Fluctuation of the seasonal snowpack in a mountainous area of the heavy-snow district in the warm-temperate zone of Japan

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ABSTRACT. The seasonal snowpack and meteorological factors associated with the accumulation and ablation of the snowpack were monitored for 11 years in a mountainous area in the warm-temperate zone of Japan. No notable rise was observed in mean wintertime air temperature, but an increase was seen in the difference between the maximum and minimum air temperatures. Precipitation exhibited annual variability but no notable reduction over the measurement period. The length of the continuous snow-cover period increased slightly over the 11 years, but no trend in variability was observed. The maximum snow depth and maximum water equivalent of snow varied greatly from year to year, depending on the amount of snowfall. In a heavy-snow year, about 1600 mm of water, which is almost the mean annual precipitation for the whole of Japan, was found to be temporarily stored in the snowpack.

1. INTRODUCTION

Some of the deepest seasonal snowpacks in the world are formed in the area of Japan facing the Sea of Japan. In winter, anticyclones develop above Siberia and cyclones develop over the Pacific Ocean, resulting in strong monsoons blowing from Siberia to the islands of Japan. The monsoons collect large amounts of vapor while passing over the warm Sea of Japan, hit the backbone mountains of Japan and bring heavy snowfall to the northwestern part of the mountains. This process is repeated every year, and deep seasonal snowpacks are formed in the area.

This area is located at low latitudes and in the warm-temperate zone; thus, even slight climate changes are likely to affect the formation of seasonal snowpacks. Fluctuations in seasonal snowpack would further complicate a series of hydrological processes, and could possibly affect not only natural environments but also human living environments. Therefore, monitored data and numerical simulation have been used to investigate actual fluctuations and predict fluctuations in the seasonal snowpack (Barry and others, 1993; Nishimori and Kawamura, 1993; Nakamura and Shimizu, 1996; Inoue and Yokoyama, 1998; Nakamura and Abe, 1998).

Most of these studies used data collected on plains and low hills, where monitoring is easy. However, fluctuations in seasonal snowpack in mountain districts have not been precisely monitored due to severe natural environments. Recent progress in monitoring technologies has enabled automatic monitoring to be conducted in otherwise difficult mountain areas, and continuous and precise fluctuations in seasonal snowpack are now being clarified (Nakamura and others, 1997; Shimizu and Abe, 2001).

We established a meteorological station (Busuno station), where we monitored snow depth, water equivalent of snow and other meteorological data for 11 years. This paper covers the statistical analysis of seasonal snowpacks and related meteorological factors using data collected by an automated data acquisition system from October 1988 to May 1999, with the objective of identifying recent changes in climate.

2. LOCATION OF BUSUNO STATION AND MONITORING METHODS

Higashikubiki District is located in north-central Japan, facing the Sea of Japan, and consists of relatively gentle hills 200–1100 m in elevation. This area is where especially deep snowpacks are formed since monsoons from Siberia directly hit the mountains. Busuno station was established on a slope at an elevation of 567 m (Fig. 1).

The station occupies an area of approximately 220 m^2, and various kinds of sensors were installed on the ground surface and on an 8 m high concrete pole built in the field. Air temperature, precipitation, snow depth, water equivalent of snow, meltwater and/or rainfall, wind direction, wind speed, shortwave radiation and ground temperature have been monitored at 1 hour intervals from December 1987 and at 30 min intervals since August 1991.

Air temperature was monitored using two types of sensors, natural-draft and forced-ventilation Pt-100 type thermometers. Precipitation was measured using a tipping-bucket rain/snow gauge equipped with a built-in heater and a windshield to better capture snow. Snow depth was monitored using ultrasonic snow-depth gauges capable of measuring up to 5 m (25 kHz) and 6 m (40 kHz). Water equivalent of snow, which is as important as snow depth, was monitored using a metal-wafer-type gauge consisting of a pressure-sensing plate filled with antifreeze solution, and a semiconductor pressure sensor (Greydanus and CDWR, 1976).

3. DATA INTERPOLATION AND CORRECTION

3.1. Methods of interpolating missing data

Some data were missed during the monitoring period due to malfunctioning of the sensors during lightning and/or freezing of the automated data acquisition system. The

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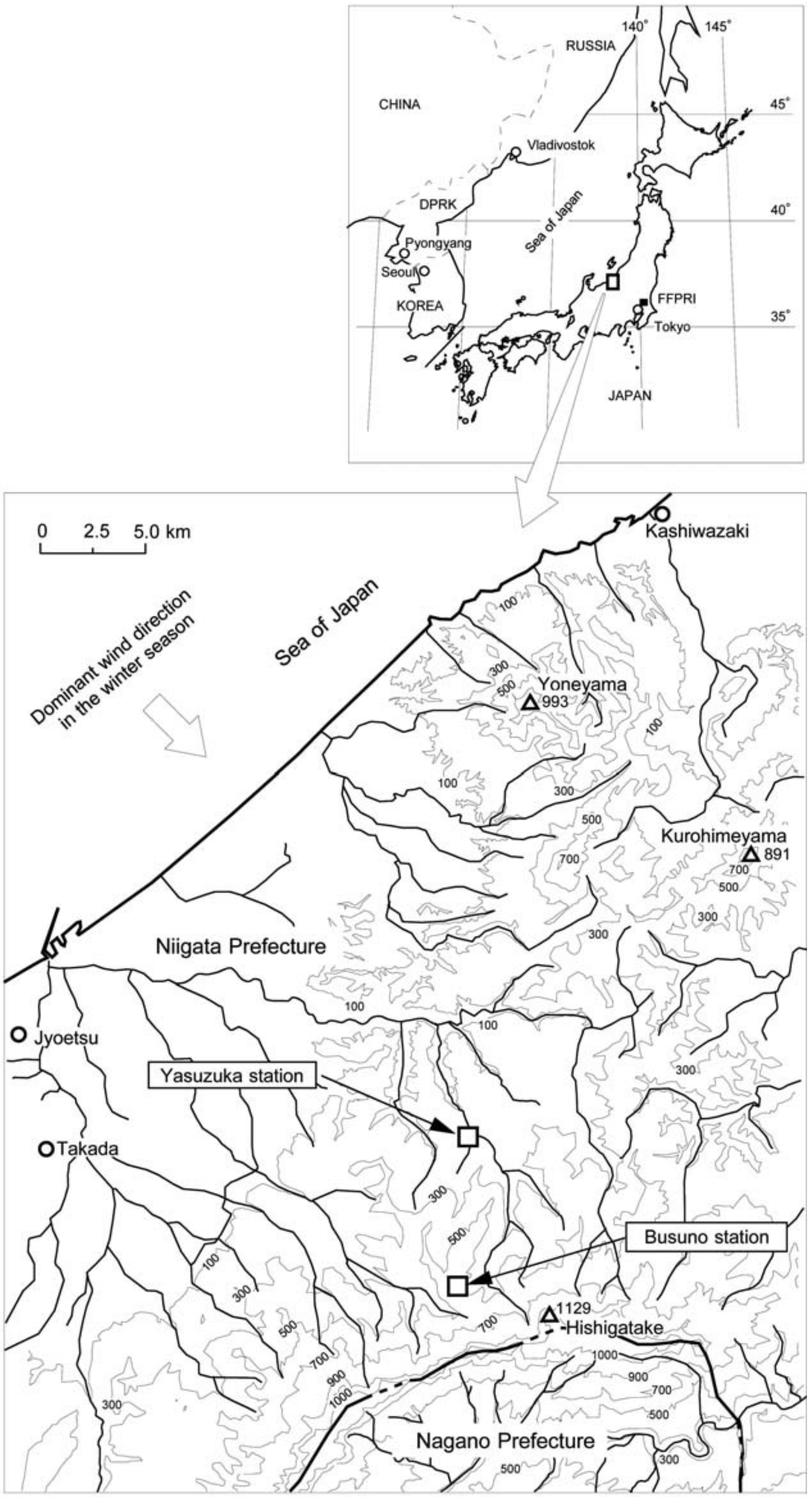

Fig. 1. Location map of Busuno station.

missing data were interpolated using data from the Yasuzuka station of the Japanese Meteorological Agency, which is located approximately 6.7 km north of Busuno station (Fig. 1). Yasuzuka station (elevation 135 m) has been monitoring air temperature, precipitation, wind direction, wind speed, sunshine duration and snow depth at 1 hour intervals since 1978.

Missing data on air temperature, precipitation and snow depth were interpolated by determining the correlation coefficients of the daily mean data monitored at the two stations before and after each missing datum, and estimating the missing hourly data from the resultant coefficients and data from Yasuzuka station.

3.2. Methods of correcting precipitation data

A rain/snow gauge equipped with a built-in heater, as was used to monitor precipitation, is easy to maintain, but tends to capture less snow as the air temperature drops due to convection caused by the heater. Thus, the data, including interpolations, were corrected by comparison with the measurements of an overflow-type rain/snow gauge, which gives the most accurate precipitation values (JMA, 1975).

The World Meteorological Organization (WMO) recommends using the Double Fence Intercomparison Reference (DFIR) to monitor solid precipitation (WMO, 1985). However, it is difficult to obtain accurate data in areas where wet snow falls heavily and adheres to the gauges. There were times when the snowfall was so intense that the heater could not melt all the snow and the gauge was unable to measure the precipitation correctly.

3.3. Calculating the amounts of snowfall and rainfall

The amounts of rainfall and snowfall were calculated from the corrected precipitation data. In general, an air temperature of 0–4°C is the limiting determinant of whether precipitation is in the form of rain or snow. Below 0°C, almost 100% of precipitation is snow. Over 4°C, almost all precipitation is rain (Ohta, 1989). Air temperature was used to classify precipitation into snowfall or rainfall. At temperatures between 0 and 4°C, precipitation was linearly complemented. For example, when the air temperature was 1°C, 7.5 mm out of 10 mm of precipitation was assumed to be snow and the remaining 2.5 mm was assumed to be rain. At 3°C, 2.5 mm was assumed to be snow and 7.5 mm was assumed to be rain.

4. FLUCTUATIONS OF METEOROLOGICAL FACTORS AND SEASONAL SNOWPACK

4.1. Overview of each winter season

During the 11 years of monitoring at Busuno station, the earliest day that snow fell was 28 October (1988), and the latest day that the snow cover disappeared was 20 May (1996) (Fig. 2). Therefore, in this study, the 8 months starting from October and ending the following May were regarded as one winter season (wintertime); 1994/95 denotes the period between 1 October 1994 and 31 May 1995.

The mean snow-cover period in these winter seasons was 166 days. Continuous snow cover appeared on 7 December, on average, and disappeared by 26 April. Thus, the district had continuous snow cover during 141 days on average. The earliest formation of continuous snow cover was observed on 24 November 1988, the winter season with the earliest snowfall.

The mean snow depth in these continuous snow-cover periods was around 180 cm. The mean maximum snow depth was approximately 360 cm, but the values varied depending on the year. The snow depth in 1988/89 was especially small at 158 cm, and it was as deep as 453 cm and 464 cm in 1994/95 and 1995/96, respectively.

In 1995/96, an especially deep snowpack was formed due to low temperatures from December to February and a large amount of snowfall. Shortwave radiation in March and thereafter was small and air temperature was lower than in an average year. Thus the snow remained for a long time. The continuous snow-cover period was 177 days, which was the longest in the 11 years.

4.2. Variations in air temperature

The mean wintertime air temperature was 5.9°C. The maximum air temperature was recorded in 1998/99 (18 October 1998) as 26.6°C, and the lowest air temperature was –10.8°C, which was recorded on 22 January 1997 (1996/97). The highest air temperature throughout the monitoring period was 33.1°C, on 12 August 1994.

Long-term monitoring in snowy areas in Japan has shown notable increases in mean air temperature (Nakamura and Abe, 1998). However, although the mean air temperature at Busuno station rose slightly, it was not significant, probably because the monitoring has been conducted for only 11 years (Fig. 3).

The maximum air temperature of each winter season has tended to increase during the monitoring period, and the minimum air temperature has lowered (Fig. 3). Thus, the standard deviation of mean air temperature has steadily increased, showing that the fluctuation in wintertime air temperature is increasing.

The monthly mean air temperature was 2.4°C in December, –0.7°C in January and –0.6°C in February. Air temperature increased thereafter from March to May, and the mean air temperature in May was 13.9°C. This is attributable to the station being located at the low latitude of approximately 37° N, where shortwave radiation is strong in spring and the air temperature rapidly rises due to the increased number of sunny days. The air temperature in April, when the snow melted, showed a large standard deviation, indicating significant air-temperature fluctuations (Fig. 4). However, the standard deviation was small in December and January, when snow started to accumulate, indicating that the air temperature was relatively stable. In February, when it was coldest, the standard deviation was large, showing that the air-temperature fluctuation was even greater than in March.

4.3. Variations in precipitation

The total average precipitation in a winter season was approximately 2235 mm. Since the annual mean precipitation at Busuno station was about 2990 mm (annual mean precipitation throughout Japan is 1690 mm), the wintertime precipitation accounted for 75% of the annual precipitation in 67% of these years.

The greatest precipitation was recorded in 1994/95 at 2773 mm, approximately 69% of which was probably snow (1906 mm). The wintertime precipitation did not decrease over the 11 years (Fig. 5), although decreases have been monitored at other stations in the boreal zone of Japan (Hideshima, 1992). However, wintertime precipitation measurements are easily affected by wind speed and air temperature, so there may be some doubt about these values.

Of the 2235 m of wintertime precipitation, 1406 mm (about 63%) was snowfall. Snowfall varied from 1906 mm in 1994/95, when the maximum snowfall was recorded, to 1011 mm in 1989/90, when the snowfall was the minimum. Standard deviation, which quantitatively shows variations of precipitation, was 72 mm for rainfall and as large as 179 mm for snowfall. The coefficient of variation (CV), which was calculated by eliminating the effects of scale from standard deviation, of snowfall was about 1.4 times larger than that of rainfall. Both the standard deviation and CV showed that snowfall varied greatly year by year (Fig. 5).

The wintertime precipitation by month was very large in December, January and February, at 420, 517 and 360 mm, respectively. The precipitation in these 3 months alone accounts for about 44% of the annual precipitation. Since snow accounted for about 75% of the precipitation in December and over 90% in January and February, the large amount of precipitation was temporarily stored on the

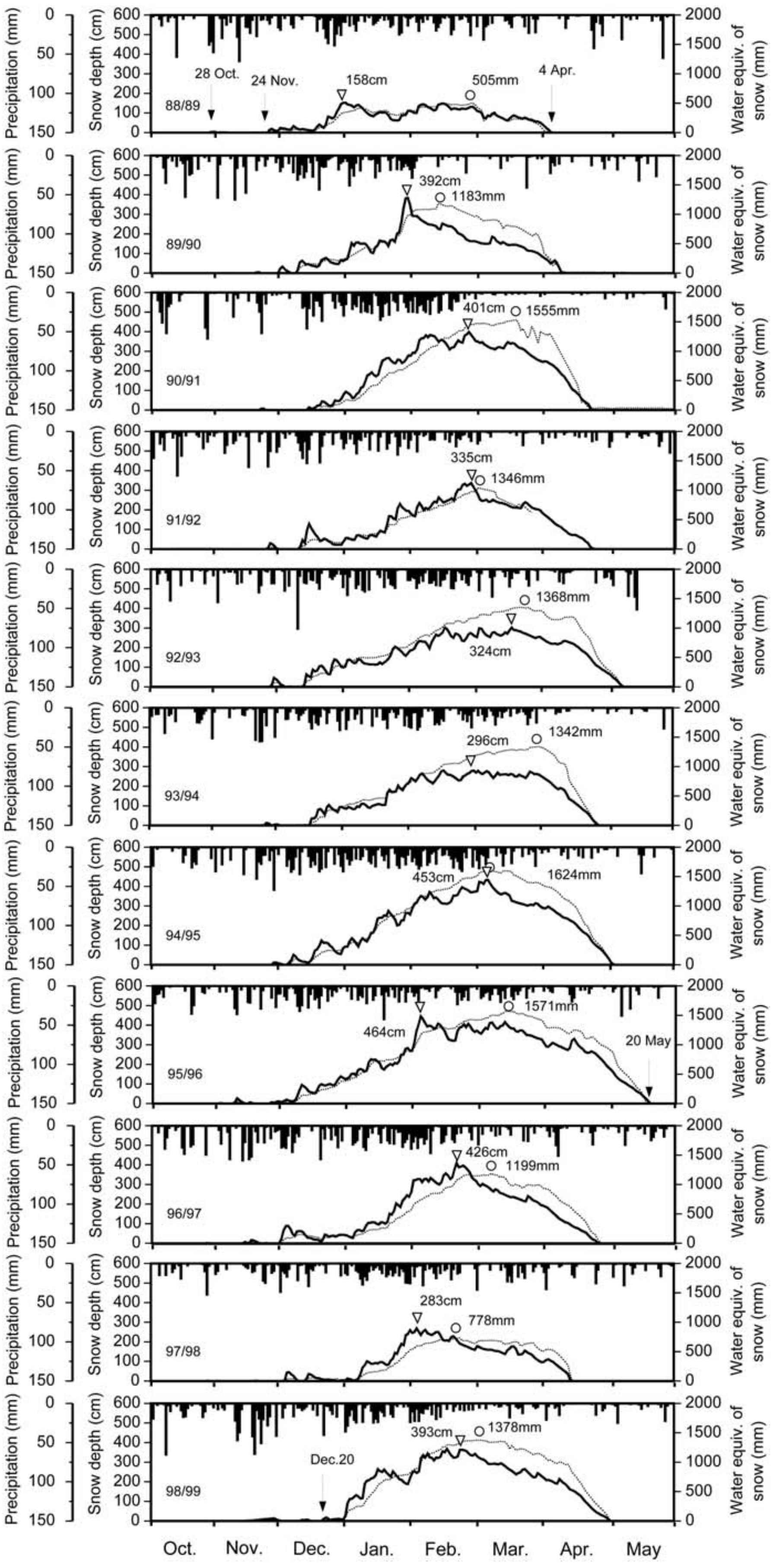

Fig. 2. Fluctuations in snow depth and precipitation for each winter season. The maximum of snow depth (solid line) is shown by open triangles, while the maximum of water equivalent of snow (dotted line) is shown by open circles.

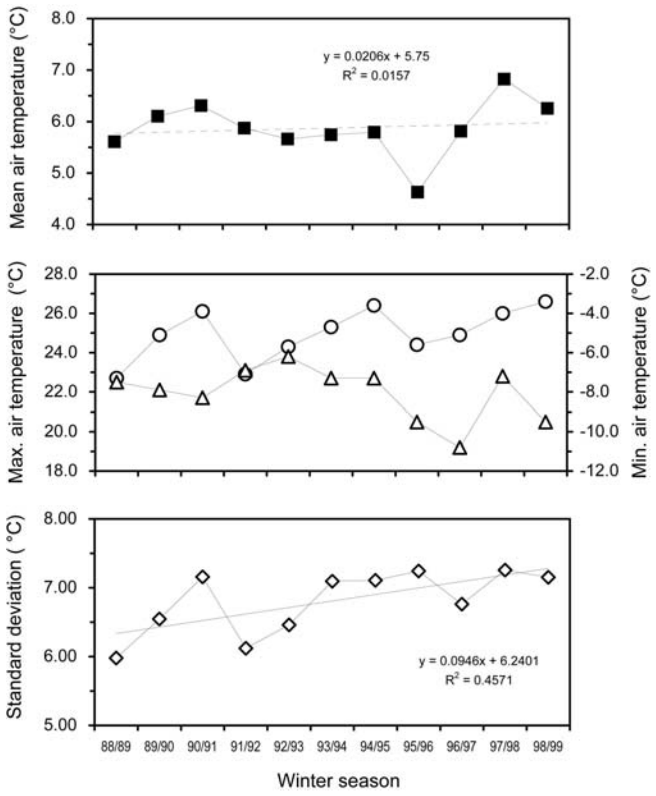

Fig. 3. Fluctuations of air temperature during the monitoring period. In the middle panel the maximum air temperature is shown by open circles, the minimum by open triangles.

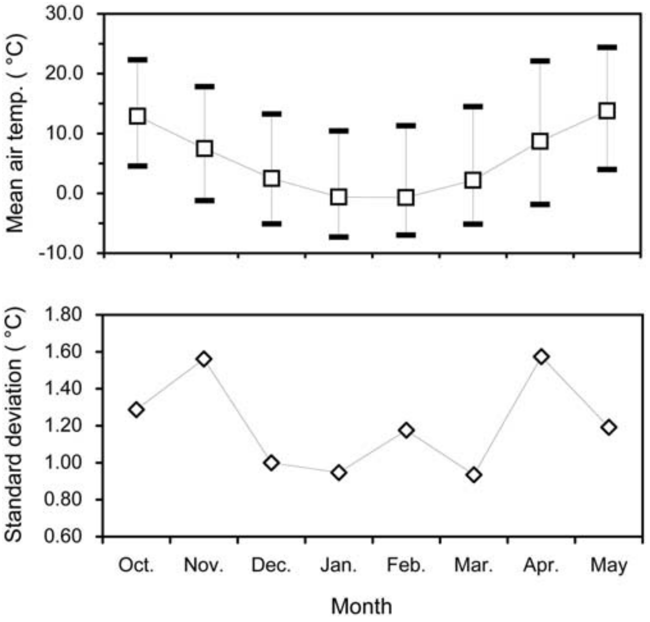

Fig. 4. Fluctuations in the mean air temperature and its standard deviation during the winter season. The error bars show the maximum and minimum mean temperatures recorded over the 11 years.

ground surface as snowpack. Thus, the precipitation in these 3 months, which is the snow accumulation period, determines years of heavy and light snow.

The standard deviation of precipitation in December and January was about 100 mm, and CV was 0.21 or smaller (Fig. 6). This shows that precipitation in these 2 months varied little year by year. Since the precipitation itself was large and the CV of snowfall was smaller than 0.25, a large amount of snow falls in these 2 months every year. The data suggest that snowpack development is most significant in December and January.

The precipitation in February was smaller than in January, and the standard deviation was larger than in December and January, as was the CV. Since the majority of precipitation was snow, the snowpack that was formed in December and January further developed in February. This is the most likely reason for the maximum snow depth being recorded in February. The precipitation in February varies greatly year by year, and when there is little snowfall in February, it becomes a light-snow year.

4.4. Changes in the length of the snow-cover period

The accumulation and ablation of seasonal snowpack are affected by various meteorological factors, particularly air temperature, shortwave radiation, wind velocity and precipitation type (which is determined by air temperature). Changes in the duration of snow-cover periods and continuous snow-cover periods, which are the results of these factors, were investigated (Fig. 7) and a close correlation was found. The snow-cover period was about 26 days longer than the continuous snow-cover period on average. As a whole, both periods were rather long in the mid- to late 1990s, but the trend was not clear. The year-to-year variation increased for both periods.

The amount of snowfall and the duration of snow-cover periods and continuous snow-cover periods had little correlation at 0.27 and 0.46, respectively. However, the mean wintertime air temperature and the duration of snow-cover periods and continuous snow-cover periods showed correlation coefficients of 0.41 and 0.72, respectively, indicating that the mean air temperature and the duration of continuous snow-cover period were most closely correlated. This suggests that the duration of continuous snow-cover period has a greater correlation to air temperature as an ablation factor than to factors involved in the accumulation of snowpacks.

4.5. Variations in snow depth

The maximum snow depth and maximum water equivalent of snow showed a greater yearly variation than the duration of the snow-cover period. The maximum snow depth in the 11 years was recorded on 2 February 1996, at 464 cm. The minimum snow depth was 158 cm in 1988/89. The mean maximum snow depth over the 11 year observation period was 357 cm, and the mean snow depth was 182 cm. Although the depth varied greatly year by year, no signs of decreasing snow depth were seen. This is unlike the results of monitoring at other stations in low-lying flatland areas, but similar to those for mountainous areas (Shimizu and Abe, 2001).

The latest day of recording the maximum snow depth of the winter season was 17 March in 1992/93. The earliest day that maximum snow depth was recorded was 30 December in 1988/89. It is unusual to record the maximum snow depth at the beginning of a continuous snow-cover period in this area. In 1988/89, the snow depth changed, showing many peaks throughout the continuous snow-cover period. This phenomenon is widely observed in areas that receive little snow and in winter seasons of light snow (Ito, 1983), but is

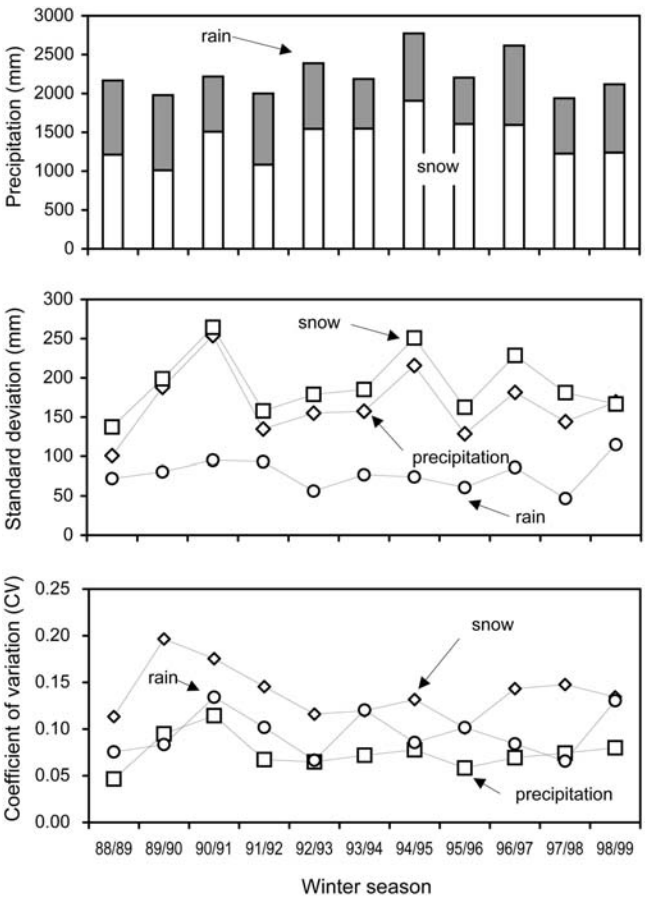

Fig. 5. Fluctuations in precipitation throughout the monitoring period.

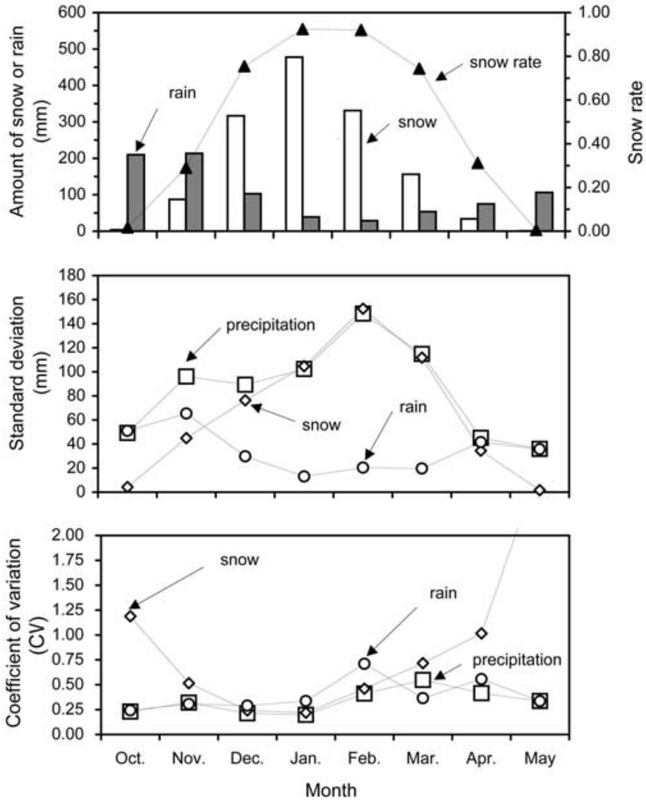

Fig. 6. Fluctuations in wintertime precipitation.

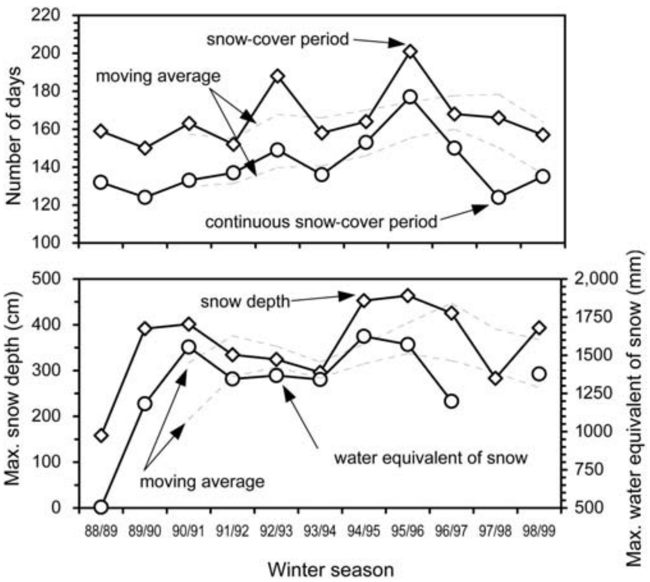

Fig. 7. Changes during the snow-cover period, maximum snow depth, maximum water equivalent of snow and lengths of the snow-cover and continuous snow-cover periods throughout the monitoring period.

not common in a snowy mountain district where snow accumulates as deep as 357 cm on average. Thus, the 1988/89 winter season was quite unusual.

Return periods of maximum snow depth were estimated from the monitored annual maximum snow-depth data (Fig. 8). Although 11 years is a short period, an extreme-value analysis of snow depth was conducted. The analysis showed that a maximum snow depth of 520 cm is likely to appear once every 20 years, and a depth of 590 cm is likely to appear once every 50 years. These estimations are considered to be valid since snow over 5 m deep was recorded by a stuff gauge in the school ground approximately 1.5 km from Busuno station in the winter of 1984.

4.6. Variations in water equivalent of snow

Water equivalent of snow is the amount of water obtained when the entire snow cover on the ground surface is melted, and is more important than snow depth in terms of water resources. However, water equivalent of snow is difficult to monitor in mountain areas since snowpacks tend to glide and creep. Data monitored at Busuno station were affected by gliding.

Although the data are less reliable than those for snow depth, we investigated the distribution of maximum values. Maximum values of water equivalent of snow were found within a more restricted period than maximum snow-depth values (Fig. 2). The maximum water equivalent of snow appeared, on average, in early March, approximately 3 weeks later than the peak in snow depth. This was probably due to the amount of snowfall, the consolidation properties of snowpacks and cumulative air temperature.

In an average winter season, approximately 1310 mm of water equivalent of snow was monitored. In 1994/95, when it snowed heavily, 1620 mm of water equivalent of snow was recorded. This is almost the same as the mean annual precipitation in Japan, and suggests that a large volume of water melts from the snow cover in the 2 months of the melting period and is discharged to the ground surface.

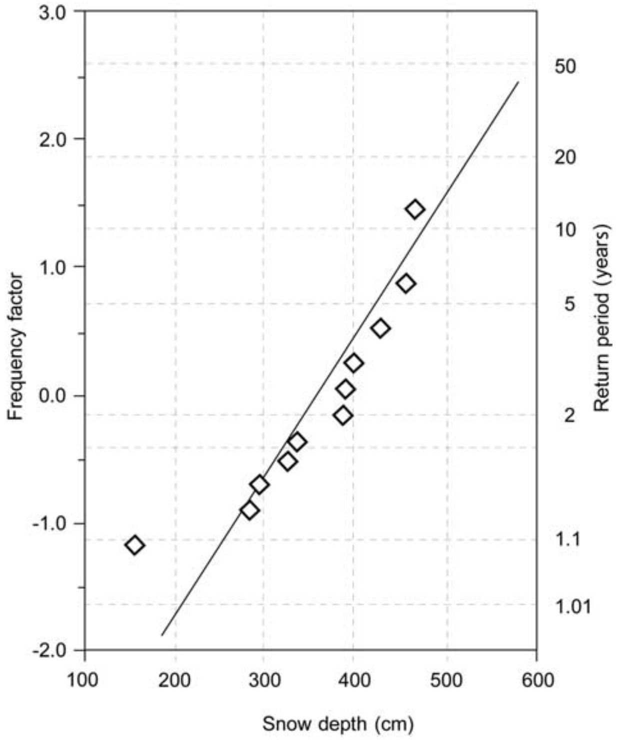

Fig. 8. Extreme-value distribution of maximum snow depth.

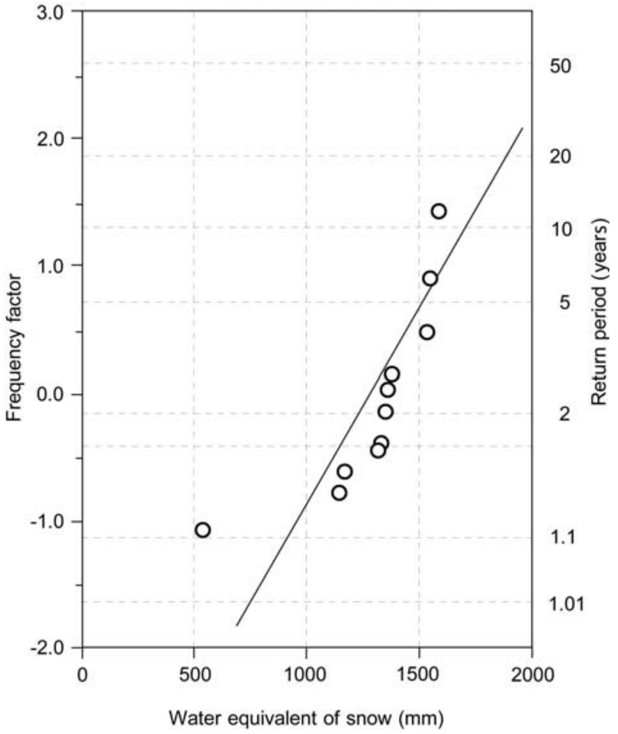

Fig. 9. Extreme-value distribution of maximum water equivalent of snow.

Therefore, it is considered that the timing and intensity of snowmelt are likely to have a large effect on the hydrological environments of this district.

As with snow depth, an extreme-value analysis was conducted for water equivalent of snow. The maximum value for 1988/89 dissociated more clearly than the snow depth. The values of water equivalent of snow fluctuated to a lesser degree than snow depth when the data of 1988/89 were excluded (Fig. 9). In terms of the amount of water temporarily stored on the ground surface, the 1988/89 winter season was very unusual. As with the snow depth, return periods of water equivalent of snow were estimated. The analysis showed that 1902 mm of water is likely to be temporarily stored as snow cover on the ground surface every 20 years, and 2132 mm is likely to be stored every 50 years.

5. SUMMARY AND CONCLUSIONS

Fluctuations in seasonal snowpack and related meteorological factors were monitored in a snowy mountainous area of Japan. No notable rise in mean wintertime air temperature was observed, but the standard deviation of mean air temperature has certainly increased, indicating that air temperature has increasingly fluctuated in recent years.

The continuous snow-cover period, which was found to correlate with the mean wintertime air temperature, also varied, especially in the mid- to late 1990s. Since the monitoring covers a period of 11 years, trend variability was observed but no periodic variability was shown.

The decreasing trend in wintertime precipitation reported in the boreal zone of Japan was not detected, but the amount of snowfall varied year by year. Since precipitation in December, January and February accounts for about 44% of the annual precipitation, the precipitation in this period should have affected the annual precipitation.

Snow depth and water equivalent of snow, which are affected by the amount of snowfall, also exhibited annual variability. Of the months of snowpack accumulation, snowfall was relatively uniform in December and January, but the snowfall in February differed greatly year by year. Thus, the snowfall in February is likely to determine the maximum amount of snow stored on the ground surface in the winter season.

Although the snow depth differed greatly between light- and heavy-snow years, the maximum snow depth has not decreased. In a heavy-snow year, the snow depth was over 450 cm, indicating that about 1600 mm of water, which is almost the mean annual precipitation in Japan, is stored on the ground surface as seasonal snowpack.

The statistical investigations showed that the seasonal snowpack in the warm-temperate zone in Japan fluctuates greatly as a consequence of slight changes in climate. Such fluctuations in seasonal snowpack affect the natural and social environments in the mountainous areas in Japan and are connected to the global atmospheric cycle and wintertime climate in Europe through teleconnections. In light of this, we plan to continue monitoring seasonal snowpacks and to continue rigorous analysis of the data.

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MS received 16 March 2004 and accepted in revised form 22 August 2005