snow layer that was formed by snowfall during the period of December 30, 2007–January 4, 2008.

same state as that during snowfall at all the sites.

The vertical profile of nssSO_4^{2-} , NO_3^- and Na^+ concentrations is shown in Figure 5. At all the sampling sites except W1950, apparent two peaks (labeled Na1 and Na2) in the Na^+ vertical profile lie above a depth of 0 cm. Above Na2, Na^+ s concentration decreases gently thus reaching a minimum value, followed by a slightly gentle increase, and then increases substantially just under the snow surface. It is impossible to observe the snow layer that corresponded to the Na1 at W1950. It is conceivable that Na1 united with Na2 since precipitation at W1950 is less than that at every other site on December 30. The shape of Na^+ vertical profile at all the sampling sites is approximately the same. Furthermore, the shapes of NO_3^- and nssSO_4^{2-} vertical profile are almost the same state as that of Na^+ . These facts indicate that chemical substances deposited at the same time during the approximately same period at all the sampling sites.

Asian winter monsoon activity was observed on the basis of a surface weather chart for the period between December 30, 2007 and January 4, 2008. On January 5, 2008, Asian winter monsoon became negatively, and weak low pressure systems occurred on Japan Sea and Pacific Ocean in Japanese waters. These low pressure systems produced light snowfall on Mt. Norikura on January 5–6 when snow pit sampling was conducted at W1950, W2230 and W2440. This snowfall corresponds to the neighborhood of snow surface that is extremely high ion concentrations. The snowpack was sorted out from the snow layers (W snow layer) that was formed by snowfall from December 30 to January 4 and also from the snow layers (L snow layer) that was formed by snowfall after January 5.

Since the relationship between Na^+ and Cl^- concentration in the W snow layer was nearly equal to that in sea water, it was confirmed that the Cl^- was

mainly of sea water origin (Fig. 4). The plot of Cl^- concentrations in L snow layer were observed to be slightly above the seawater line. This change could be due to small amount of anthropogenic and/or volcanic Cl^- present in the L snow layer. Many black particles were included in the L snow layer at all the sampling sites. No chemical composition of black particle was measured. This particle might not be Asian dust (KOSA) since pH was recorded extremely low and EC extremely high (Fig. 3). There might exist a close relation between the extremely high ions concentrations in the snow layers, the existence of nssCl^- and the black particle. It is therefore necessary to clarify the source and/or chemical composition of the black particle. Since snow pit samplings on the western slope were conducted in the snowfall and those on the eastern slopes were after the snowfall, in this study, we discuss W snow layer that was formed during the more accurate same period.

3.4 Spatial variability of snow chemistry

Figure 6 shows the altitudinal distribution of nssSO_4^{2-} , NO_3^- , Cl^- , nssCa^{2+} , nssMg^{2+} and NH_4^+ concentrations in the W snow layer. The nssSO_4^{2-} , NO_3^- , nssCa^{2+} , nssMg^{2+} and NH_4^+ concentrations on the western and eastern slope alike were low at the upper part of the mountain; high at the middle part and low at the lower part. Each ion concentration at E1810 is the highest at all the sites. The altitudinal distribution of Cl^- concentration on western and eastern slope alike showed altitude effect that the Cl^- concentration exhibits decreases slightly with elevation. In other words, the pattern of altitudinal distribution of every ion concentration in the W snow layer on the western slope was nearly the same as that on the eastern slope.

Every ion concentration in the W snow layer on the eastern slope is compared with that on the western slope. Each ion concentration at W2440 and E2420 that is located at the upper part of the mountain was recorded almost the same value. Below W2440 and E2420, the Cl^- concentration on the eastern slope was lower than that on the western slope. On the contrary, the nssSO_4^{2-} and NH_4^+ concentrations on the eastern slope were higher than that on the western slope. The NO_3^- , nssCa^{2+} and nssMg^{2+} concentrations at E2240 were nearly the same as those at W2230, but those at E1990 and E1810 were slightly higher than those at W1950.

The altitudinal distribution of snow water equivalent (SWE) in the W snow layer is shown in Fig. 7. The SWE at W1950-W2440 on the western slope was recorded variability at a range of 100–191 mm, and

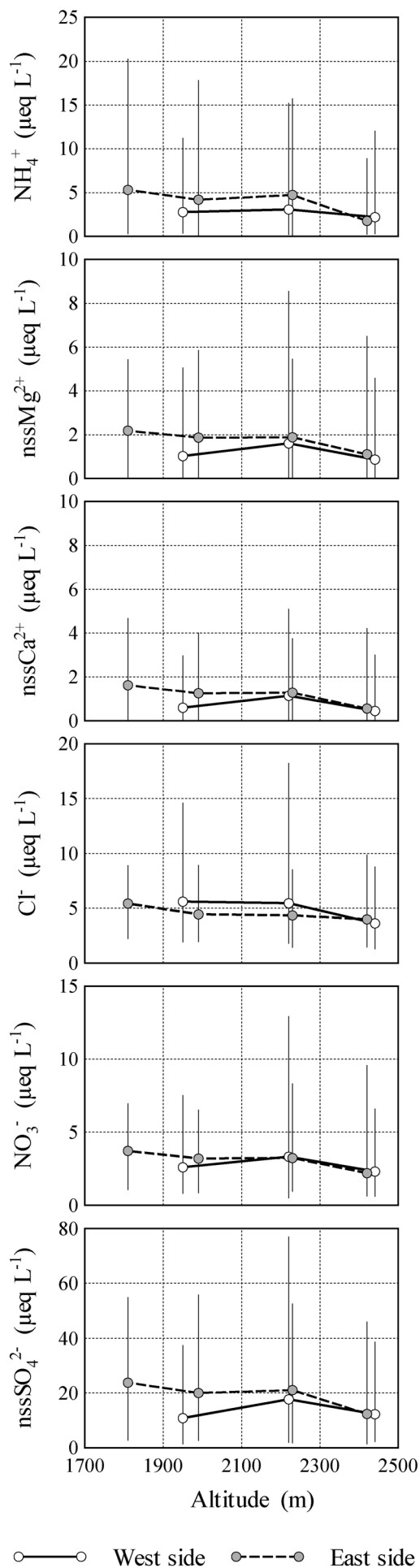


Figure 6 Altitudinal distribution of weighted mean ion concentrations in the W snow layer. The error bar represents maximum and minimum concentrations at each sampling site.

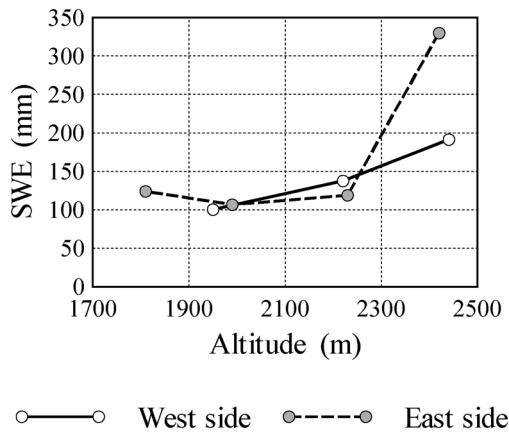


Figure 7 Altitudinal distribution of SWE in the W snow layer.

showed an increase with elevation. On the other hand, the SWE at E1810-E2240 on the eastern slope showed a little variability at a range of 107–124 mm, and the SWE at E2420 showed a sudden jump at 330 mm. In the mountainous areas that have a relatively mild climate and are mainly under forest cover just as Japan, the SWE is known to exhibit a positive linear relationship with elevation (Yamada, 1982; Kazama and Sawamoto, 1995). In the top of the mountain that is above timberline, snow in the alpine area that is above timberline is transported to the east by westerlies and the snow transported re-deposits on the eastern slope below timberline altitude. Tanaka and Suzuki (2008) researched the relationship between the SWE at western-eastern side below timberline altitude and alpine area on Mt. Koma (Fig. 1), and reported that 49–55% of the SWE at eastern side just below the timberline was the snow transported from alpine area. In Mt. Norikura, the SWE at W2440 that is nearly the same altitude as E2420 was recorded 191 mm. The SWE at E2420 was much greater than that at W2440. This fact indicates that snow that was transported from alpine area re-deposited at E2420. Assuming that genuine precipitation without snow re-deposition is almost equal at the same altitude at W2440 and E2420, approximately 140 mm of SWE at E2420 can be explained by snow re-deposition. Though the chemical constituents in W snow layer at E2420 could be strongly influenced by that in the snow transported from alpine area, the nssSO_4^{2-} , NO_3^- , Cl^- , nssCa^{2+} , nssMg^{2+} and NH_4^+ concentrations in W snow layer at E2420 was recorded almost the same as those at W2440. Therefore, it is surmised that the nssSO_4^{2-} , NO_3^- , Cl^- , nssCa^{2+} , nssMg^{2+} and NH_4^+ constituents in the snow re-deposited at E2420 (i.e. snow transported from alpine area), the snowfall (i.e. genuine precipitation without snow re-deposited) at E2420, and the snowpack at W2440 make a little difference.

At E1810-E2240, the snowpack might include a little snow transported from alpine area. Since the

nssSO_4^{2-} , NO_3^- , Cl^- , nssCa^{2+} , nssMg^{2+} and NH_4^+ concentrations in the snow transported from alpine area is lower than those in the snowpack at E1810-E2240, it is conceivable that each concentration in the snowfall at E1810-E2240 is higher than that in the snowpack at E1810-E2240. In other words, it is evident that the western-eastern variability of snowfall chemistry is qualitatively the same as that of snowpack chemistry.

3.5 Transportation process of aerosol in Mt. Norikura

In high mountainous areas at middle latitudes in the northern hemisphere, air mass that is transported by westerlies dashes against the western side of the mountain at first. Then aerosol in the air mass occurs with wet and dry deposition on the western slope of the mountain. As a result, the aerosol concentration in the air mass that flows to the eastern side of the mountain is lower than that in the air mass before flowing over the mountain (Inoue *et al.*, 1985). In Mt. Norikura, the Cl^- concentration in the W snow layer on the eastern slope was lower than that on the western slope. This implies that the Cl^- concentration in the air mass on the eastern slope of Mt. Norikura was lower than that on the western slope. However, the nssSO_4^{2-} , NO_3^- , nssCa^{2+} , nssMg^{2+} and NH_4^+ concentrations in the W snow layer on the eastern slope were recorded higher than those on the western slope. This suggests that these chemical substances supplementary supply in air mass on the eastern slope in the process by which air mass flow over mountain barrier.

Figure 8 shows wind direction on 700 hpa height at 9 and 21 o'clock (JST) at Wajima and hourly mean wind direction at E1590 from December 28, 2007 to January 7, 2008. The wind direction changed from south-southwest to northwest or west on 700 hpa height at Wajima, when atmospheric pressure shifted from the low-pressure passing along the southern coast of Japan on December 28–29 to the Asian winter monsoon on December 30–January 4. Since the 700 hpa height corresponds to an altitude of approximately 3000 m and few barriers to wind as mountain are on this altitude, the wind direction on an alpine and western part of Mt. Norikura was almost the same as that on 700 hpa height at Wajima. On the other hand, at E1590 leeward of westerlies, dominant wind direction was southwest-northeast on December 28–29, 33% of wind was easterly. Furthermore, at E1590 on December 30–January 4, prevailing wind direction was north-south, 80% of wind was easterly. Ishihara and Hibi (2000) simulated three-dimensional behavior of wind that flow over one steep mountain barrier. The wind upward along the slope at the upstream side, and the wind flowed over the mountain barrier form separated flow at the rear of the mountain barrier. This separated flow, shows open stream line. In other words, the separated flow shows that, the wind raised by the ascending current that occurs at

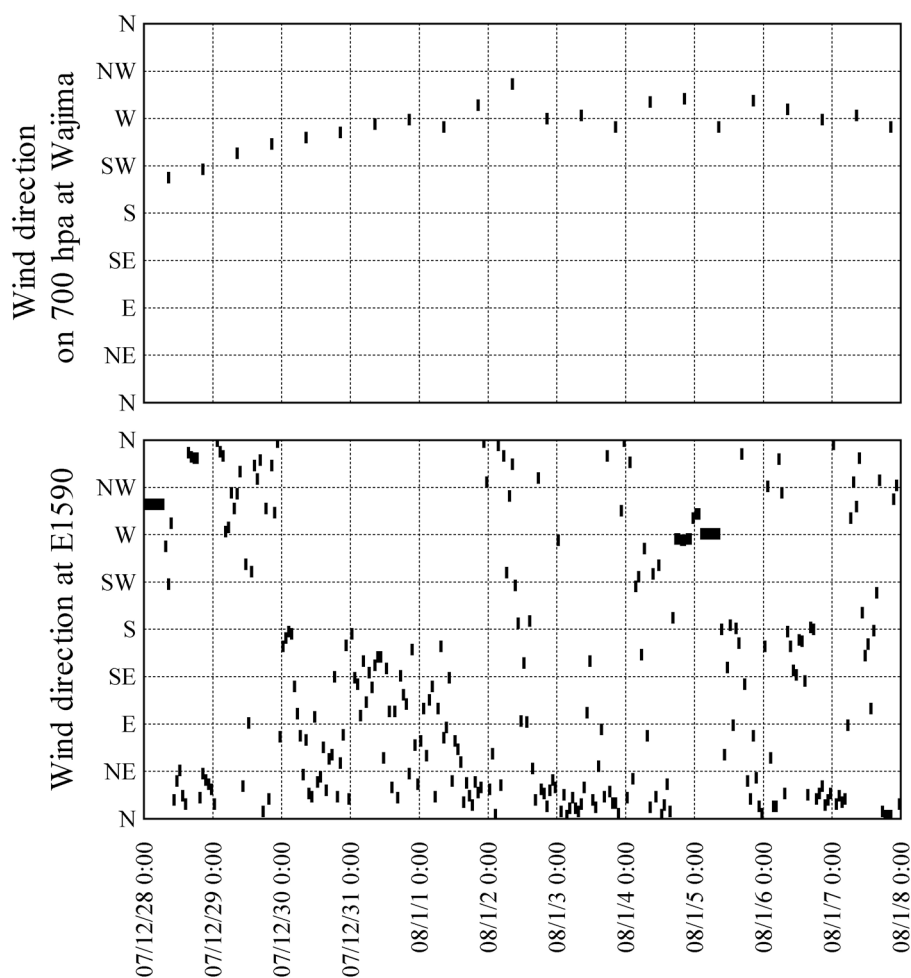


Figure 8 Variation of wind direction at the E1590 and on 700hpa height at wajima from December 28, 2007 to January 7, 2008.

the leeward side reached the top most part of the mountain and flows into the downstream side. It is conceivable that, on December 30-January 4, the dominant easterly wind as ascending current was formed on the eastern part of Mt. Norikura since westerlies raged at an alpine and western part of Mt. Norikura.

1) Every ion concentration in the W snow layer at W2440 and E2420 made a little difference. 2) Below W2440 and E2420, nssSO_4^{2-} , NO_3^- , nssCa^{2+} , nssMg^{2+} , NH_4^+ concentrations in the W snow layer at the eastern slope was higher than that at the western slope. In contrast, Cl^- concentration in the W snow layer at the eastern slope was lower than that at the western slope. 3) Dominant easterly wind as ascending current occurred on the eastern slope. It is conceivable that transport process of aerosol on Mt. Norikura is as follows. When air mass that is transported by westerlies dashes against the western side of the mountain at first, aerosol in the air mass occurs with deposition on the western side of mountain. Consequently, when air mass flows over a top of the mountain, the aerosol concentration in the air mass was lower. Above an altitude of 2420 m on the eastern slope, the air mass is just transported to the eastward by wester-

lies. On the other hand, Below an altitude of 2420 m, the air mass that is transported to the eastern part of the mountain mixes with the other air mass containing nssSO_4^{2-} , NO_3^- , nssMg^{2+} , nssCa^{2+} and NH_4^+ that emit from the east of Mt. Norikura by the easterlies as ascending current on the eastern slope of mountain. The volcanic SO_4^{2-} emits from nearby the foot of Mt. Norikura. And although it is difficult to pinpoint the emission source in this study, the anthropogenic SO_4^{2-} , NO_3^- and NH_4^+ emit from urban areas that is to the east of the mountain (Fig. 1). Furthermore, since these urban areas have no snowpack, it is conceivable that soil dust as the origin of nssCa^{2+} and nssMg^{2+} might be stirred up by wind at these urban areas. It is conceivable that since no emission source of Cl^- that originates mainly from sea-salt origin is to the east of mountain, the Cl^- concentration in the mixed air mass was lower than that in air mass on western side. Every ion concentration in the W snow layer at W2440 and E2420 made a little difference. Therefore, it is conceivable that the effect of the mountain as the barrier to decrease aerosol concentration in the air mass is little at the upper part of Mt. Norikura.

Tanaka and Suzuki (2007) reported that the snow-

pack on the eastern ridge in Mt. Koma (Fig. 1), in comparison to that on the western one, was under relatively greater influence of the local emission of the chemical constituent. The influence of local emission reached throughout upper part of the eastern ridge in Mt. Koma. The result of this study agrees with that of Tanaka and Suzuki (2007) with regards to the greater influence of the local emission on snow on eastern slope of mountain. However, in Mt. Norikura, the influence of local emission reached to the range of alt. 2240–2420 m on the eastern slope, but above alt. 2420 m, there was no influence of local emission. The altitude of local chemical constituents that was transported by the ascending current in Mt. Norikura was lower than that in Mt. Koma. Mt. Norikura is relatively gentler than Mt. Koma. The reason for the difference in altitude may be due to topographic characteristics of mountain slope that controls ascending current which transports local chemical constituent; but it is not yet clear in this study. On the leeward slope in the steep mountain, there is the possibility that, air pollutant in atmospheric boundary layer is transported to the free troposphere with more active ascending current.

4. Conclusion

The spatial variability of chemical constituents of the snow produced by Asian winter monsoon from December 30 2007 to January 4, 2008 on the windward-leeward (western-eastern) slope in Mt. Norikura of Japan Northern Alps was examined. The objective of this study was to clarify the transport process of aerosol that flows over the mountain barrier.

The results revealed the following:

1. Each ion concentration in the snow layers at W2440 and E2420 just below timberline was recorded almost the same value. Below W2440 and E2420, the Cl^- concentration in the snow layers on the eastern slope was lower than that on the western slope; the nssSO_4^{2-} , NO_3^- , nssMg^{2+} , nssCa^{2+} and NH_4^+ concentrations were higher than the western slope.
2. At E2420, the snowpack consisted of snowfall at E2420 and the snow that is transported from alpine area. It is surmised that the each ion concentration in the snow re-deposited at E2420, the snowfall at E2420, and the snowpack at W2440 make a little difference.
3. The prevailing westerlies raged at the western and alpine parts of Mt. Norikura. In contrast, the ascending easterlies current were predominant in the eastern lower part of Mt. Norikura.
4. The transport process of aerosol on Mt. Norikura is as follows: As air mass is transported by westerlies against the western slope of the mountain, at first aerosol in the air mass occurs with

deposition on the western slope. when air mass flows over a top of the mountain, the aerosol concentration in the air mass was lower. Above an altitude of 2420 m on the eastern slope, the air mass is just transported to the eastward by westerlies. On the other hand, below an altitude of 2420 m of the eastern slope, the mixture of air mass that is transported to the eastern part of the mountain and the other air mass containing chemical constituents that are emitted from the east of Mt. Norikura occur as a result of the ascending easterlies current on the eastern slope of mountain.

The snow at altitude above 2420 m in Mt. Norikura reflects lithometeor without the local chemical constituents emitted from the east of the mountain. On the other hand, the snow at altitude below 2420 m on the eastern slope, in comparison to that on the western one, was under relatively greater influence of the local emission of the chemical constituents. The result of this study is on the basis of one winter precipitation event produced by one Asian winter monsoon. Therefore, in order to clarify the seasonal variation of the transport process of aerosol that flows over the mountain barrier, it is necessary to observe many mountainous areas throughout the snow season.

Acknowledgments

The authors would like to thank the anonymous reviewer and editor for their useful comments. The assistance offered by Dr. Larry Pax Chegbeleh of the Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, in the English-proofreading of this manuscript is gratefully acknowledged. This research was supported by a Grant-in-Aid for Scientific Research (No. 17310007) from the Japan Society for the Promotion of Science, and the Global Environment Research Fund (C-6 and C-052) of the Japanese Ministry of the Environment.

References

- Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K. and Sokratov, S.A. (2009): The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology **83**, IACS Contribution NO.1, UNESCO-IHP, Paris, 90pp.
- Hanya, T., Takai T. and Oguri N. (1999): Guide book to water research (in Japanese). Maruzen, Tokyo, 177pp.
- Inoue, J., Okuyama, K., Watanabe, O. and Fushimi, H. (1985): The mountain snowfall in Chugoku district, west Japan (in Japanese with English abstract). Journal of the Japanese Society of Snow and Ice, **47**, 97–104.
- Inoue, K. and Yoshida, M. (1978): Yellow sand contained in "red snow" felled in Morioka city, Iwate prefecture (in Japanese). Japanese Society of Soil Science and Plant Nutrition, **49**, 226–230.
- Ishihara, T. and Hibi, K. (2000): Numerical simulation of turbulent flow over a steep hill (in Japanese with English

- abstract). *Journal of Wind Engineering*, **83**, 175–188.
- Kazama, S. and Sawamoto M. (1995): Estimation of the snow depth distribution and water resources volume using NOAA/AVHRR (in Japanese with English abstract). *Journal of Japan Society of Hydrology and Water Resources*, **8**, 477–483.
- Kido, M., Osada, K., Yabuki, H., Iida, H., Seko, K., Kohshima, S. and Tusima, K. (1997): Dating of seasonal snow layers at Murodo, Mt. Tateyama, Japan (in Japanese with English abstract). *Journal of the Japanese Society of Snow and Ice*, **59**, 181–188.
- Kurita, H. and Ueda H. (2006): Long-term decrease of pH of river and lake water in the upper-most stream part of the mountainous region in Central Japan - Decrease of pH in past 30 years in relation with acid rain (in Japanese). *J. Jpn. Soc. Atmos. Environ.*, **41**, 45–64.
- Okita, T., Kaneda, K., Yanaka, T. and Sugai, R. (1974): Determination of gaseous and particulate chloride and fluoride in the atmosphere. *Atmos. Environ.*, **8**, 927–936.
- Osada, K. (2001): Atmospheric environment of mountain (in Japanese). Dokiya, Y., Iwasaka, Y., Osada, K. and Naoe, H., Yokendo Ltd., Tokyo, 185pp.
- Osada, K., Iida, H., Kido, M., Matsunaga, K. and Iwasaka, Y. (2004): Mineral dust layers in snow at Mount Tateyama, Central Japan: formation processes and characteristics. *Tellus*, **56B**, 382–392.
- Suzuki, K. (1984): Spatial distribution of concentration of chemical constituent in the snow cover (in Japanese with English abstract). *Geographical review of Japan*, **57**, 349–361.
- Suzuki, K. (1987): Spatial distribution of chloride and sulfate in the snow cover in Sapporo, Japan. *Atmos. Environ.*, **21**, 1773–1778.
- Suzuki, K. (1994): Concentration changes of acidic ions in winter precipitation in Tohkamachi, Japan (in Japanese with English abstract). *Quarterly Journal of Geography*, **46**, 161–172.
- Suzuki, K. (1997): Hydro-chemical cycle in process of precipitation (in Japanese with English abstract). *Journal of Japanese Association of Hydrological Science*, **36**, 185–196.
- Suzuki, K. (2000): Review on snow chemistry in Japan (in Japanese). *Journal of the Japanese Society of Snow and Ice*, **62**, 185–196.
- Tanaka, M. and Suzuki, K. (2007): Spatial variability of snow chemistry in Mt. Komagatake, Japanese Central Alps (in Japanese with English abstract). *Journal of the Japanese Society of Snow and Ice*, **69**, 371–381.
- Tanaka, M. and Suzuki, K. (2008): Spatial variability of snow water equivalent in a mountainous area of the Japanese Central Alps, *J. Geophys. Res.*, **113**, F03026.
- Toyama, K., Satake, H., Takashima, S., Natsda, T., Tsuruta, M. and Kawada, K. (2007): Long-range transportation of contaminants from the Asian Continent to The Northern Japan Alps, recorded in snow cover on Mt. Nishi-Hotakadake. *Bulletin of Glaciological Research*, **24**, 37–47.
- Tsuruta, H. (1989): Acid rain in East Asia (in Japanese). *Kagaku*, **59**, 305–315.
- Ueno, K. (1993): Spatial distribution of chemical constituents of the precipitation particles cover from the coastal area to the mountain ranges of Central Japan (in Japanese with English abstract). *Geographical Review of Japan*, **66A**, 401–415.
- Watanabe, O., Kanamori, N., Sugimoto, A., Iida, H. and Higuchi, K. (1986): Regional characteristics snow cover in the mountain region of central Japan, *J. Earth Sci. Nagoya Univ.*, **34**, 67–108.
- Yamada, T. (1982): Studies on accumulation-ablation processes and distribution of snow in mountain regions, Hokkaido, *Contr. Inst. Low Temp. Sci.*, **A31**, 1–33.