Snow Disaster Forecasting System on Roads

K. Nishimura[1], H. Hirashima[1], K. Kosugi[1], T. Kobayashi[1], T. Sato[1], A. Sato[1] and M. Lehning[2]

[1] Nagaoka Institute of Snow and Ice Studies, NIED,
Suyoshi, Maeyama, Nagaoka, Japan 940-0821
Email: nishi@bosai.go.jp
[2] WSL, Swiss Federal Institute for Snow and Avalanche Research, SLF
Fluelastrasse 11, CH-7260 Davos Dorf, Switzerland
Email: lehning@slf.ch

ABSTRACT

We started to construct a snow disaster forecasting system. It is composed of three steps; firstly meteorological conditions, such as temperature, wind speed and direction, short and long wave radiation and amount of snowfall is calculated by regional weather model with a fine space resolution. Secondly the change in the property of snow cover is obtained with SNOWPACK model developed by Swiss Federal Institute for Snow and Avalanche Research (SLF). Thirdly, based on the above two steps, forecasting of the snow avalanche danger, the decrease in the visibility due to a blowing snow, and the condition of snow and ice along the road were carried out.

Keywords: snow disaster, regional weather model, SNOWPACK

1. INTRODUCTION

More than half of Japan Islands suffer from heavy snowfall in winter and it causes various disasters; snow avalanche, blowing snow, snow accretion, and traffic accidents due to snowy/icy road surface. From 500 to 600 accidents and nearly 200 fatalities are counted in a year. In order to mitigate such tragedies, we have started constructing a snow disaster forecasting system [14]. In this paper we introduce the total scenario of this project briefly and, then, describe more in detail about the forecasting of snow avalanche danger, and snow and ice condition on roads.

Meteorological conditions, which will be the key for the individual disaster forecasting, are given by Non Hydrostatic Model (NHM) developed by the Japan Meteorological Agency (JMA). This is a multipurpose non-hydrostatic atmospheric model that includes the cloud physics schemes explicitly, and was recently adapted for the operational weather forecasts in Japan. In this study we applied the model onto heavy snowfall areas with higher space resolution. A nested grid system was utilized with an outer grid of 10km spacing and an inner grid of 2km. Fig. 1 shows a calculated precipitation rate within one hour. NHM simulates the meteorological conditions for seventy-one hours after the initial condition. However, the data of ten hours later are utilized, because of the spin–up of the model. Not only the snow fall but also air temperature, relative humidity, wind speed, wind direction, incoming short and long wave radiations are given.

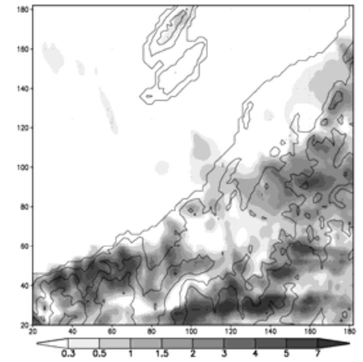

Fig. 1 Calculated precipitation rate around Niigara area on January 14, 2003.

Amount of precipitation and wind speed distribution given by the NHM are utilized to evaluate the blowing snow development [15]. Then visibility is calculated based on the empirical observational results. Although the NHM is a powerful tool, it is still under development at this stage. Thus we set the measuring instrument in the study area and utilized for the development of the forecasting system of the snow avalanche and the snow and ice condition on roads.

2. SNOW AVALANCHE FORECASTING

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 4000 km^2). We have set our study area in Niseko, which is in northern part of Japan "Hokkaido" and is one of the most popular ski resorts in Japan.

An automatic weather station (AWS) was set up at 800 m a.s.l., where air and snow surface temperature, wind speed and direction, shortwave and longwave radiation, and snow depth were measured. Nearly every day, we made snow pit observations on avalanche prone slopes. We measured grain shape and size, snow temperature and snow hardness.

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. The avalanches in Niseko were mostly slab avalanches that were caused by shear failure and fracture propagation in the snowpack parallel to the slope [12]. 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.

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 [1], [8], [9]. 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) found that this model was useful for the conditions in Niseko [4].

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 [7]. 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 [2], [10], [11], [13]. In this study, we used SnowTran3D, which was originally developed by Liston and Sturm [11] 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 with the wind speed u_{AWS} (m/s) at the AWS. W is a function of inclination Ω_s (deg) and curvature Ω_c:

$$\mathrm{W} = 1.0 + \gamma_s\Omega_s + \gamma_c\Omega_c \qquad (1)$$

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

where γ_s and γ_c are constants set equal to 1.0 and 35.0, respectively [3]. 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 Sturm [11]. 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.

In addition to the wind speed, we calculated the distributions of other meteorological variables including air temperature and incoming shortwave radiation (solar 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. 2. These plots show only the region around the avalanches of 14-16 February 2003.

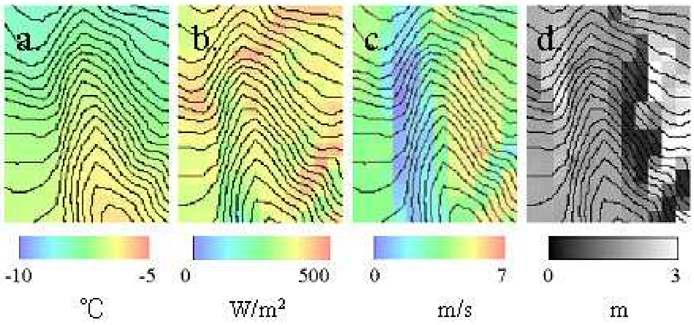

Fig. 2. Distribution of air temperature, solar radiation, wind speed, and snow depth at noon on 10 February. The area is 600 m x 800 m. Terrain is indicated by 25 m contour lines.

By substituting the derived distributions of meteorological data into the SNOWPACK model, the stability index *SI* was calculated. 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. Figure 3 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 [12].

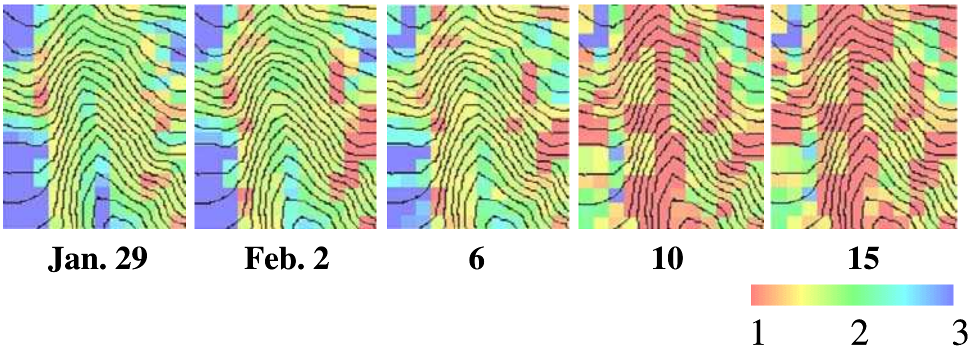

Fig. 3. Change in SI from 29 January to 15 February 2003. Same area shown as in Fig. 2.

3. SNOW AND ICE CONDITION ON ROADS

Prediction of the road surface condition in winter is also important for both drivers and road maintenance stuff. Precise observation started at Nakadai on a mountain pass of national highway 112 to obtain the video image of the road, surface temperature, air temperature, incoming and outgoing short and long wave radiation, wind velocity and some other elements (Fig.4). In addition to the measurement at the fixed point, observations with a vehicle, on which various sensors are set, were carried out. Along the road of 40 km distance, meteorological data and road surface conditions are obtained twice a winter.

A forecasting model of road surface temperature is constructed based on the heat balance theory and observations. Heat balance on the snowy/icy road surface can be expressed with Eq. (3).

$$I_r(1-\alpha_r)+\Delta L_r+S_r+E_r+C_G+X=Q_M \qquad (3)$$

First term of the left side shows the net shortwave radiation, where I_r is the incoming short wave radiation and α_r is albedo. ΔL_r is the net long wave radiation, S_r is the sensible heat, and E_r is the latent heat. C_g is the heat conduction through the snow/ice and asphalt, X is the effect of the vehicle, and Q_M is the heat for snow/ice melting. ΔL_r is the sum of incoming long wave radiation A and outgoing one R $(=\varepsilon\sigma T_0^4)$, where ε is the emissivity, δ is the Stephan constant and T_0 is the road surface temperature.

$$\Delta L_r = A + R \tag{4}$$

S_r and E_r are expressed respectively as:

$$S_r = K(T_r - T_0)V_r \tag{5}$$

$$E_r = K_E(e_r - e_0)V_r \tag{6}$$

where K and K_E are the bulk constant of the sensible and the latent heat transfer. T_r is the air temperature at 1 m high, and e_r and e_0 are the vapor pressure at 1 m high and on the road surface respectively.

Fig. 4 Observational instruments set at Miyadai, a mountain pass of the national highway, 112.

Substituting the meteorological data measured at Nakadai into above equations, the road surface temperature T_0 was obtained. Since the road goes through the mountainous region, the traffic is much less than the one in the urban area. Thus the effect of vehicle X in Eq. (3) was not taken into account in the calculation. As is shown in Fig. 5, predicted temperature from 29 to 30 January 2003 agrees fairy well with the observed one.

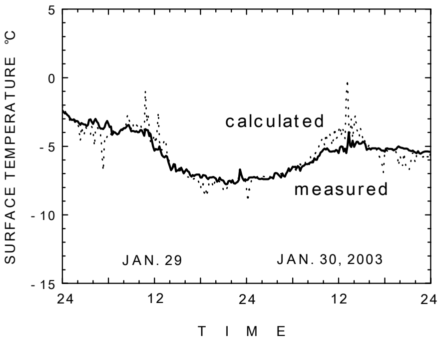

Fig. 5 Road surface temperature at Miyadai in winter.
Solid line shows the measurement and dotted line the calculation.

Applying the above procedure, we calculated the surface temperature distribution along the road. Meteorological data were estimated with a grid size of 50 m, as is explained in the previous section. Field of the wind speed, the air temperature, the solar radiation and the calculated road surface temperature are shown in Fig. 6, and are compared with the measurements with the observation vehicle. Although air temperature agrees fairly well except in the tunnel, wind and the solar radiation differ largely. This is probably because we used Snow/Tran3D for a mountainous terrain much rougher than the tundra for which it was developed [11]. Further, 50 m grid altitude data are not fine enough to calculate the wind field precisely; small ridges and valleys presumably modify the wind field substantially. On the other hand, for the solar radiation calculation our study site (40 km long distance) may be too large to apply the data of single point, Nakadai directly. The cloudiness obviously varies and, accordingly, the solar radiation changes. In addition, sky view factor, which indicates the relation between the visible area of the sky and the area covered by trees, mountain and urban structures, needs to be evaluated accurately. Dew to the disagreement appeared on the estimated meteorological data, the calculated road surface temperature shows the 2 deg difference with the observed one at the maximum.

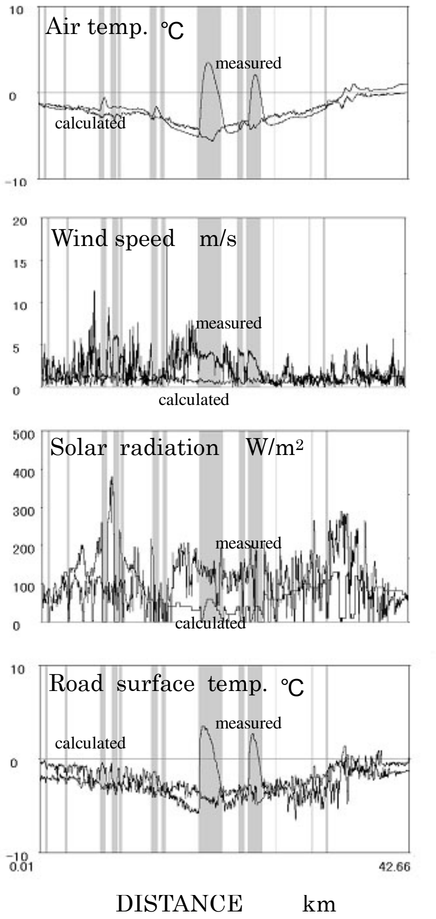

Fig. 6. Distribution of meteorological data and road surface temperature along the 40km road.
Gray part is in the tunnel.

Not only the surface temperature but also road surface conditions, such as dry, wet, compacted snow and slush, are important information for the vehicle drivers and is worth forecasting. Heat balance calculation, which is the useful method to obtain the surface temperature, does not give the condition directly. In consequence, we applied the discriminant function analysis; it is used to determine which variables discriminate between two or more naturally occurring groups. In this study, we chose air temperature, humidity, solar radiation, incoming long wave radiation, wind speed, amount of snow fall and road surface temperature as discriminating variables (predictors). The criterion variable is a road surface condition (dry, wet, slush and compacted snow). In the analysis, all the data observed at Nakadai from Jan. to Feb. 2004 were utilized. As is shown in Table 1, the discriminant function is able to forecast the road surface condition with in an accuracy of about 80%.

4. CONCLUSIONS

We have developed the snow disaster forecasting system, which gives the warning for the snow avalanche danger, the decrease in the visibility due to a blowing snow, and the slippery condition of snow and ice on the road. Although a prototype of the system has been completed, a number of improvements are still necessary in each of the processes. For instance, though we set our focus on the prediction of the road surface temperature and condition so far, change in the road surface friction is also practically important. We have investigated how the friction depends on the traffic and the temperature using a real vehicle in the cold room [6]. Evaluation of heat exchange between cars and road surface is also conducted on the real road. Subsequently, we are going to formulate mechanical and thermal effects of the vehicle and put them into the snow disaster prediction system as well.

Table 1 Road surface condition predicted by the discriminant analysys
I: dry, H: wet, E: slush, and D: compacted snow

Predicted

Observed

	H	H+I	I	E	D
H	1103	190	59	169	59
H+I	36	305	40	6	0
I	37	101	219	3	0
E	71	36	0	123	18
D	46	3	0	68	1632

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