Development of Snow Avalanche Forecasting System in Japan

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Abstract

We describe the development of an avalanche warning system in Japan. Study area was set on southern part of Niigata prefecture, where we had huge amount of snow in winter 2005–2006 and the snow depth exceeded 4 m in February. The snow cover model SNOWPACK, which was developed at the Swiss Federal Institute for Snow and Avalanche Research, was used. Input data was collected from newly installed meteorological stations, as well as the Automated Meteorological Data Acquisition System (AMeDAS) by Japan Meteorological Agency. Snow depth distributions in the study area were measured directly by the aircraft-borne laser profilers. To verify the model output, snow pit observations were made every week. In addition, air temperature, solar radiation, wind speed, and snow depth in the study area were estimated for grid points with 10 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 and the avalanche release map obtained by the aerial photograph.

Keywords: Snow avalanche forecasting, SNOWPACK, Aircraft-borne laser profilers, Aerial photograph

Introduction

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 4,000 km^2). Local communities as well as road and 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 Japan. The system involves a numerical snow cover model and collecting snow and meteorological data.

Observations

We have set our study area in southern part of Niigata prefecture, where we had huge amount of snow in winter 2005–2006 and the snow depth exceeded 4m in February. Although the avalanche research was carried out at two districts of Akiyamago (35 km^2) and Yuzawa (22 km^2), this paper introduces the former results only. Figure 1 shows the change in air temperature and snow depth at Tsunan AMeDAS station in winter 2005–2006.

This automatic weather station is located at the northern end of Akiyamago. Comparing to the average, the temperature was low and the snow depth was extremely high in particular from December to January. Snow depth amounted more than 4 m in February. A mountain pass of national highway 405 which goes through from north to south in this area was closed for long period due to the snow avalanche danger. Two automatic weather stations (AWS) were additionally set up at Sakasamaki (544 m a.s.l.) and Tochikawa (995m a.s.l.) as shown in Figs. 2 and 3. These station measured air temperature, wind speed and direction, and snow depth. The data were recorded every 10 min using a digital logger. In addition to the measurements at the

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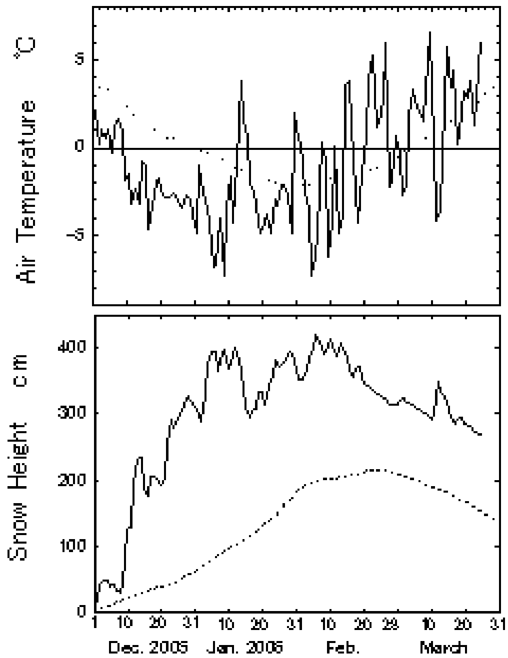

Fig. 1. Air temperature and snow height at Tsunan AMeDAS station. Solid line indicates the data in winter 2005–2006 and dotted line the average (Air temp. 1979–2000 and Snow height 1989–2000).

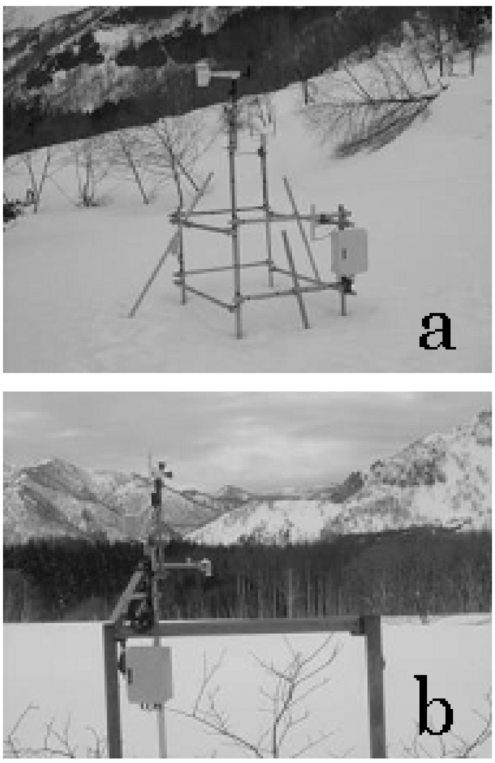

Fig. 2. Two automatic weather stations (AWS) at Sakasamaki (a) and Tochikawa (b).

fixed points, observations with a vehicle were carried out. Along the road of 15 km distance, air temperature and the incoming short and long wave radiations are obtained.

Nearly every week, we made snow pit observations. Grain shape and size, snow temperature and snow density were measured according to ICSSG (Colbeck et al., 1990). Also, a shear frame was occasionally used

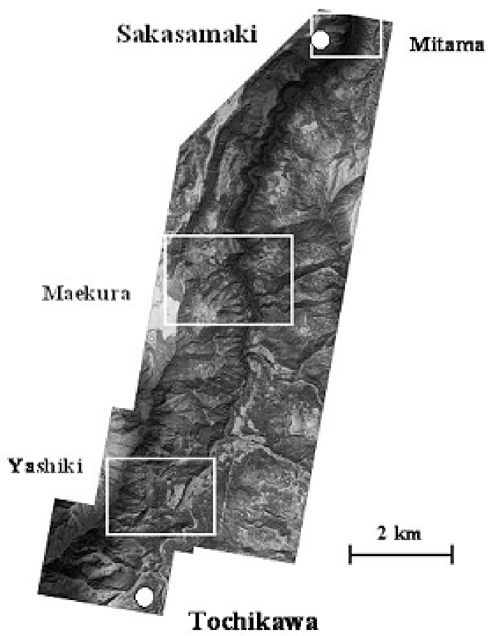

Fig. 3. Surface elevations in Akiyamago shown as a shaded map. Observations were made by aircraft-borne laser profilers on 25 February 2006.

to identify potentially weak layers or interfaces and thus provides a measure of snowpack stability (Jamieson and Johnston, 1999).

Aircraft-borne laser profilers provided direct measurements of the snow surface elevations as shown in Fig. 3. The accuracies of the measurements are known to be 30 cm in the location and 15 cm in the altitude. However, since no observations with the laser profiler were carried out at no snow seasons so far, the snow depth were obtained calculating the altitude difference with the digital elevation map of 10 m space resolution. Thus, the accuracy was much less than the value above described.

On 4 March 2006 the aerial photograph was taken over the same area and the avalanche release map was drawn. Roughly 260 avalanches were observed to occur in the study area. Angle of the inclination at the starting zone indicated the normal distribution of 35 deg. in average. Although the runout distance was less than 400 m for most avalanches, one was large enough to flow along the avalanche track for nearly 2 km.

Numerical simulation

Methods

Avalanches were caused by shear failure and fracture propagation in the snowpack parallel to the slope in general. Shear failure breaks out 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 and others, 2002a, 2002b). 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. (2004) and Nishimura et al. (2005) found that this model was useful for the conditions in Niseko, a ski resort in Hokkaido. 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, 1998; Liston and Sturm, 1998). Nishimura et al. (2005) used SnowTran3D, which was originally developed by Liston and Sturm (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. 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 Sturm (1998). Nishimura et al. (2005) also did wind-tunnel experiments using a terrain model on a scale of 1:10'000. Although reasonable results were obtained qualitatively, further consideration is needed.

Thus, in this study we utilized the snow depth distributions calculated with the aircraft-borne laser profiler measurements on 25 February 2006. Change in the snow depth from December 2005 to March 2006 was estimated on referring the amount of the precipitation at Tsunan AMeDAS. In the calculation procedure, firstly the coefficients which are functions of the altitudes and the slope angles and directions are obtained in order to fit the snow depth on 25 February. Then the snow depth at every grid of 10 m size was calculated with multiplying the coefficients by the precipitation amount at Tsunan.

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 Yamanoi and Endo (2002) and Abe et al. (2005),

$$\sigma = 9.40 \times 10^{-1} \rho^{2.91} \text{ Pa}, \tag{1}$$

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

$$\sigma = 4.97 \times 10^{-4} \rho^{2.91} \exp(-0.235\theta) \text{ Pa}, \tag{2}$$

for granular snow (wet grains) and

$$\sigma = 3.91 \times 10^{-2} \exp(0.0141\rho) \text{ Pa}, \tag{3}$$

for faceted crystals and depth hoar, we determined the stability index SI. Here σ is the shear strength of snow, ρ is a dry density (density without liquid phase) and θ is a water content. The stability index SI. 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.

Results of numerical simulations

Figure 4 indicates the simulated and measured snow profiles at the Tsunan AMeDAS station from January to March 2006. Overall, the simulated snow types agree well with the observed ones. However, some discrepancies are found. For instance, the model predicts more granular snow (wet grains) than actually appeared.

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. In addition to the wind speed, we calculated the distributions of other meteorological variables including air temperature and incoming short wave radiation. According to the meteorological observations at Sakasamaki, Tochikawa and Tsunan, the temperature distributions in the study area 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. By substituting the derived distributions of meteorological data into the SNOWPACK model, the stability index SI was calculated with a grid size of 10 m.

Figure 5 shows the distributions of SI on 22 February 2006 at Mitama, Akiyamago (660 m × 1210 m); the area is indicated in Fig. 3. Avalanche release map in Figure 5 was drawn based on the aerial photograph on 4 March 2006, but these avalanches were known to occur before 26 February by the field observations. The avalanche danger had a maximum on 22 February, which is nearly consistent with the dates when the snow

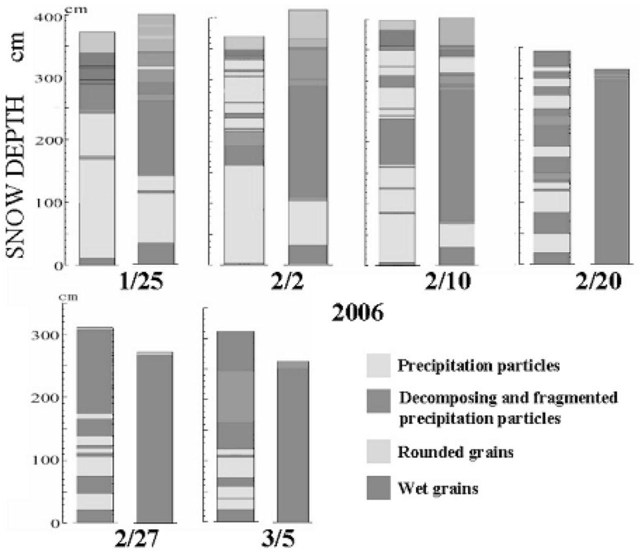

Fig. 4. Simulated (left) and measured (right) snow profiles at the Tsunan AMeDAS station from January to March 2006.

Fig. 5. Calculated SI distribution on 22 February 2006 at Mitama, Akiyamago. Solid line indicates the avalanche area.

avalanches occurred. The avalanche starting zones agrees with grid points having a low stability index fairly well. Thus, the model gave results consistent with the occurrence of three avalanches.

Figure 6 shows the distributions of SI from 23 to 25 December 2006 at Maekura, Akiyamago (1150

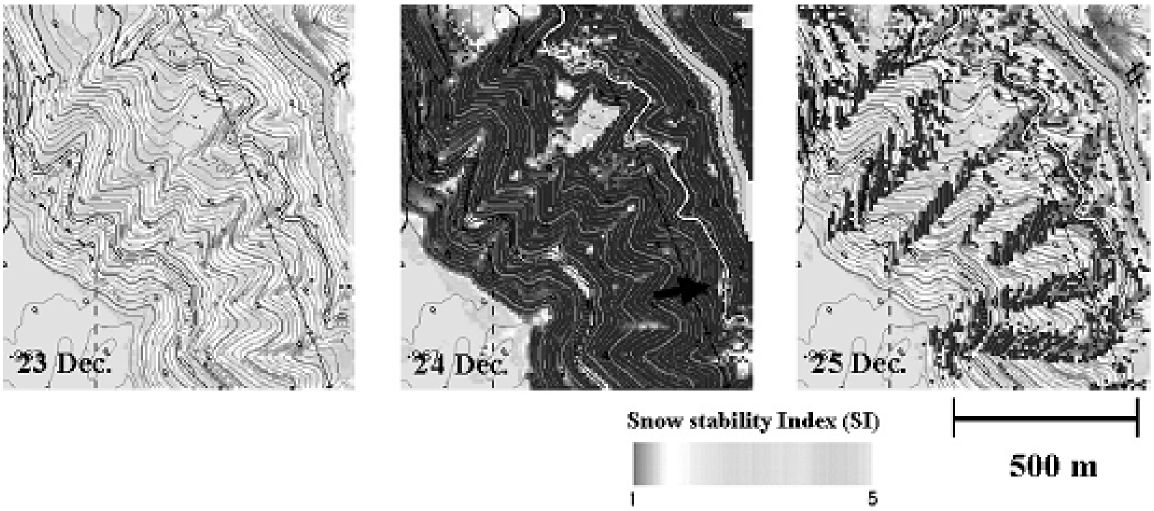

Fig. 6. Calculated *SI* distribution from 23 to 25 December 2006 at Maekura, Akiyamago. An arrow on 24 Dec. indicates the avalanche location.

Fig. 7. Snow avalanche track on 24 December 2006 at Maekura, Akiyamago marked with an arrow in Fig. 6 (left) and an automobile swept away from the road (right).

m × 970 m) as is indicated in Figure 3. The avalanche danger increased remarkably on 24 December 2006, which is consistent with the dates when a snow avalanche occurred as marked in Figure 6 and an automobile was swept away from the road (Fig. 7).

On 5 February 2006, a large dry snow avalanche was released at Yashiki, Akiyamago. It ran down the avalanche track nearly for 2 km as described in Figure 3. The avalanche danger on the day in this area (1310 m × 900 m) is shown in Figure 8. Again the avalanche starting zones agrees fairly well with grid points having a low stability index.

Conclusions

To develop an avalanche warning system in Japan, we set up meteorological stations in the winter of 2005–2006. Snow pit observations were also carried out almost every week. During this winter, we had huge amount of snow and the snow depth in the study area exceeded 4 m in February. The simulated snow profiles from the SNOWPACK model roughly agreed with the observed profiles.

Fig. 8. Calculated SI distribution on 5 February 2006 at Yashiki, Akiyamago. Solid line indicates the avalanche area

To expand the forecasting area to cover the study area, we used data from AWSs and a digital elevation map with a grid size of 10 m to estimate the distributions of air temperature, solar radiation, and wind speed. Snow depth distributions were measured directly by the aircraft-borne laser profilers. With these estimated distributions the model calculated snow properties such as grain type and density, and finally the snow stability index SI. The stability predictions agreed reasonably well with the field observations and the avalanche release map obtained by the aerial photograph.

However, a number of improvements are still necessary in each of the processes. In particular we need to develop a method that can estimate the snow depth distribution precisely. Measurements with the aircraft-borne laser profiler cost extremely high and are not suitable for the practical implementation in general. The goal is to increase the accuracy so that the model can become part of the avalanche danger forecasting operations.

Acknowledgements

This work was partly supported by the Grant-in Aid for Scientific Research of Ministry of Education, Science and Culture, Japan.

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