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Comparison of snowpack on a slope and on flat land focusing on the effects of water infiltration

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ABSTRACT

Water infiltration of snowpack plays an important role in the formation of wet avalanches. Several studies have examined water infiltration of snowpack on flat land. However, because water flow has a directional component parallel to the slope in snowpack on a slope, the effects of water infiltration into snowpack may differ between flat land and slopes, where avalanches are more likely to occur. From January 2012 to April 2012, we simultaneously observed snow pits on flat land and on a slope (40° incline; NE aspect). The observations showed that MF_r (the ratio of the total thickness of the layers composed of melt forms to the thickness of all layers of the snowpack) was, on average, 23% higher for the snowpack on the slope than for the snowpack on flat land, despite the slope's being a shaded side slope. The largest difference between the MF_r of the slope and that of the flat land was observed in early March, when MF_r was 99% at the slope and 46% at the flat-land site. We analyzed these observations using a one-dimensional multi-layer snowpack model proposed by Katsushima et al. (2009). The model included parameterization of the vertical water-channel process in snowpack. Based on the results, to represent the MF_r at each site, the amount of water infiltrating through vertical water channels was estimated at 27.4 mm (2% of the total amount of water provided from the snow surface) for the slope and 797.2 mm (54%) for the flat land. Our results indicate that in wet-snow regions, differences in the water infiltration process can generate notable differences between snowpack on a slope and that on flat land.

1. Introduction

In regions such as the Hokuriku Distinct of Japan, where heavy snow can persist during warm air temperatures, liquid water is supplied to snowpack by both snowmelt and rainfall even in mid-winter. Under these circumstances, the risk of wet-snow avalanches exists throughout the winter period. Infiltration of liquid water into snowpack plays an important role in the formation of wet avalanches through the alteration of snow layer structure, grain type, density, water content, and strength (Baggi and Schweizer, 2009; Conway et al., 1988; Kattelmann, 1985; McClung and Schaerer, 2006; Techel and Pielmeier, 2010; Yamanoi and Endo, 2002). Many studies of water infiltration into snowpack have been conducted for snowpack on flat land (Colbeck, 1979; Jordan, 1983; Wakahama, 1963; Waldner et al., 2004). Furthermore, in recent years, water infiltration models for snowpack that realistically simulate wet snowpack have been developed. Yamaguchi et al. (2010), Hirashima et al. (2010), and Yamaguchi et al. (2012) developed a water transport model based on van Genuchten's (1980) model with parameters obtained from new measurements of the water retention curve for snow of different grain sizes. On the other hand, Katsushima et al. (2009) and Katsushima et al. (2013) tried to represent preferential flow, such as flow in vertical water channels in snowpack, and its effects on layer structure and snow grain type. However, water flow in snowpack on slopes has a directional component parallel to the slope, as pointed out by Colbeck (1978) and Wankiewicz (1979), which suggests that infiltration processes may differ between flat land and slopes, creating different snowpack conditions. For these reasons, it is necessary to clarify differences in water infiltration processes and their effects on snowpack structure and properties between flat land and slopes to develop snowpack models for wet-avalanche forecasting. Furthermore, we believe that such knowledge is useful for the interpretation of meteorological parameters necessary to develop statistical wet-avalanche forecasting models. Thus, we conducted simultaneous snow-pit observations at a flat site and on a slope during a winter season and compared the results, focusing on snow layer structure and snow grain types.

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2. Study site and methods

2.1. Study site

The study was conducted at the Tohkamachi Experimental Station of the Forestry and Forest Products Research Institute in Niigata, Japan (37°08′N, 138°46′E; 200 m a.s.l.). The average maximum annual snow depth at the site is 2 m, and the average temperature is near 0 °C, even during January and February (Yamanoi et al., 2000). Snowmelt and rainfall often occur even during mid-winter and typically create moist or wet snowpack throughout the winter. Study sites established on flat land (FLT) and on a slope (SLP) were selected to avoid typical wind loading and wind erosion (Fig. 1). The slope angle of SLP was 40°, and a NE slope aspect was selected to avoid large differences in snow melting caused by solar radiation.

2.2. Observation methods

2.2.1. Meteorological observations

The following meteorological data were collected automatically every hour at a weather station located at FLT (Fig. 1): precipitation (including both liquid and solid types), snow depth, air temperature, humidity, wind speed, shortwave radiation (upward and downward), net radiation, and heat flux to the soil at ground level. The form of precipitation (rain or snow) was predicted using the method proposed by Yamazaki (1998), which uses the estimated value of the wet-bulb temperature of 1.1 °C as the threshold value.

2.2.2. Snowpack observations

In each snowpack, a snow pit was dug from the snow surface to ground level. Observations of the pit wall were made following the international classification for seasonal snow on the ground (Fierz et al., 2009). Observations were conducted approximately every 20 days on selected dates from January to April 2012 (5 and 25 January, 15 February, 5 and 26 March, and 13 April). In total, 12 pits (FLT: 6, SLP: 6) were dug and observed. To obtain better representativeness for each site (eliminate spatial variability as much as possible), we dug forward approximately 1 m from the pit wall that was last observed to make a snow pit wall with a width of 1.5 m for each measurement and confirmed by the digging that there was no notable spatial variability. We also conducted such an evaluation at three completed walls (one 1.5-m and two 1-m width walls). The items observed and methods used are as follows.

- Snowpack layer structure: the position and thickness of layers were determined by visual means and by touch using the hands or fingers.
- Snow grain type and diameter: determined by using a snow crystal screen, which had three grids of 1, 2, and 3 mm, and a hand loupe (10×).
- Hardness: measured by push gauge (Takeuchi et al., 1998) every 10 cm (or greater as needed to measure all layers).
- Snow temperature: measured with a thermistor thermometer every 10 cm.
- Density: measured with a 100-cm^3 sampler every 10 cm (or greater as needed to measure all layers).
- Water equivalent of total snowpack: measured with a snow sampling tube (38-cm^2 cross section) with enough length to sample all snow layers at once from the surface to ground.

3. Results

Fig. 2 shows the meteorological conditions of the study site from December 2011 to the end of April 2012. The maximum snow depth and total amount of rainfall reached 302 cm and 376.4 mm, respectively. Rainfall events occurred often even during January and February (total rainfall for January and February was 63.1 mm). The average air temperature during the period was 5.6 °C, and it was common for the daily maximum air temperature to exceed 0 °C even during January and February.

The layer structure and snow grain type of each layer of SLP and FLT are shown in Fig. 3, and the change in the melt form (MF) ratio MF_r (%) (the ratio of the total thickness of the layers constituting the MF to the thickness of all the layers of the snowpack) is shown in Fig. 4. MF_r was calculated as follows:

$$MF_r = \frac{\sum_{i=1}^{n} h_{MF_i}}{HS} \times 100, \quad (1)$$

where h_{MF} is the height of each layer constituting the MF, n is the number of layers constituting the MF, and HS is the total snow height of the snowpack.

Figs. 3 and 4 show clear differences in layer structure and dominant grain types. We believe that these differences between SLP and FLT were not related to spatial variability because they were observed with the same tendency in all of our data. Most of the middle and lower parts of the SLP snowpack changed in MFs earlier than those of the FLT snowpack, and some rounded-grain layers persisted in the middle and lower parts of the FLT. Additionally, the MF_r was higher for the SLP snowpack than for the FLT snowpack. The average MF_r values for SLP and FLT were 73% and 50%, respectively. The largest difference in MF ratio between the sites was observed on 5 March, when the MF ratio for SLP was 99%, and that for FLT was 46%. Observations of snowpit walls showed that vestiges of vertical water channels were less common at SLP than at FLT and that the snowpack was more uniformly affected by water at SLP than at FLT (Fig. 5).

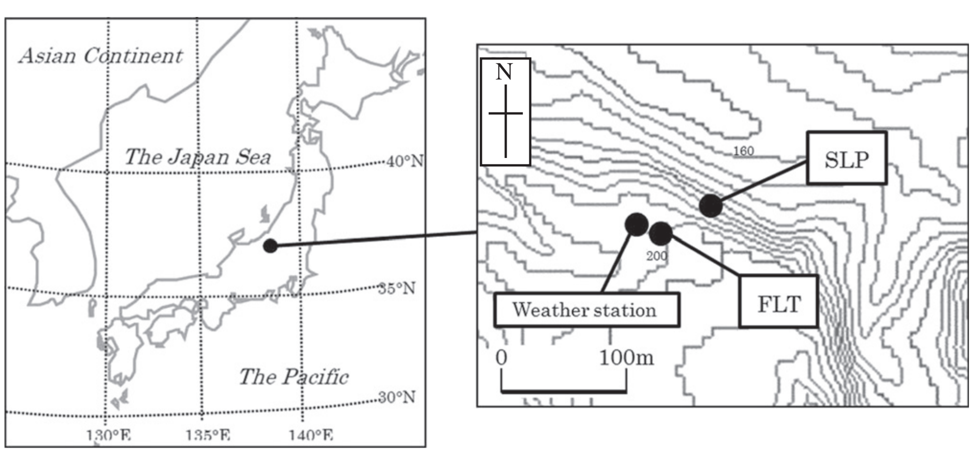

Fig. 1. The study site.