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Application of the snow cover model SNOWPACK to snow avalanche warning in Niseko, Japan

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Abstract

We describe the use of the snow cover model SNOWPACK for avalanche warning in Niseko, Japan. Input data was collected from a newly installed meteorological station at 800 m a.s.l. To verify the model output, snow pit observations were made almost everyday during the winter 2002–2003. Ten dry snow slab avalanches occurred during the observation period. Most of them were released after a heavy storm and had fracture depths of 40–60 cm. Pit observations revealed that the fracture layers in the snowpack consisted of either graupel or stellar precipitation particles without rime (70%) or faceted crystals (30%). Slab layers consisted of precipitation or decomposing and fragmented particles, which indicated that these avalanches occurred soon after the snow deposition. Snow profiles simulated with SNOWPACK roughly agreed with the observed profiles. The model reproduced faceted crystals on a crust that became the weak layer and caused the avalanches on 14–16 February 2003. In addition, air temperature, solar radiation, wind speed, and snow depth in the study area were estimated for grid points with 50 m spacing. This allowed to calculate for each grid point snow properties such as grain type and density as well as the snow stability index SI. The predictions agreed reasonably well with the field observations.

Keywords: Snow avalanche warning; Snow cover simulation; Snow stability evaluation

1. Introduction

There have been eight snow avalanche fatalities for the past 15 years in Niseko, a ski resort in Hokkaido, the northernmost main island of Japan. To reduce the number of avalanche-related accidents, the Japanese Meteorological Agency issues an avalanche warning during winters. However, their method depends only on the air temperature and the estimated storm snow depth. Moreover, the warning covers an area as large as a prefecture (i.e. about

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Fig. 1. The automatic weather station (AWS) in Niseko.

4000 km^2). Although the altitude of the resort's summit is only about 1300 m a.s.l., the snow in the area is completely dry in winter. Local communities as well as ski area managers strongly desire a more precise avalanche danger prediction system. In this paper, we describe the development of an avalanche warning system in the Niseko area. The system involves a numerical snow cover model and collecting snow and meteorological data.

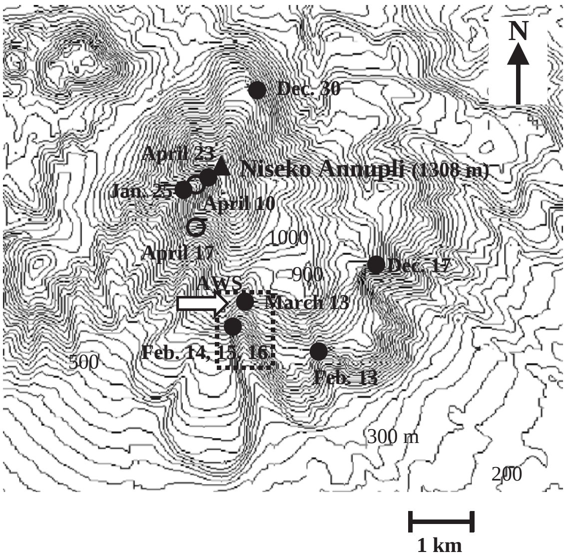

Fig. 2. Locations of avalanche starting zones and the AWS. (●) Dry snow slab avalanches, (○) wet snow full-depth avalanches. Two avalanches released from about the same area on 13 March 2003. White arrow shows AWS position. The dotted rectangle shows the area considered in Figs. 11 and 12.

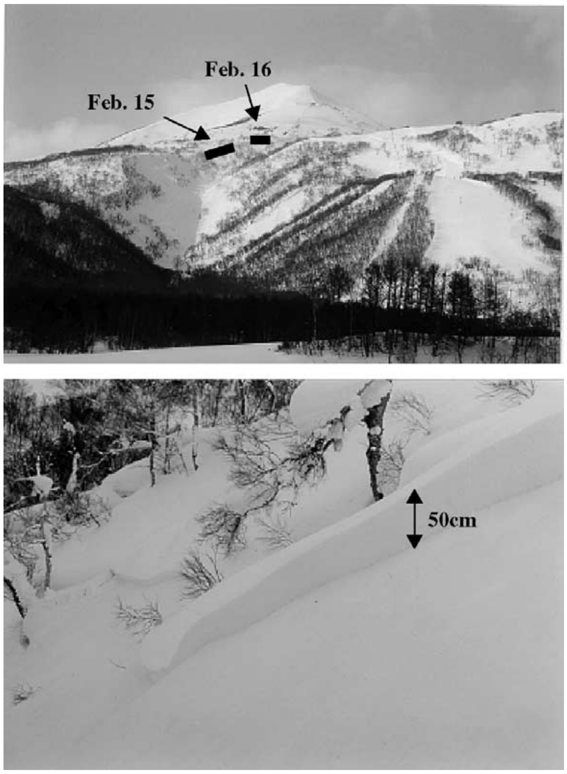

Fig. 3. Snow avalanches on 15 and 16 February 2003. Upper figure indicates fracture lines of two avalanches. The lower figure shows a fracture depth of the 15 February avalanche.

2. Observations

An automatic weather station (AWS) was set up at 800 m a.s.l. in December 2002 (Fig. 1). This station measured air and snow surface temperature, wind speed and direction, shortwave and longwave radiation, and snow depth. The data were recorded every 10 min using a digital logger.

Nearly everyday, we made snow pit observations on avalanche prone slopes. We measured grain shape and size, snow temperature and snow hardness according to ICSSG (Colbeck et al., 1990). Also, a compression test was used to determine the snow stability. This test can identify potentially weak layers or interfaces and thus provides a measure of snowpack stability (Jamieson and Johnston, 1999).

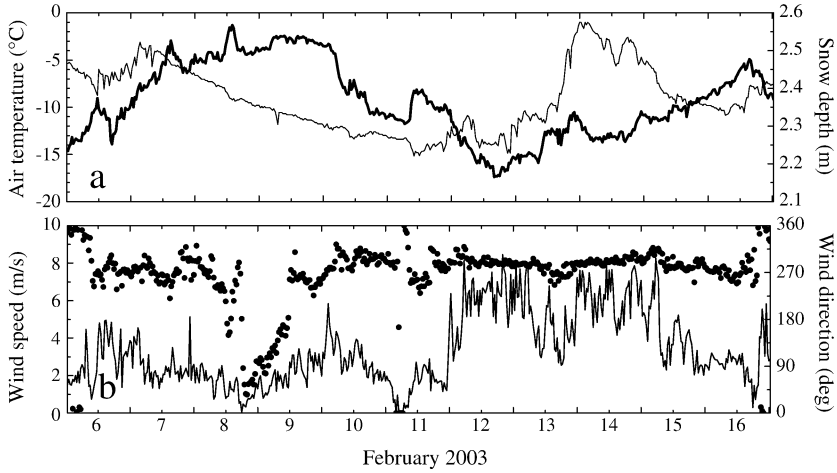

Fig. 4. Weather conditions and snow depth at the AWS from 6 to 17 February 2003. (a) Air temperature (solid line) and snow depth (bold solid line). (b) Wind speed (solid line) and wind direction (circles).

During the observation period of winter 2002–2003, 12 avalanches occurred in the study area. Ten were dry snow slab avalanches and two were wet snow full-depth avalanches. Their starting zones are marked in Fig. 2. From the 10 dry snow slab avalanches 7 were triggered by the dynamic loading of skiers, snowboarders, or snow pit observers.

Fig. 3 shows the location where avalanches occurred on 15 and 16 February 2003. The failure plane (weak layer) was composed of both precipitation particles without rime and partly faceted particles above the crust. The slab thickness was 50 cm. Both avalanches were triggered by the observers during pit observations, and the avalanches traveled about 300 m down towards the valley. The weak layer and the slab were formed by the weather conditions from 6 to 17 February 2003. During 7–10 February 2003, the weather was fine and the air temperature increased gradually to near 0 °C (Fig. 4). A melt-freeze process occurred near the snow surface mainly due to the high solar radiation at daytime and freezing at night. Thus, a crust formed. On 11 February 2003, when a low-pressure system approached, stellar precipitation particles without rime accumulated on the crust under calm conditions. It formed a layer of about 1 cm thickness and with a density of 32 kg/m^3. After the low-pressure had passed by, the atmospheric pattern changed. A strong and cold monsoon brought large amounts of snow, particularly on leeward slopes (more than 50 cm). The first avalanche released naturally on 14 February 2003. On 15 and 16 February, when we walked along the upper edge of the slope, the loading was large enough to release two avalanches. All these avalanches started from slopes that were 35–40° steep and facing southeast.

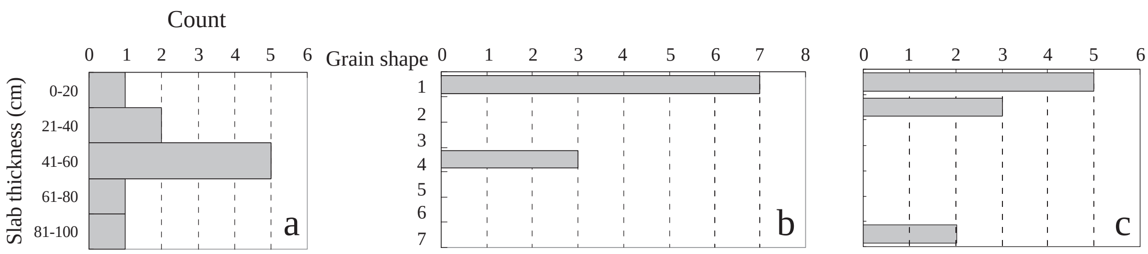

Fig. 5. Snow conditions measured after the release of 10 dry snow slab avalanches. (a) Slab thickness; (b) grain type in the fracture layer; and (c) grain type in the slab layers. (1) Precipitation particles, (2) decomposing and fragmented precipitation particles, (3) rounded grains, (4) faceted crystals, (5) depth hoar, (6) wet grains, and (7) surface hoar crystals.

On 13 March 2003 two dry snow slab avalanches were triggered during the pit observations. A rapid snow temperature increase after the storm, due to a rise in air temperature and strong radiation had presumably increased the deformation in the slab layer leading to increased strain and strain rates at the slab/weak layer interface (Schweizer et al., 2003).

Considering all 10 dry snow slab avalanches, the fracture layers in the snowpack were mostly composed of stellar precipitation particles without rime, whereas faceted crystals were found only in three cases (Fig. 5). Moreover, weak layers or interfaces were formed above a crust in 7 out of 10 avalanches. This type of weak layer formation–facets above crust–was described by Colbeck and Jamieson (2001).

The fracture depth, or slab thickness, was between 40 and 60 cm for most avalanches. The slab layers consisted of precipitation particles, including decomposing particles and fragmented particles. We rarely found rounded grains in the slab layers. This finding indicates that the avalanches occurred fairly soon after a snowfall.

3. Numerical simulation

3.1. Methods

The avalanches in Niseko were mostly slab avalanches that were caused by shear failure and fracture propagation in the snowpack parallel to the slope. Shear failure results when a weak layer with low shear strength fractures due to loading. Numerical simulation can be used to determine whether or not a snowpack has such weak layers and thus can be used to predict avalanche danger. McElwaine et al. (2000) applied the Crocus model, developed by Meteo France for the avalanche warning service in France, to explain an avalanche that occurred on 28 January 1998 in Niseko. Though the model did not predict the weak layer that caused the avalanche, it did predict a different type of weak layer at the correct depth.

In this study, we used the snow cover model SNOWPACK, which was developed at the Swiss Federal Institute for Snow and Avalanche Research. It is a one-dimensional model of the snow cover and has been used in the Swiss Alps to predict snowpack settlement, layering, surface energy exchange, and mass balance (Bartelt and Lehning, 2002; Lehning et al., 2002a,b). Its Lagrangian finite element layout is suited for modeling the layered snow cover, including the settling time, growth through snowfall, erosion through wind, and ablation through melting. Hirashima et al. (2004a) found that this model was useful for the conditions in Niseko. Moreover, after extending the snow metamorphism formulation of the model, it predicted the weak layer that caused the avalanche on 28 January 1998, described by McElwaine et al. (2000).

The meteorological data and a snow profile output with SNOWPACK at a single position give little information on the avalanche probability on slopes and even less for a region. Precise, fine-scale meteorological conditions over the whole study area are required. Local variations in the deposition of snow and redistribution of previously deposited snow are governed by the interaction between topography, vegetation, and wind (Lehning et al., 2000). Wind speed variations over complicated terrain, and in particular, the subsequent erosion of snow from a ridge and deposition in a valley are key factors for determining the avalanche danger in a given area.

Snowdrift modeling over complex terrain is a difficult problem that is still under development (Liston et al., 1993; Pomeroy et al., 1997; Gauer, 2001; Liston and Strum, 1998; Hirashima et al., 2004b). In this study, we used SnowTran3D, which was originally developed by Liston and Strum (1998) for Alaskan tundra. The advantage of the model is its simplicity and speed. The model has the following four steps: (1) snowfall input is assumed to be uniform over the entire study area, (2) calculation of the wind field, (3) calculation of snow transport by saltation and suspension, and (4) calculation of the accumulation and erosion of snow on the surface. The wind speed field was obtained using a digital elevation map with a grid size of 50 m. Variations of wind speed depended on terrain inclination and curvature. For example, the wind speed increased when blowing uphill and decreased when blowing downhill. More specifically, the wind speed u (m/s) at a specific grid point was calculated as the product of a non-dimensional weighting factor W

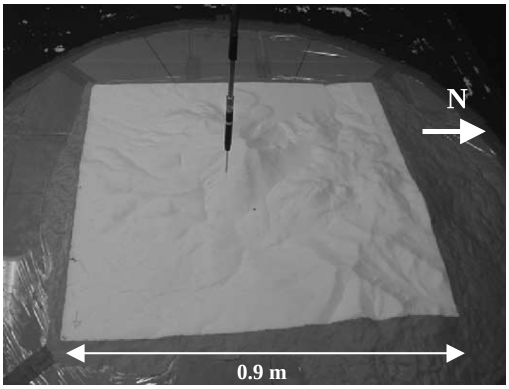

Fig. 6. Terrain model of Niseko with scale of 1:10,000 for the wind tunnel experiments. Working section of the system is 1.5 m × 1.5 m. The wind speed distribution was measured with a hot wire anemometer.

with the wind speed u_{AWS} (m/s) at the AWS. W is a function of inclination Ω_s (deg) and curvature Ω_c:

$$W = 1.0 + \gamma_s \Omega_s + \gamma_c \Omega_c \quad (1)$$

$$u = W u_{AWS} \quad (2)$$

where γ_s and γ_c are constants set equal to 1.0 and 35.0, respectively (Hasholt et al., 2003). Change of wind direction was not considered. Once the wind speed was obtained, we determined the friction velocity u^* at each position and estimated the snow transport by saltation and suspension according to the procedures proposed by Liston and Strum (1998). When the value of u^* at a given grid point was higher than a threshold value, snow was eroded and saltation begun, otherwise snow was deposited.

We used SnowTran3D for a mountainous terrain much rougher than the tundra for which it was developed (Liston and Strum, 1998). Thus, we also did wind-tunnel experiments using a terrain model of the Niseko area on a scale of 1:10,000 (Fig. 6). The experiments were done in a wind tunnel of the Hokkaido Northern Regional Building Research Institute, as shown in Fig. 7. The wind tunnel has a working section of 1.5 m × 1.5 m, and the wind speed distribution over the terrain was measured with a hot wire anemometer.

We also used the wind tunnel to examine how snowdrift develops in the Niseko area and thus to test the numerical simulation. Activated clay was used instead of snow. Although the similarity rule for snow and activated clay has not been established yet, such clay is known to be a useful material to

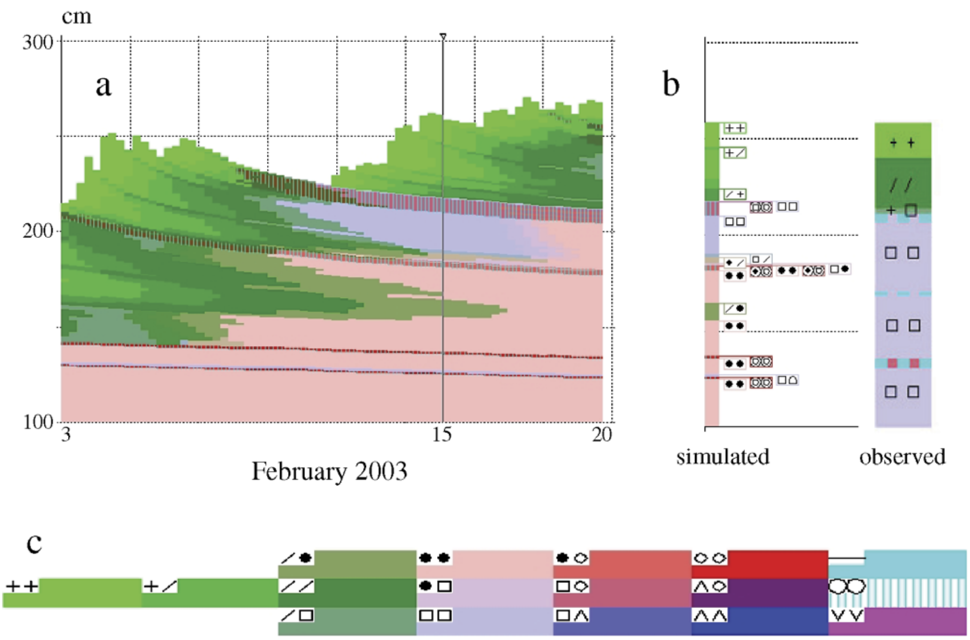

Fig. 7. Simulated and measured snow profiles at Niseko in February 2003. (a) Simulated snow cover structure for 3–20 February; (b) comparison between simulated and observed snow profile on 15 February 2003; and (c) relations between colors and snow types.

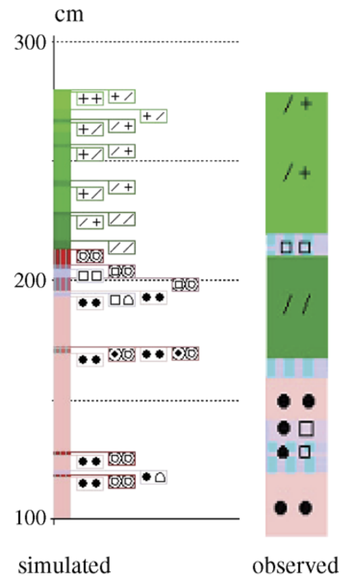

Fig. 8. Simulated and measured snow profiles at Niseko on 13 March 2003.

reproduce snowdrift formation around buildings, roads, and snow fences in a wind tunnel (e.g., Anno, 1984). However, our terrain model (1:10,000) is significantly smaller than typical models for the above building- or fence-scale studies (1:100 to 1:1000). Although reasonable results were obtained qualitatively, further consideration is needed. To verify the experimental results and to better understand the snowdrift process, we are currently analyzing the new snow deposition data obtained from the snow pit observations.

Snow properties, including grain type and density were obtained, by substituting the derived distributions of meteorological data into the SNOWPACK model. Using the slope inclination and the shear strength relations proposed by Jamieson and Johnston (2001),

$$\sigma = 14.5 \times 10^3 \left(\frac{\rho}{\rho_\mathrm{i}}\right)^{1.73} \mathrm{Pa}, \tag{3}$$

for rounded grains and precipitation particles, including decomposing and fragmented precipitation particles, and

$$\sigma = 1.85 \times 10^3 \left(\frac{\rho}{\rho_\mathrm{i}}\right)^{2.11} \mathrm{Pa}, \tag{4}$$

for faceted crystals and depth hoar, we determined the stability index SI. This index is defined as the ratio of snow shear strength to the shear stress exerted by the snow load. Thus, a low index indicates low stability and vice versa.

3.2. Results of numerical simulations

For the cases of 15 and 16 February 2003, we found that the simulated snow profiles roughly agreed with the observed snow profiles (Fig. 7). In particular, the SNOWPACK model reproduced the faceted crystals on the crust at 50 cm, which formed the weak layer that caused three avalanches on 14–16 February 2003.

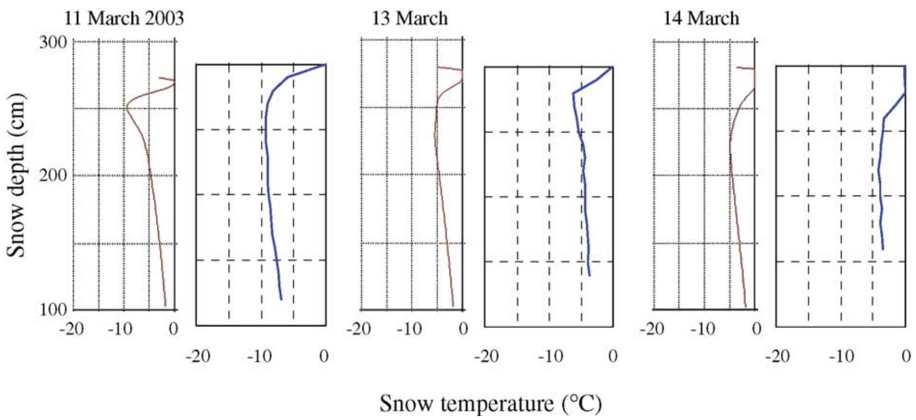

Fig. 9. Simulated (left) and measured (right) snow temperature distributions at Niseko for 11–14 March 2003.

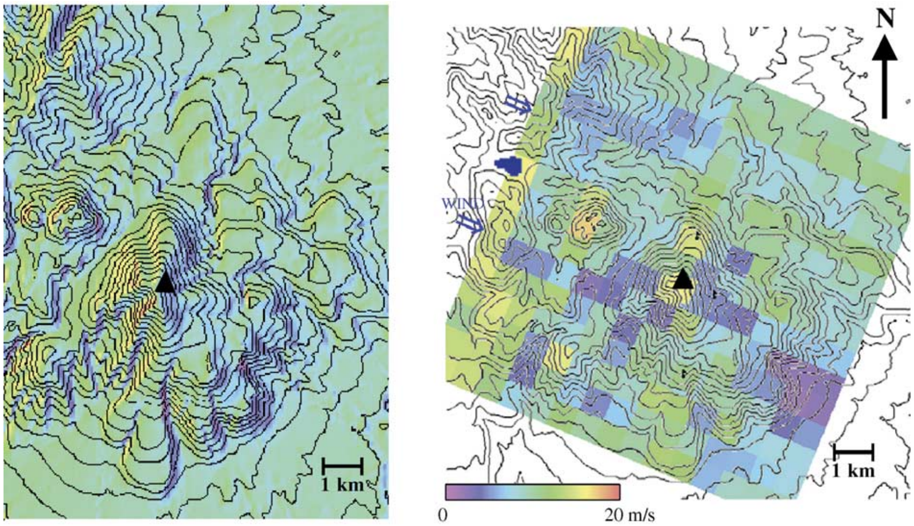

Fig. 10. Wind speed distribution from the wind tunnel experiment (left) and the numerical simulation (right) for a wind speed of 10 m/s from the direction of west–northwest.

Figs. 8 and 9 indicate the comparisons between the observations and the SNOWPACK simulations on 13 March 2003. Calculated snow profile in Fig. 8 showed a 60 cm thick slab composed of precipitation particles and decomposing and fragmented precipitation particles, which roughly agreed with the observation. Further, as shown in Fig. 9, close agreements were found between observed and calculated snow temperature distributions on 11–14 March 2003. As described above, a change in snow temperature was considered as the key contributing factor for the release of two avalanches.

However, as described above, the meteorological data and a snow profile output with SNOWPACK at a single position give little information on the avalanche probability on slopes and even less for a region. Precise, fine-scale meteorological conditions over the whole study area are required.

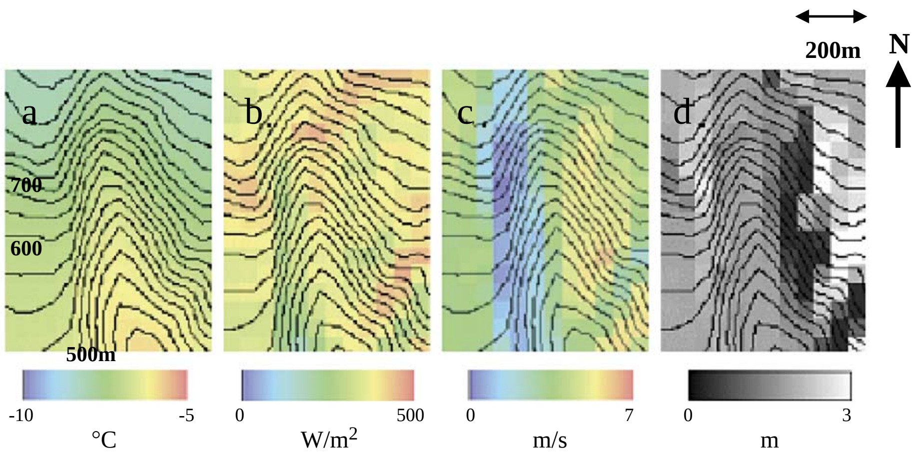

Fig. 11. Distribution of air temperature, solar radiation, wind speed, and snow depth at noon on 10 February. The area is 600 m × 800 m and located in the dotted rectangle in Fig. 2. Terrain is indicated by 25 m contour lines.

Qualitatively, the wind speed distribution from the wind tunnel experiment was consistent with the numerical simulation based on Eqs. (1) and (2). The case when the 10 m/s of the wind blew from the west–northwest is shown in Fig. 10. Quantitative comparisons were beyond our scope because the grid size differed between the model and the experiment (wind-tunnel grid size: 500 m; simulation grid size: 50 m). Nevertheless, both the experiment and the numerical simulation show that the wind speed generally increases on windward slopes of the mountain and conversely, the wind speed decreases on the leeward slopes. Thus, the simulation shows the correct trends.

In addition to the wind speed, we calculated the distributions of other meteorological variables including air temperature and incoming shortwave radiation. The temperatures were obtained assuming a temperature lapse rate of 0.6 °C/100 m and the local shortwave radiation was calculated using a digital elevation map of the area. For noon of 10 February 2003, we show the distributions of wind speed, air temperature, solar radiation, and snow depth in Fig. 11. These plots show only the region around the avalanches of 14–16 February 2003.

By substituting the derived distributions of meteorological data into the SNOWPACK model, the stability index SI was calculated. Fig. 10 shows the distributions of SI from 29 January to 15 February 2003. In general, the stability index decreased day-by-day, and, at the same time, the area of low instability increased. The avalanche danger had a maximum on 15 February 2003, which is nearly consistent with the dates when four snow avalanches occurred. The avalanche starting zones marked in Fig. 2 agree with grid points having a low stability index in Fig. 12. According to the observations at the avalanche trigger point, SI on 15 and 16 February 2003 were 0.5 and 0.8, respectively. Thus, the model gave results consistent with the occurrence of three avalanches on 14–16 February 2003.

4. Conclusions

To develop an avalanche warning system in Niseko, Japan, we set up a meteorological station at 800 m a.s.l. in the winter of 2002–2003. Snow pit observations were also carried out almost everyday. During this winter, 10 dry snow slab avalanches occurred in the area. Pit observations revealed that the weak layers in the snowpack consisted of either graupel or stellar precipitation particles without rime (70%) or showed evidence of faceted growth (30%). The simulated snow profiles from the SNOWPACK model roughly agreed with the observed profiles; in particular, the model reproduced the faceted crystals on the crust that became the weak layer and thus caused the avalanches during 14–16 February 2003. Simulated snow stratigraphy and snow temperature distribution agreed reasonably well with the observation in the middle of March 2003.

To expand the forecasting area to cover the study area, we used data from an AWS and a digital elevation map with a grid size of 50 m to estimate the distributions of air temperature, solar radiation, wind speed, and snow depth in the study area. With

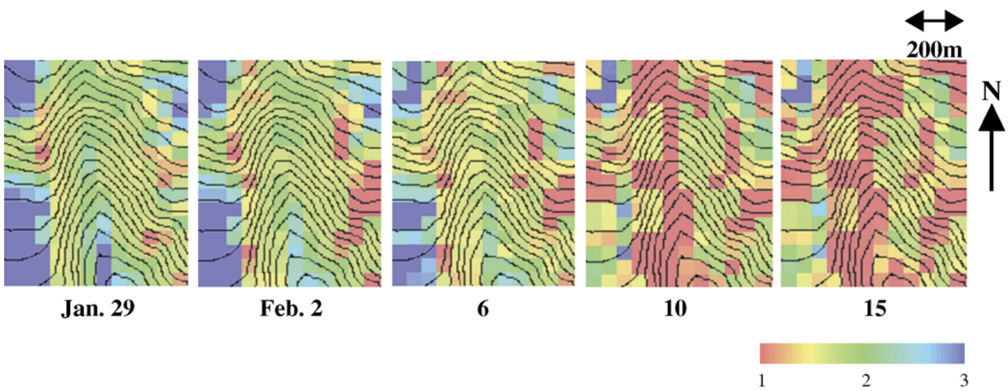

Fig. 12. Calculated SI distribution from 29 January to 15 February 2003. Same area shown as in Fig. 11. Contour lines are 25 m apart.

these estimated distributions the model calculated snow properties such as grain type and density, and finally the snow stability index SI. The stability predictions for three avalanches, which occurred in the dotted rectangle area in Figs. 2, 9 and 10 on 14–16 February 2003, agreed reasonably well with the field observations.

However, a number of improvements are still necessary in each of the processes. Recently, Lehning et al. (2004) improved the SNOWPACK model by considering bond size when calculating the snow stability index and by introducing a deformation instability index. In addition to the meteorological and snow pit observations, we will use the system operationally. The goal is to increase the accuracy so that the model can become part of the Niseki Resort operations.

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