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METEOROLOGICAL AND SNOW CONDITIONS IN THE MOUNTAINOUS AREAS OF JAPAN

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1. INTRODUCTION

On the two largest islands of Japan, Honshu and Hokkaido, located on the east side of the Eurasian continent, the areas facing the Sea of Japan have some of the world’s deepest seasonal snowpacks. In winter, strong northwesterly monsoons blow from Siberia to the islands of Japan. The monsoons, collecting 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.

The mountainous areas are located at low latitudes and in a warm temperature zone as well, thus, even slight climate changes are likely to affect their snowy environments. Moreover, because meltwater from snow is a valuable water resource for Japan, it is very important to know the fluctuation in the mass of snow cover in the country’s mountainous areas. Until recently, however, there were few continuously operating meteorological sites in the Japanese mountains due to the severe conditions.

About 15 years ago, the National Research Institute for Earth Science and Disaster Prevention (NIED) constructed a Snow and Weather observation Network (SW-Net) in mountainous areas of Japan in order to measure meteorological and snow conditions (Nakamura et al., 1997; Shimizu and Abe, 2001). The primary aims of SW-Net are to obtain basic information on meteorological conditions and to determine the sensitivity of snowpack properties to climate changes, particularly, to global warming.

Using SW-Net data up to 2005 (The winter season of 2004/2005 is designated as 2005; hereafter, the same rule is applied to describe the winter season), Yamaguchi et al. (2007) discussed the recent fluctuations. In this paper, we show the newest data, including the heavy snowfall winters (2005, 2006) and an anomalous warmer winter (2007), and discuss the fluctuations in snow conditions.

2. OBSERVATION SITES

SW-Net is composed of six mountainous areas with seven sites, and each site in SW-Net is located on a representative mountain of the local region, generally the mountain with the largest snowpack in the region (Fig.1a). Air temperature, snow depth, and snow mass (snow weight) are recorded at all sites. Each SW-Net site is paired with a nearby flatland site for a comparison of both snowy environments. At each flatland site, air temperature, precipitation, and snow depth are recorded (Fig.1a).

In addition to the SW-Net, NIED has another network (C-net) distributed throughout one of the heaviest snowfall regions on Honshu Island (Fig 1-b). The aim of C-net is to investigate, in detail, the altitudinal distribution of snow depth in the local area; thus only snow depth has been measured at each C-net site since 1998. The location and elevation of each site in both Nets are given in Table 1.

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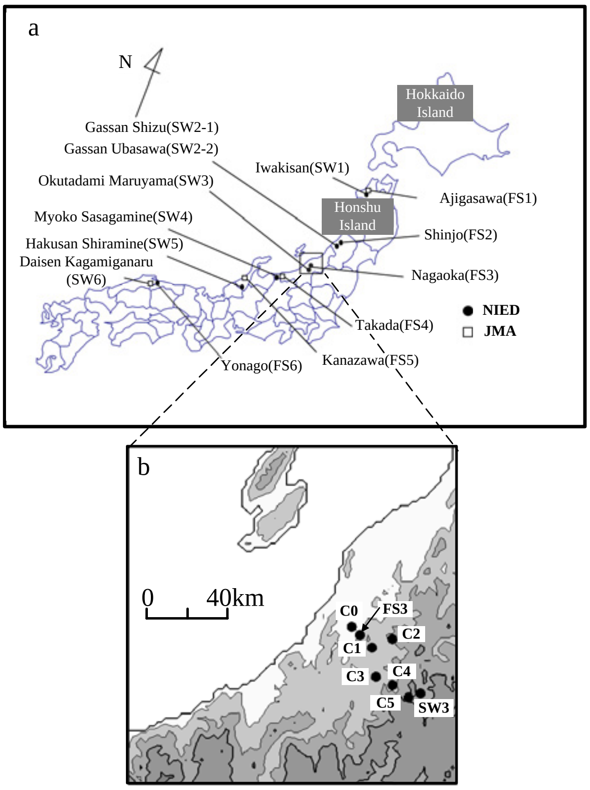

FIG.1. Location of the observation sites.
a: SW-Net. b: C-Net.

TABLE 1. Location of observation sites in SW-Net and C-Net.

SW-Net

Site		Location	Horizontal separation[#] (km)	Altitude (m a.s.l.)	Altitude separation[#] (m)
Pair 1	SW1	40°39´N 140°18´E	17	1238	1198
	FS1*	40°47´N 140°12´E		40	
Pair 2	SW2-1	38°29´N 140°00´E	43	710	583
	(SW2-2)**	(38°30´N 140°00´E)		(1150)	
	FS2	38°47´N 140°19´E		127	
Pair 3	SW3	37°09´N 139°14´E	42	1205	1108
	FS3	37°25´N 138°53´E		97	
Pair 4	SW4	36°52´N 138°05´E	31	1310	1297
	FS4*	36°06´N 138°15´E		13	
Pair 5	SW5	36°11´N 136°38´E	45	835	829
	FS5*	37°35´N 136°38´E		6	
Pair 6	SW6	35°20´N 133°35´E	17	875	869
	FS6*	35°26´N 133°20´E		6	

[#] Between mountain and flatland site
*Station of the Japan Meteorological Agency.
** SW2-2 was established in 2002

C-Net

Site	Location	Horizontal separation[##] (km)	Altitude (m a.s.l.)	Altitude separation[##] (m)
C0*	37°27´N 138°49´E	7	23	-74
C1	37°22´N 138°57´E	8	423	326
C2	37°24´N 139°05´E	17	510	413
C3	37°13´N 138°14´E	22	110	13
C4	37°11´N 139°04´E	31	293	196
C5	37°11´N 139°04´E	39	769	672

[##] Between each station and FS3
*Station of the Japan Meteorological Agency.

3. RESULTS

3.1 *Variations in maximum snow depth in SW-Net*

The variations in maximum snow depth at each SW-Net site are shown in Fig. 2. The maximum snow depth shown in Fig. 2 was 771 cm at SW2-2 in 2003. Data have been collected at SW2-2 since then, and the 2003 conditions do not seem to be very different from those in other years. In fact, the maximum snow depth at SW2-2 has been more than 700 cm in four of the five winters during which measurements have been taken. Therefore, in the mountainous areas around SW2-2, the snow depth must normally reach 700 cm accumulated by snowfall.

The large trends of interannual fluctuation in maximum snow depth at each site are similar in that they have two peaks: one in 1996 and the other in 2000. In addition, they have troughs in 1998 and 2007. Although a large trend of interannual fluctuation was observed, no notable reduction of snow depth was recognized.

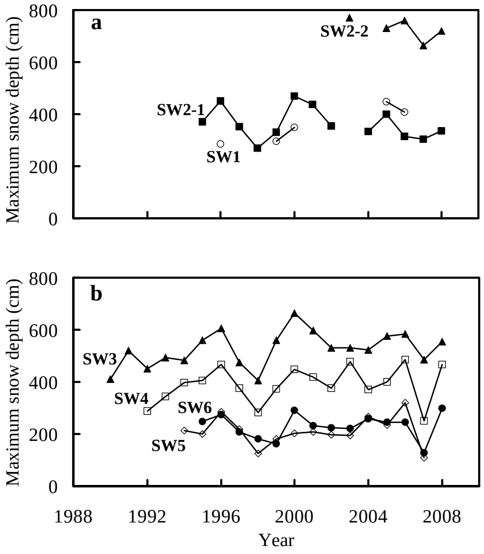

FIG.2. Maximum snow depth at SW-Net.
The top plot shows the northern sites; the bottom plot shows the southern sites.

A detailed examination of the trends of interannual fluctuation at each site reveals some differences. For example, SW4 and SW5 had conspicuous peaks in 2006, while other sites had no such peaks. Moreover, even sites in the same region (SW2-1 and SW2-2) sometimes show different trends. For example, the maximum snow depth in 2006 was slightly greater than that in 2005 at SW2-2, while SW2-1 show the opposite trend. This result is very interesting, but data sets pairing SW2-1 with SW2-2 do not yield sufficient numbers for detailed analyses.

3.2 *Variations in mean winter air temperature in SW-Net*

Figure 3a and 3b show the variations in the mean winter air temperature at each site in SW-Net. Here, we define the winter season as the period from December to March. The large trends of interannual fluctuation in the mean winter air temperature at each site shown in Fig. 3b are similar in that there are peaks in 1995, 1998, 2004, and 2007. On the other hand, the trends shown in Fig 3a seem to be somewhat different those shown in Fig. 3b; i.e., the mean winter air temperatures in 2000, as shown in Fig. 3a, were higher than those in 1999, while the opposite trend is shown in Fig 3b. However, this interpretation is open to discussion because the sites represented in Fig. 3a, except for SW2-1, did not yield enough data for the accurate detection of a trend.

The averaged values over 10 winters from 1995 to 2004 are -1.6 (0.6) ˚C at SW2-1, -3.9 (0.6) ˚C at SW3, -3.9 (0.7) ˚C at SW4, -0.1 (0.7) ˚C at SW5, and -0.2 (0.6) ˚C at SW6. Here, each value in parentheses indicates the standard deviation. Although the averaged temperature varies from site to site, no notable increases in mean winter air temperature was recognized at any of the sites.

To investigate the relationship between the interannual fluctuation in maximum snow depth and that in mean winter air temperature, the correlation coefficients were calculated at sites yielding useful data for more than 10 years (Table 2). These results indicate that the interannual fluctuation in maximum snow depth at SW-2 scarcely correlated to the fluctuation in mean winter air temperature, while other sites show good correlations between both fluctuations.

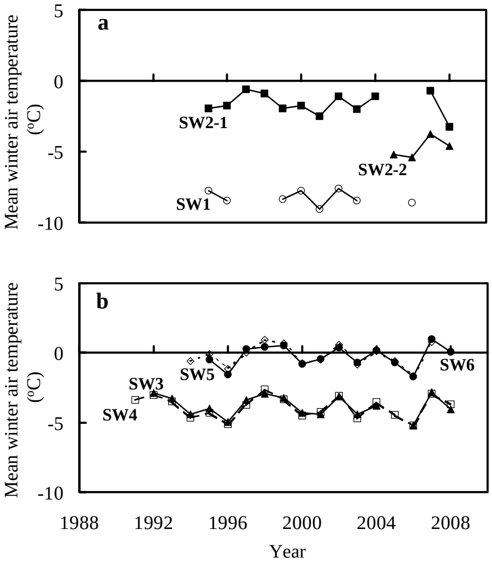

FIG. 3. Mean winter air temperature at SW-Net. The top plot shows the northern sites; the bottom plot shows the southern sites.

TABLE 2. Correlation between maximum snow depth and mean winter air temperature.

Site	Correlation coefficient
SW2-1	-0.38
SW3	-0.68
SW4	-0.84
SW5	-0.78
SW6	-0.64

3.3 *Comparisons of maximum snow depth in mountain and flatland sites*

To better understand the difference between the snowy environments in the mountain and flatland areas, we calculated the correlation coefficients between the maximum snow depths of the mountain sites and the nearby flatland sites. The results are summarized in Table 3. In the analyses, we used only data for 1995 to 2008 in order to compare the same number of samples. Pair 2 in the northern part of Honshu Island has a statistically significant score, while the other sites do not have statistically significant scores. These results suggest that it is difficult to estimate differences between fluctuations in snow cover in mountainous areas and nearby flatland areas in the middle and western parts of Honshu Island.

TABLE 3. Correlations of maximum snow depth between mountain and adjacent flatland sites.

Pair	Correlation coefficient
Pair2	0.67
Pair3	0.50
Pair4	0.43
Pair5	0.36
Pair6	0.36

3.4 *Altitudinal distributions of maximum snow depth in C-Net*

In the previous section, we indicated that interannul fluctuations in the maximum snow depth sometimes differ between mountain sites and nearby flatland sites. To examine this result in detail, we analyzed the data for snow depths measured at several sites (C-Net), each site is located at a different altitude within a small local region (Fig. 1b).

Data for the amount of snowfall at each site are useful for discussing the altitudinal fluctuation in snow depth. However, there are no measured data in C-Net. The interannual fluctuation in snowfall should result from two fluctuations: the amount of winter precipitation and the percentage of snow against winter precipitation. Hence, we adopted two parameters: One is winter precipitation (P) at FS3 for the representative value in this area and the other is the altitude (H_{T1}), the mean winter air temperature of which is 1˚C, for the estimation of the percentage of snow against winter precipitation, because snow should be the dominant form of winter precipitation at the higher altitude. We calculated the lapse rate at each winter using data at FS3 and SW3, and decided H_{T1} with the rapes rate at each winter.

Variations in the maximum snow depth at each site are shown in Fig. 4a and b. Each interannual fluctuation in maximum snow depth seems to be similar, but there are three considerable differences. First, the maximum snow depth was at SW3 in 2000. At other sites, the maximum appeared in 2005, although some sites had a peak in 2000. Second, the maximum snow depths in 2001 were higher than those in 2000 at C0, FS3, and C2, but the other sites show an opposite trend. Third, the maximum snow depths at C0 and SF3 showed an increase in 2003, while the other sites shown opposite trend.

In 2000, H_{T1} was located near the average altitude (373 m a.s.l.), and winter precipitation in 2000 was the greatest in 10 winters (approximately 1.3 times greater than the average year). Therefore, the higher sites, especially SW3, may have had an obvious peak in 2000 due to the large amount of winter precipitation. Moreover, the difference between the maximum snow depth in 1999 and 2000 shows altitudinal dependence; in other words, it increases with altitude. On the other hand, snow depths at the lower sites may not have experienced the strong effect of the fluctuation in winter precipitation due to the normal temperature conditions. In the case of the difference in 2001, H_{T1} was located at a lower altitude than it was in 2000, but the amount of winter precipitation in 2001 was less than that in 2000. Therefore, maximum snow depths at higher sites do not show a strong increase. On the other hand, the lower sites could have had a high percentage of snow against the total amount of winter precipitation because H_{T1} was lower than the average. In the case of the difference in 2003, H_{T1} was located at a lower than the average altitude, and the winter precipitation was below average. Therefore, the amounts of snowfall at higher sites could have been smaller than the average. On the other hand, the lower sites could have had more snowfall due to the lower temperatures.

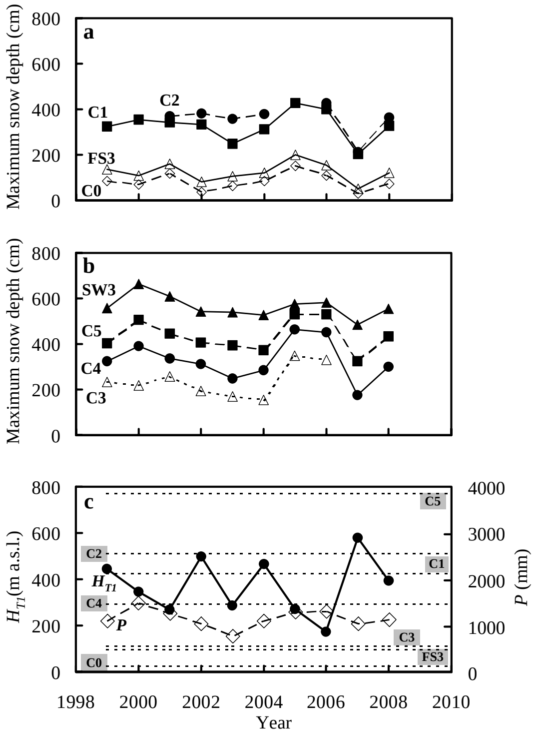

FIG. 4. Maximum snow depth at C-Net and meteorological factors.

a b: Fluctuation in maximum snow depth at each site.

c: Fluctuation in H_{T1} and winter precipitation at FS3.

Black circle indicates H_{T1} where mean winter air temperature is 1 ˚C.

White diamond indicates winter precipitation.

Altitude at each site is shown by a broken line in the figure.

4. DISCUSSION

As we have seen, the mean winter air temperature is a dominant factor in the maximum snow depth in flatland areas, while the maximum snow depth in mountainous areas has a stronger connection with winter precipitation than does mean winter air temperature.

The dependence of the maximum snow depth on winter precipitation should increase with altitude because the fluctuation in mean winter temperature does not have a large influence on the percentage of snow against winter precipitation if the mean winter air temperature decreases.

To examine this hypothesis, we compared two kinds of the correlation coefficients (*Rt* and *Rp*) at each site in C-Net. Here, *Rt* is the correlation coefficient between the maximum snow depth at each site and mean winter air temperature at FS3. *Rp* is that between the maximum snow depth at each site and winter precipitation at FS3.

There is an obvious boundary between C3 and C4; namely, *Rt* is larger than *Rp* in the lower group (C0, FS3, and C3), while the upper group (C4, C1, C5, and SW3) has an opposite trend (Table 4). Therefore, the response of snowy environment in the middle part of Honshu Island to global warming should change from 110 to 290 m a.s.l. because the dominant factor influencing fluctuations in maximum snow depth changes from the mean winter temperature to winter precipitation. To put it another way, the area below the boundary altitude should be more sensitive than the area above the boundary.

TABLE 4. Correlation coefficient between maximum snow depth at each site and mean winter air temperature at FS3 (*Rt*) and that between maximum snow depth at each site and winter precipitation at FS3 (*Rp*).

Site	Altitude (m a.s.l)	Correlation coefficient	
		Rt	*Rp*
C0	23	-0.60	0.44
FS3	97	-0.60	0.43
C3	110	-0.71	0.56
C4	293	-0.56	0.78
C1	423	-0.40	0.78
C2	510	***	***
C5	769	-0.71	0.76
SW3	1205	-0.38	0.82

*** Insufficient sample population.

5. CONCLUSIONS

We collected and analyzed more than 10 years' data on snow depth and air temperature in mountain regions of Japan. In the mountain areas, neither a notable reduction of snow depth nor an increase in mean winter temperature was recognized.

To better understand the correlations between these variables, data from each mountain site was compared to that from a nearby flatland site. The fluctuations in maximum snow depth in the mountainous areas sometimes show different trends from those in flatland areas because the maximum snow depth at mountain area depends more on winter precipitation than on mean winter air temperature, while mean air temperature is the dominant factor influencing fluctuations in the maximum snow depth in flatlands.

In the middle of Honshu Island, the boundary where the dominant factor influencing fluctuations in maximum snow depth changes from the mean winter temperature to winter precipitation is located between 110 m and 293 m a.s.l. Therefore, it is likely that the response of snowy environments to global warming changes at the boundary altitude.

Although the data in this study cover more than 10 years, a longer study period is needed to determine clearly the effects of climate change on mountain snowpack. For this reason, data will continue to be collected at these sites.

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