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Article

Stability of drifting snow-type perennial snow patches

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Abstract

Perennial snow patches exist one kilometer or more below the climatic snow line at the same places for many years and have very small sizes in autumn. They could not exist stably without powerful negative feedbacks in their sizes through ablation/accumulation. Those feedbacks were examined for snowdrift-type snow patches (Hisago, Kaigata and Hamaguri snow patches) in Japan. Data on these snow patches that were obtained over period of more than 7 years were used to obtain indexes of snow patch size, accumulation and ablation. The results showed that when the size of a snow patch in autumn was large (small), the accumulation in the following winter became small (large), and when the size of a snow patch at the beginning of ablation period was large (small), the ablation in the following summer became large (small).

1. Introduction

There are at least three important reasons for investigating perennial snow patches. First, they are transitional forms between seasonal snow covers and glaciers, and their characteristic change to snow cover or glacier would indicate an event of climatic shift. Second, they constitute a significant element of high mountain landscapes and their change can substantially affect high alpine summer runoff (Shultz, 1956; Sosedov and Seversky, 1963; Higuchi *et al.*, 1979). Third, issues related to glaciers such as bottom ice formation (Kawashima, 1997) can be easily investigated using smaller snow patches.

Current perennial snow patches generally exist about one kilometer or more below the climatic snow line, where, on a regional basis, annual snowfall is less than snowmelt. Therefore, the initial formation of perennial snow patches results from the local process of snow accumulation, perhaps by redistribution of snow and/or a local reduction in ablation, which makes the accumulation/ablation different from the regional mean. For the stable existence of perennial snow patches, the long-term mass balance must be zero. Otherwise, they would become glaciers or seasonal snow covers. Since snow accumulation and ablation depend mainly on meteorological conditions, the annual mass balance of snow patches is strongly affected by year-to-year changes in seasonal weather conditions.

Despite the dependence of sizes of perennial snow patches on yearly weather conditions, they can exist for many years in the same place (Glazirin, 1985; 1997; Yamaguchi *et al.*, 1998). Yearly variation of weather conditions is not likely to regulate perennial snow patches for their stable existence. There must exist mechanisms by which the existence of snow patches is stabilized. If such mechanisms did not exist, the snow patches would either grow or disappear. Based on results of studies in the Pamirs, Glazirin (1985, 1997) and Glazirin *et al.* (1993) suggested that there existed stabilizing feedbacks such that mass balance was inversely related to patch size. We speculate that the same stabilizing feedback works also for snow patches in Japan. In this paper, we review the feedback processes on snow patches and show that they also apply to snow patches in Japan.

2. Stabilizing processes of perennial snow patches

Stabilizing feedback processes can be divided into two groups, accumulation and ablation processes (Table 1). One may dominate or they may interact.

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Table 1. Classification of feedbacks controlling accumulation and ablation.

Mechanisms	Control on accumulation		Control on ablation		
Feedback process	Maximum size is limited by the size of depression.	Accumulation decreases with increasing snow patch size.	Change in solar radiation with size change	Ablation decrease caused by debris	Breakdown of cornices
Typical location	Depression	Lee side of ridges and hills	Any location, typically on a north-facing slope	Any location, typically of avalanche type	Ridge
Formation	Snowdrift	Snowdrift	Any	Any	Cornice

2.1. Accumulation processes

For perennial snow patches to exist in a region far below the regional equilibrium line altitude, the snow pack cannot be a uniform layer but must be redistributed and accumulated preferentially in some locations at magnitudes greater than the regional mean ablation. Such accumulation occurs due to wind redistribution of snow and avalanching. Favorable topography for accumulation by wind redistribution is depressions in flat terrain or a slope with abrupt changes in steepness. The topography limits the sizes of snow patches because once a depression is completely filled with drifted snow, the depression, which initially favored deposition, no longer exists (Fig.1-I). When snow patch volume exceeds the volume of the depression, wind ablates the more exposed snow.

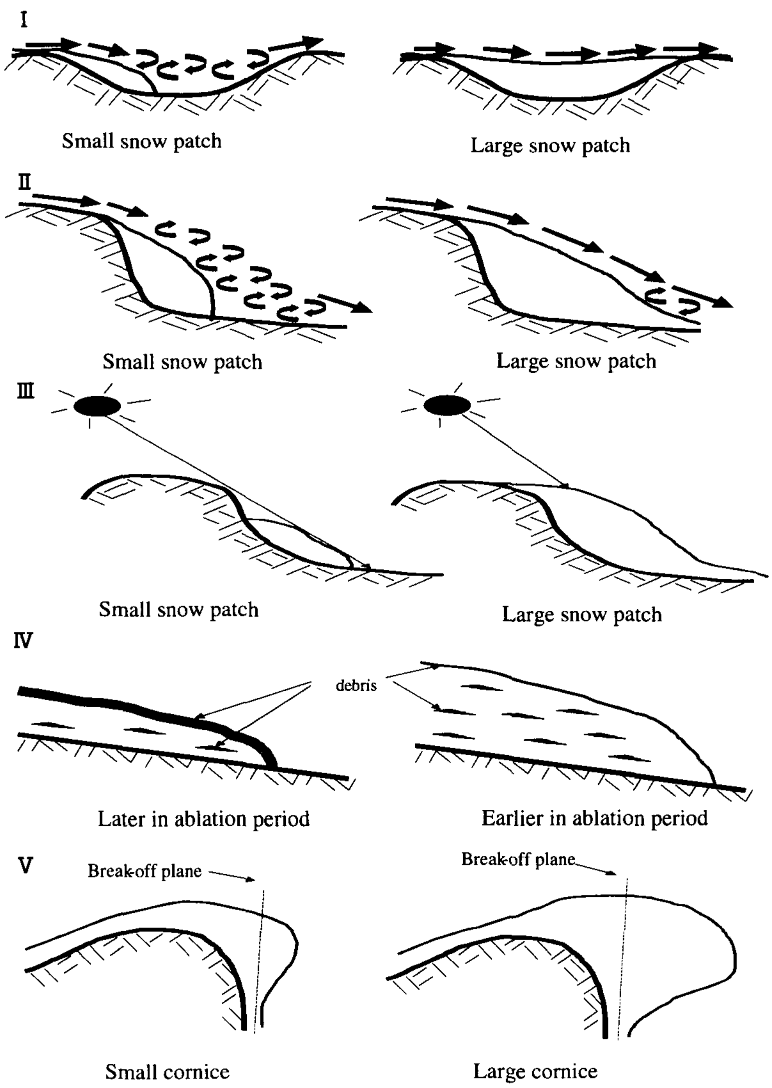

Fig. 1. Schematic diagrams of stabilizing mechanisms of accumulation (I, II) and ablation (III-V).

Therefore, accumulation on a snow patch is inversely proportional to the size of the patch relative to the size of topographic depression (Fig. 1-II). A large amount of snow can accumulate if the patch is small relative to the size of the depression, and less snow accumulates if the patch is larger. Snow is rapidly lost if the patch is larger than the depression.

Those mechanisms were briefly discussed by Inoue and Matsuda (1973) for Yukikabe perennial snow patch in Daisetsu Mountains, Hokkaido, which is formed leeward of a ridge by snowdrift. They pointed out that the upper part of the patch is flat at the same height as that of the ridge regardless of the amount of snow drift in winter. This indicates that the size of the snow patch is limited by the topography mentioned above.

There is no stabilizing processes for snow patches on which snow accumulates primarily by avalanches, because the size of the snow patch does not control the magnitude of avalanching. This type of snow patch is controlled by seasonal snowfall and by the contributing area of the avalanche zone.

2.2. *Ablation processes*

Ablation processes, which lead to stabilization of snow patch size, can be found in the effects of solar radiation, debris and breaking-off of cornices.

The largest energy source for ablation of snow patches, as for snow and glaciers in general, is solar radiation (*e.g.* Munro and Young, 1982; Paterson, 1994). The intensity of the solar radiation depends on slope, aspect and shadowing by surrounding topography (Arnold *et al.*, 1996). The general effect of slope, aspect and shadowing is reduction in the intensity of incident solar radiation received by the surface of the snow patch (Arnold *et al.*, 1996). The slope of a snow patch, especially one on a north-facing slope, becomes steeper as the ablation proceeds (Glazirin *et al.*, 1993). Therefore, the incident angle of solar radiation to the patch surface becomes smaller, and eventually the patch is shaded by the surrounding topography, such as ridges (Fig. 1-III). This effect depends on the aspect: the magnitude of the effect is greatest on patches on north-facing slopes and is less patches on east- and west-facing slopes, and there is almost no effect on patches on south-facing slopes. The effect of shadowing of the snow patch surface by the surrounding topography on short-wave radiation is also important, due to the enclosed nature of a basin (Arnold *et al.*, 1996). A snow patch that outgrows the area shaded from the sun is ablated more. When the ablation proceeds and the snow patch becomes smaller, the possibility of receiving solar radiation is less because the initially frequently-exposed area of the patch surface to solar radiation disappears. Then the intensity of ablation becomes smaller due to the less exposure to solar radiation. This is one of the stabilizing processes of ablation. Like the effect of incident solar radiation stated above, this effect can be seen more clearly for snow patches on north-facing slopes than for snow patches on south-facing slopes.

Another stabilizing mechanism of ablation can be seen when the redistribution of snow by avalanches as well as snowdrift occurs with the transportation of a large amount of splinter material, dust or sand, and these materials are progressively surfaced as thawing proceeds and protect the snow patch from further melting (Fig. 1-IV). This process resembles the effect of debris on debris-covered glaciers. When the thickness of the debris layer or the amount of splinter material, dust or sand is just suitable for ablation, it enhances melting. However, if the layer of debris is very thin or the amount of materials is very small, progressive melting will cause the materials that are present inside the snow patch to surface and the thickness of the debris layer or amount of materials at the surface will soon exceed the thickness suitable for melting, and the surfaced materials will reduce the intensity of melting.

A special type of stabilizing mechanism of ablation can be found on snow cornices formed usually on ridges (Pertsiger, 1984) (Fig. 1-V). Large cornices become perennial snow patches (Pertsiger, 1984). When a cornice grows and becomes larger than a critical size, which is determined by the physical properties of the cornice, mechanical break-off can occur. Mechanical break-off does not occur if the cornice is small. The larger the cornice is, the larger the amount of break-off is. This is one type of stabilizing processes of ablation.

3. Snow patches in Japan

There are no glaciers in Japan, but perennial snow patches exist (Fig. 2). and they have been well studied (See summary papers by Higuchi *et al.*, 1979 and Tsuchiya, 2002.). Data on the three most well-known snow patches in Japan are summarized below.

3.1. *Hisago snow patch*

Hisago snow patch is located on a south-east facing slope at an elevation of about 1700 m a.s.l. in the south-eastern part of Daisetsu Mountains, Hokkaido (Fig. 2). This patch is formed due to the accumulation of drifting snow on the lee side of a ridge in winter. The patch starts to melt in April, and the melting ends at the beginning of October (Kodama and Takeuchi, 1993). The mean area and approximate depth at the end of the ablation period (end of September) are 8.5×10^3 m^2 and 7 m, respectively. Yamaguchi *et al.* (1998) estimated the annual mass balances since 1890 based on correlations of mass balance with summer temperature and winter precipitation. An ice body was found at the base of the snow patch (Kawa-

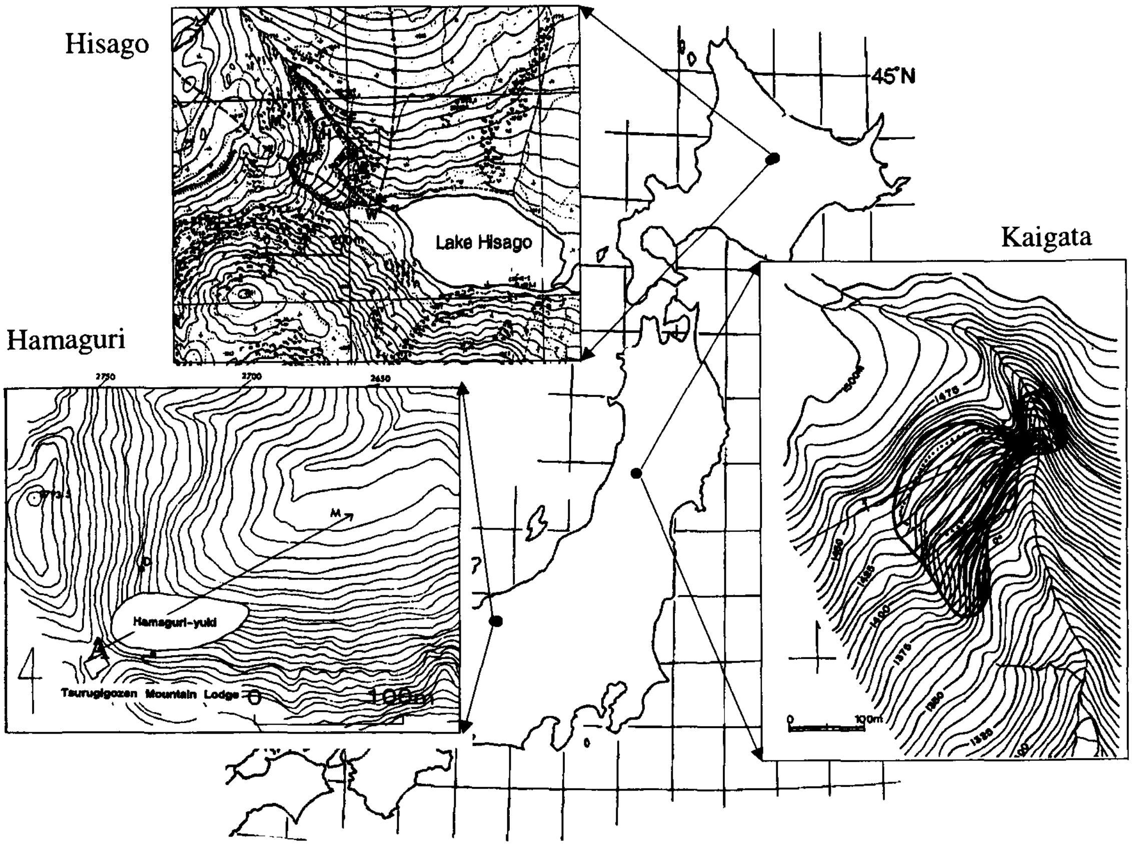

Fig. 2. Map of the snow patches analyzed.

shima, 1997; Kawashima *et al.*, 1993) and the existence of this ice body suggests a more glacier-like character of the snow patch than was previously thought.

The thickness of the snow patch at the end of ablation period were measured over a period of seven years, from 1991 to 1997. The surveys were carried out on various dates from the end of September to the beginning of October depending on logistical conditions, but the difference in survey dates considered not to have greatly influenced the size and depth of the snow patch, because the mean daily air temperature at the patch was near or below 0 ℃. Data was collected along a transect, but only data from the thickest central part of the patch were used because of yearly change in snow patch size. The average density of the patch is about 650 kgm^{-3} (Kodama and Takeuchi, 1993). Consequently, the average annual specific mass balance, b, is calculated to be $650dh$ $kgm^{-2}a^{-1}$, where dh is the annual thickness change. Summer ablation is calculated using the summer mean air temperature from the low-land Asahikawa station (Kodama and Takeuchi, 1993):

$$a = 15.3(7.7T_p + 10.6) \tag{1}$$

where a (kgm^{-2}) is the annual specific ablation and T_p (℃)is the summer (from May to September) mean air temperature at the snow patch estimated from the low-land Asahikawa station and a lapse rate. T_p is calculated by

$$T_p(Z_p) = T_0(Z_0) + \gamma(Z_p - Z_0) \tag{2}$$

where Z_p ($=1700$ m) is the elevation of the snow patch, Z_0 ($=110$ m) is the elevation of the Asahikawa station and γ (-6.5×10^3 ℃m^{-1}) is the mean lapse rate. The annual specific accumulation, c, was calculated from the difference between the measured balance and calculated ablation (Eq. 1) and the results are summarized in Table 2.

Table 2. Mass balance of Hisago snow patch. b: annual mass balance, Sb: accumulated mass balance, $T_p(Z_p)$: summer mean air temperature at the patch, a: annual ablation, c: annual accumulation.

Year	b $\times 10$ kg $m^{-2}a^{-1}$	Sb $\times 10$ kg m^{-2}	$T_p(Z_p)$ ℃	a $\times 10$ kg $m^{-2}a^{-1}$	c $\times 10$ kg $m^{-2}a^{-1}$
1991	–	0	–	–	–
1992	242	242	6.0	872	1114
1993	420	662	5.8	848	1268
1994	−411	251	8.2	1134	723
1995	−53	198	6.9	971	918
1996	162	360	6.0	872	1034
1997	−71	289	6.5	924	853

3.2. Hamaguri snow patch

Hamaguri snow patch is located on a northeast-facing slope at an elevation of about 2730 a.s.l. between Mt. Tsurugi and Mt. Tateyama in the Northern Japan Alps (Fig.2). This patch is formed due to the accumulation of drifting snow at the NNE side of a pass (A in Fig.2). The patch starts to melt in May, and the melting ends when snow starts to fall in October. This patch was surveyed over a period of 25 years, from 1967 to 1991 (Ohata *et al.*, 1993). The mean area and approximate depth at the end of ablation season (end of September) are 7×10^3 m^2 and 20 m, respectively (Ohata *et al.*, 1993). The snow patch was surveyed twice a year in 23 of the 25 years, in spring at the end of the period of accumulation and in autumn at the end of the period of ablation, providing measured seasonal balance data.

The data used here are data on snow patch depth distribution along a transect line from a base point on the pass (A in Fig.2) in a direction 60 degrees east from north. The surface altitude was measured and the depth was calculated by subtracting the basal surface altitude. The basal topography was mapped in 1980 and 1990 years, when the snow patch was quite small (Ohata *et al.*, 1993). Only the central part of the transect line (between the horizontal distances of 60 m and 100 m from the base point A), where snow existed both in spring and autumn, was taken for calculation. Unlike in the analysis of data for Hisago snow patch, data on depth change of the snow patch were used in this analysis (Table 3). In Table 3, *Hs* is the mean depth of the central part of the snow patch profile in spring, and *Ha* is the same value in autumn. Accumulation, *c*, is the difference between the depth in spring and that in autumn of the previous year, and ablation, *a*, is the difference between the depth in spring and that in autumn of the same year.

3.3. Kaigata snow patch

The Kaigata snow patch is located on a southeast-facing slope at an elevation of about 1400 m a.s.l. on Mt. Chokai in the northeastern part of Honshu, the main island of Japan (Fig.2). This patch is also a drifting snow type. The patch starts to melt in April, and the melting ends when snow starts to fall in November. This patch has been surveyed since 1972 (Tsuchiya, 1999). The mean area and approximate depth at the end of the ablation period (middle of October) are 1.2×10^4 m^2 and 8 m, respectively (Tsuchiya, 2002). Tsuchiya (2001) found an ice body at its bottom, observed the snow patch's movement and therefore named this snow patch "Glacieret." The snow patch completely disappeared several times (1990, 1995, 1998). Tsuchiya (2002) reported that the sizes of two other perennial snow patches, located higher on the same mountain, fluctuated similarly but

Table 3. Mass balance components of Hamaguri snow patch. *Hs* is the mean depth of the central part of the snow patch profile in spring, and *Ha* is the same value in autumn. Accumulation, *c*, is the difference between the depth in spring and that in autumn of the previous year, and ablation, *a*, is the difference between the depth in spring and that in autumn of the same year.

Year	*Hs* m	*Ha* m	*c* ma^{-1}	*a* ma^{-1}
1967	20.7	4.2	-	16.5
1968	21.2	6.1	17.0	15.1
1969	19.0	2.7	12.9	16.3
1970	18.0	-	15.3	-
1971	17.7	0.8	-	16.9
1972	21.5	1.5	20.7	20.0
1973	18.2	4.2	16.7	14.0
1974	18.0	5.0	13.8	13.0
1975	22.6	5.6	17.6	17.0
1976	19.3	2.1	13.7	17.2
1977	17.8	1.4	15.7	16.4
1978	20.5	4.8	19.1	15.7
1979	19.1	1.9	14.3	17.2
1980	12.2	1.5	10.3	10.7
1981	22.7	5.6	21.2	17.1
1982	19.4	5.6	13.8	13.8
1983	17.7	6.2	12.1	11.5
1984	22.7	9.9	16.5	12.8
1985	17.3	0.9	7.4	16.4
1986	20.7	5.3	19.8	15.4
1987	18.1	-	12.8	-
1988	13.1	1.7	-	11.4
1989	20.0	-	18.3	-
1990	18.0	1.4	-	16.6
1991	16.5	0.8	15.1	15.7

that those patches never disappeared. This finding indicates that Kaigata snow patch is quite near the lower limit for its existence.

Both the area and maximum depth of Kaigata snow patch were measured at the end of the ablation period each year from 1972 to 1983 (Tsuchiya, 1999). From 1984 to 2001, only the area was measured by *in situ* surveys or estimated using satellite images and pictures taken from an aircraft and on the ground at a fixed point (Tsuchiya, 2002). The maximum snow water equivalent, *Smax*, at the end of the ablation period from 1972 to 1983 was calculated as the product of the maximum depth, *Hmax*, and mean snow patch density (800 kgm^{-3}) (Tsuchiya, 1999). We tried to extend this data set, *Smax*, up to 2001 by correlating it with the snow patch area, *A* (Fig. 3). The regression line can be expressed as follows:

$$Smax = 4.06 \times 10^{-4} A. \quad (3)$$

The correlation coefficient is 0.98, and the p- value of the slope of the regression line is less than 0.001, indicating the positive correlation is significant with a significance level of 95%. The p-value indicates the provability that denies the existence of correlation in the two variables. *Smax* was calculated for the period from 1984 to 2001 using Eq. 3, and results are summarized in Table 4. Mass balance was calculated by the same method as that used in the case of Hisago snow patch. The annual mass balance, *b*, was calculated as the difference from *Smax* of the previous year. Ablation, *a*, was calculated using Eqs. 1 and 2, and accumulation, *c*, was calculated as $c = b - a$. Mean summer air temperature at the snow patch, $T_p(Z_p)$, was extrapolated from data obtained from a meteorological station in Sakata located 25 km away at an elevation of 0 m a.s.l.

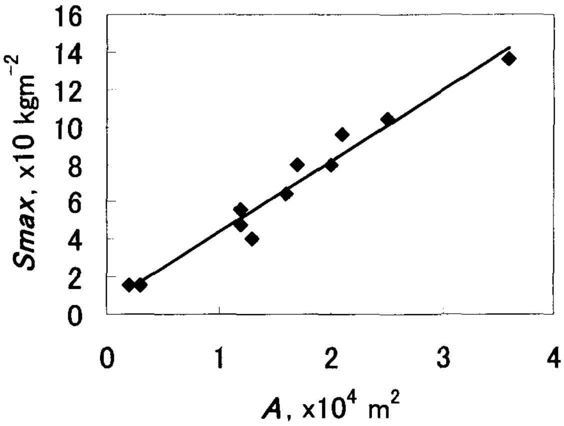

Fig. 3. Dependence of the maximum snow water equivalent of Kaigata snow patch (*Smax*) on its area (*A*).

Table 4. Mass balance components of Kaigata snow patch. *b*: annual mass balance, *Smax*: maximum snow water equivalent at the beginning of the accumulation period, $T_p(Z_p)$: summer mean air temperature at the patch, *a*: annual ablation, *c*: annual accumulation.

Year	b $\times 10\ kgm^{-2}a^{-1}$	*Smax* m	$T_p(Z_p)$ ℃	a $\times 10\ kgm^{-2}a^{-1}$	c $\times 10\ kgm^{-2}a^{-1}$
1972/1973	4.0	1.6	12.08	15.9	19.9
1973/1974	8.0	5.6	11.48	15.1	23.1
1974/1975	−5.6	13.6	12.12	15.9	10.3
1975/1976	−4.0	8.0	10.56	14.1	10.1
1976/1977	4.0	4.0	11.30	14.9	18.9
1977/1978	−3.2	8.0	12.54	16.4	13.2
1978/1979	−3.2	4.8	11.70	15.4	12.2
1979/1980	4.8	1.6	11.02	14.6	19.4
1980/1981	3.2	6.4	10.86	14.4	17.6
1981/1982	0.8	9.6	11.46	15.1	15.9
1982/1983	−5.6	10.4	11.66	15.4	9.8
1983/1984	4.1	4.8	12.58	16.4	20.6
1984/1985	−3.2	8.9	12.62	16.5	13.2
1985/1986	1.6	5.7	11.50	15.2	16.8
1986/1987	−4.5	7.3	12.40	16.2	11.8
1987/1988	−2.4	2.8	11.74	15.5	13.0
1988/1989	−0.4	0.4	12.28	16.1	15.7
1989/1990	0	0	13.00	16.9	16.9
1990/1991	0	0	12.28	16.1	16.1
1991/1992	0	0	11.66	15.4	15.4
1992/1993	3.7	0	10.60	14.1	17.8
1993/1994	4.5	3.7	13.58	17.6	22.1
1994/1995	−8.1	8.1	11.96	15.7	7.6
1995/1996	16.2	0	11.50	15.2	31.4
1996/1997	−6.9	16.2	12.22	16.0	9.1
1997/1998	−9.3	9.3	12.76	16.7	7.3
1998/1999	2.4	0	13.38	17.4	19.8
1999/2000	0.8	2.4	13.44	17.4	18.3
2000/2001	−1.2	3.2	12.72	16.6	15.4

4. Stabilizing feedbacks found in snow patches in Japan

4.1. *Hisago snow patch*

In Fig.4, annual accumulation, c, is plotted against cumulative specific mass balance, Sb, of the preceding autumn, which is correlated well with snow patch size (not shown). The correlation coefficient of the two variables is -0.75. The slope and the goodness-of-fit of the regression line are -0.67 and 0.56, respectively. Since the p-value for the slope of the regression line is 0.087, the negative correlation of the two variables is statistically significant with significance level of 10%. This inverse relation indicates that annual specific accumulation becomes smaller as the snow patch becomes larger, as predicted from the results obtained by Glazirin (1985).

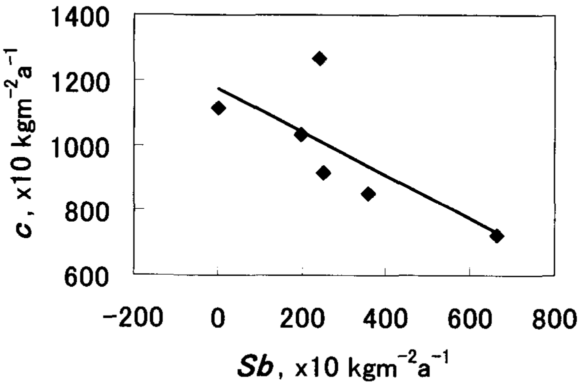

Fig. 4. Dependence of the specific snow accumulation of Hisago snow patch (c) on its area in the preceding autumn (A).

4.2. *Hamaguri snow patch*

Dependence of accumulation, c, on mean snow patch depth, Ha, in the previous autumn for Hamaguri snow patch is shown in Fig. 5. Since no description of snow density of the patch was found in reports on Hamaguri snow patch, depth of the snow patch instead of snow water equivalent was used for analysis. The mean snow patch depth of the selected part of the transect line is an indicator of snow patch size. Again, the greater the snow patch depth in autumn (hence larger snow patch) was, the smaller was the accumulation in the following winter. The correlation coefficient of the two variables is -0.71, with the goodness-of-fit of 0.50. Since the p-value for the slope of the regression line is less than 0.001 with significance level of 5%, the negative correlation of the two variables is statistically significant.

Since seasonal mass balance values for this snow patch are available, we were able to examine the dependence of ablation on snow patch size in spring. The relationship between summer ablation and snow patch depth in spring is shown in Fig. 6. The correlation coefficient of the two variables is 0.55, with the goodness-of-fit of 0.30. Since the p-value for the slope of the regression line is less than 0.01 with significance level of 5%, the correlation of the two variables is statistically significant. It can be seen that the larger the snow patch depths, the greater is the summer ablation.

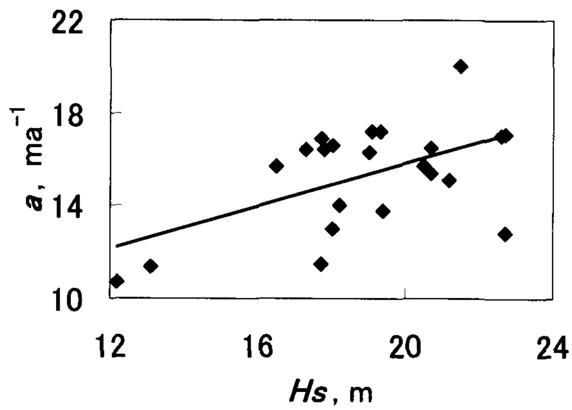

Fig. 6. Dependence of the snow ablation of Hamaguri snow patch (a) on the snow patch depth in spring (Hs).

4.3. *Kaigata snow patch*

The relation between winter accumulation and snow patch "size" (Smax) in the previous autumn for Kaigata snow patch is shown in Fig. 7. Like the other

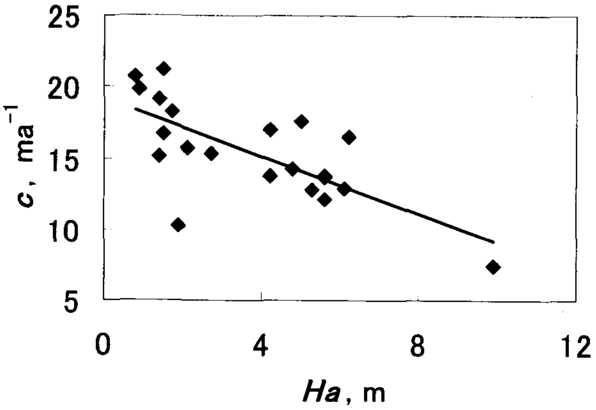

Fig. 5. Dependence of the snow accumulation of Hamaguri snow patch (c) on the mean snow patch depth in the preceding autumn (Ha).

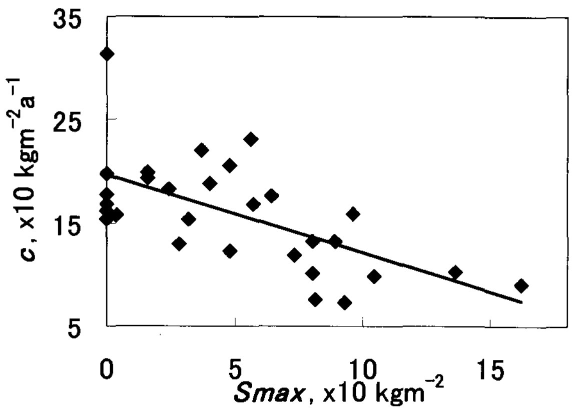

Fig. 7. Dependence of the snow accumulation of Kaigata snow patch (c) on the maximum snow water equivalent in autumn ($Smax$).

snow patches, the greater the "size" is, the smaller is the accumulation. The correlation coefficient of the two variables is -0.63, with the goodness-of-fit of 0.40. The p-value of the slope of regression line is less than 0.001 with significance level of 5%.

5. Summary and future studies

Analysis of data on snow patches in Japan confirmed that there is a stabilizing effect on snow patch size. When the size of a snow patch is large (small) in autumn, snow accumulation in the following winter is small (large). The effect of size on ablation rate is less clear, but the data suggest that ablation is greater for larger snow patches. The specific causal factors controlling the change in accumulation and ablation as the snow patch size changes are unknown. These factors should be examined in future works in order to develop predictive models of snow patch changes with climate.

Snow patches in Japan might be the remnants of past glacial conditions, and their changes are important indicators of climatic variations. Whether continued global warming will overcome the local stabilizing effects, which we have found, is unclear. Global warming can bring more winter rainfall and less snowfall. Continued monitoring of these perennial snow patches is critical for maintaining our long-term record of these features. The data record would be greatly enhanced by twice-yearly measurements so that a seasonal component can be deduced. Snow patches other than snowdrift-fed snow patches analyzed here, such as those that are fed by avalanches and those located at higher and lower altitudes, should also be included.

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