# Forecasting Experiments Using the Regional Meteorological Model and the Numerical Snow Cover Model in the Snow Disaster Forecasting System

Katsushi IWAMOTO, Satoru YAMAGUCHI, Sento NAKAI and Atsushi SATO
Snow and Ice Research Center, National Research Institute for Earth Science and Disaster
Prevention, Suyoshi, Nagaoka 940-0821, Japan

(Received for 24 May, 2007 and in revised from 6 June, 2008)

## ABSTRACT

The Snow and Ice Research Center (SIRC) of the National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan has been developing a snow disaster forecasting system. This system consists of an atmospheric mesoscale model NHM, the numerical snow cover model SNOWPACK, and three diagnostic models of snow disasters. In this paper, the performance of NHM and SNOWPACK is investigated in the Niigata area, selecting the events of December 2005 as the case for the experiment. NHM reproduces precipitation events but tends to underestimate the amount of precipitation. This is because the positions of snow clouds are not precisely reproduced in the simulation. The predicted snow depth by SNOWPACK is in a good agreement with the observation. However, the snow type has a large prediction error. A snow cover forecasting experiment with a combination of NHM and SNOWPACK reproduces the observed snow depth and snow density well for 24 hours with slight prediction errors. The snow depth tends to be underestimated when NHM does not suitably reproduce the precipitation. To apply the system to a wet snow region, such as Niigata, accurate predictions of temperature and precipitation are needed.

## 1. INTRODUCTION

Japan receives some of the heaviest snowfall in the world. The snowfall occurs mainly on the Japan Sea side of Japan and in Hokkaido, which account for more than one half of the country's landmass. Many snow disasters occur in these areas every winter. They are caused by various snow-related phenomena, such as avalanches, blizzards, and the accompanying poor visibility, frozen road surfaces, snow accretions, and snow on roofs. To prevent these disasters, various facilities have been constructed. These hardware countermeasures are effective for preventing snow disasters. However, since hardware methods are expensive to build and maintain, building them throughout a snowfall region is difficult. Hence, software management is important to mitigate the damage of snow disasters as an alternative or collaborative method.

The Snow and Ice Research Center (SIRC) of the National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan has been developing a snow disaster forecasting system for predicting snow disasters, as shown in **Fig. 1** (Sato et al., 2003, 2004a). This system could provide the software management necessary to deal effectively with snow disasters. A similar system for avalanche prediction is currently being used in Switzerland (Lehning et al., 2002a). In that system, snow cover properties are nowcasted with a numerical snow cover model to predict avalanches. The system of NIED-SIRC is, on the other hand, a forecasting system that combines numerical weather prediction (NWP) using a regional meteorological model with a numerical snow cover model and diagnostic models of the probability of snow disasters, aiming at prediction within a few days before their occurrence. A prototype of the system has already been completed, and its performance is currently being improved. In the system, the accuracy of NWP and the snow cover model, which supply the basic data for the disaster models, could significantly influence the performance of the system.

In this paper, by conducting a forecasting experiment using the regional meteorological model and a nowcasting experiment

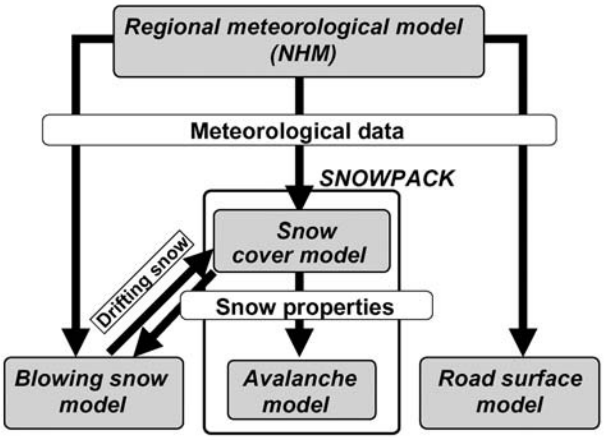

**Fig. 1** Schematic structure of the snow disaster forecasting system. The arrows indicate the data flow (after Sato et al., 2004a).

KEY WORDS: snow disaster forecast, numerical weather prediction, snow cover prediction, NHM, SNOWPACK

using the snow cover model, the performance of each model and views for improvement of the models are investigated. In the next section, we give a brief outline of the snow disaster forecasting system of NIED-SIRC. Experiments involving NWP and snow cover properties are then performed, and the results are discussed. In addition, forecasting experiments of the snow cover properties using a combination of a snow cover model with NWP are conducted in order to discuss the influence of the prediction inaccuracy of NWP on the prediction of snow cover.

## 2. THE SNOW DISASTER FORECASTING SYSTEM

**Fig. 1** illustrates the schematic structure of the snow disaster forecasting system. The system consists of a regional meteorological model, a numerical snow cover model, and diagnostic models of snow disasters. Since the models operate independently, a model can be selected arbitrarily and treated as a module. In addition, the snow cover model and the snow disaster models can be used both for a forecast based on the prediction of the regional meteorological model and for a nowcast based on the observed data.

First, a numerical weather prediction (NWP) is carried out with a regional meteorological model. The predicted meteorological data, such as air temperature, wind direction/speed, snowfall amount, and downward shortwave and longwave radiation at target points, are inputted into the snow cover model, the blowing snow model, and the road surface model. For the prediction of snow disasters, it is required for the NWP to resolve a snow cloud that has a horizontal scale of less than a few kilometers. Therefore, a model that explicitly represents convections of the atmosphere is necessary for the NWP. Then, the numerical snow cover model diagnoses the physical properties of the snow cover, such as the snow type, temperature, density, and water content, using the meteorological data from the beginning of the winter to the present time. These data are then inputted into the blowing snow model and the avalanche model. Finally, the mass flux of blowing snow and its related visibility, the occurrence probability of an avalanche, and the road surface conditions and friction are diagnosed by each disaster model based on the meteorological data and the physical properties of the snow cover. The dataflow between the models in the system is basically one way, that is, feedback is not considered, except between the snow cover model and the blowing snow model. The calculated amount of snow redistribution is transferred from the blowing snow model to the snow cover model as feedback.

At present, we use the nonhydrostatic model (NHM), developed by the Japan Meteorological Agency (JMA) (Ikawa and Saito, 1991; Saito et al., 2006), as the regional meteorological model, and SNOWPACK, developed by the Swiss Federal Institute for Snow and Avalanche Research (Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b), as the numerical snow cover model. SNOWPACK is also used as the avalanche model. The avalanche model estimates avalanche danger based on a stability index (SI), which is the ratio of the shear strength and shear stress of the snow cover. The properties of the snow cover and the angle of the target slope are used to estimate the shear strength and shear stress. To apply SNOWPACK, which was developed for the prediction of dry snow avalanches in the Swiss Alps, to the wet snow region in Japan, the melting processes (Yamaguchi et al., 2004) and the formulation of the shear strength (Hirashima et al., 2006) have been improved. The blowing snow model and the road surface model have been developed by SIRC. The blowing snow model diagnoses visibility at a height of 1.2 m, which represents the height from which a typical vehicle driver views the road, and estimates the depth of the snow drift (Sato et al., 2004b, 2004c). The road surface model diagnoses the surface temperature and the road surface conditions based on a heat budget method (Nishimura et al., 2004). The conditions are categorized into dry, wet, slush, and compacted snow.

## 3. FORCASTING EXPERIMENT OF NHM

NHM, used as the regional meteorological model in the system, is a nonhydrostatic mesoscale model. Since atmospheric vertical motion is explicitly treated in the governing equations, convections and convective clouds are well represented in this model. Therefore, this model is suitable for forecasting convective snow clouds in winter. NHM uses three classes of precipitation particles (rain, snow, and graupel) and a bulk method with empirical formulae as cloud microphysics. In the snow disaster forecasting system, only the regional meteorological model is a forecasting model, while others are diagnostic models. The accuracy of the regional meteorological model, therefore, could be a critical factor in the system's performance. In this section, conducting the forecasting experiment throughout a month, the performance of NHM is evaluated.

### 3.1 Setting of NHM and experimental design

Heavy snowfall and related snow disasters were frequent in Japan in December 2005. We selected this month as an experimental case to investigate the performance of NHM. The initial and lateral boundary data of NHM are given by the grid point value (GPV) of the regional spectrum model (RSM) provided by JMA. RSM-GPV consists of an atmospheric analysis and three-hourly 51-hour forecasts of the geopotential height, the horizontal and vertical wind components, the potential temperature, and the mixing ratio of water vapor. The horizontal resolution is about 20 km at the surface and about 40 km above the surface. For resolving convective snow clouds in NWP, a horizontal grid interval of 2 km is employed as the inner NHM (NHM02km) using a one-way dual-nesting method from RSM-GPV through the outer NHM with a grid interval of 10 km (NHM10km). The experimental area of NHM10km and NHM02km is shown in **Fig. 2**. The domain of NHM02km extends 200 km × 200 km and roughly corresponds to the Niigata area, the central part of the Japan Sea side of Japan. The vertical grid interval varies from 40 m at a lower boundary to 1,180 m at an upper boundary with a height of about 20 km.

The analysis and forecasts of RSM-GPV are interpolated linearly to the grid points of NHM10km as the initial and the lateral boundary data, respectively. NHM10km forecasts the mixing ratio of the cloud water and cloud ice, the mixing ratio of the precipitation particles, and the amount of the precipitation as well as the meteorological data. The initial and the boundary data of NHM02km are also made by interpolation of the output data of NHM10km. NHM02km outputs the same data as NHM10km. In lower-boundary conditions, classification of the sea surface and the

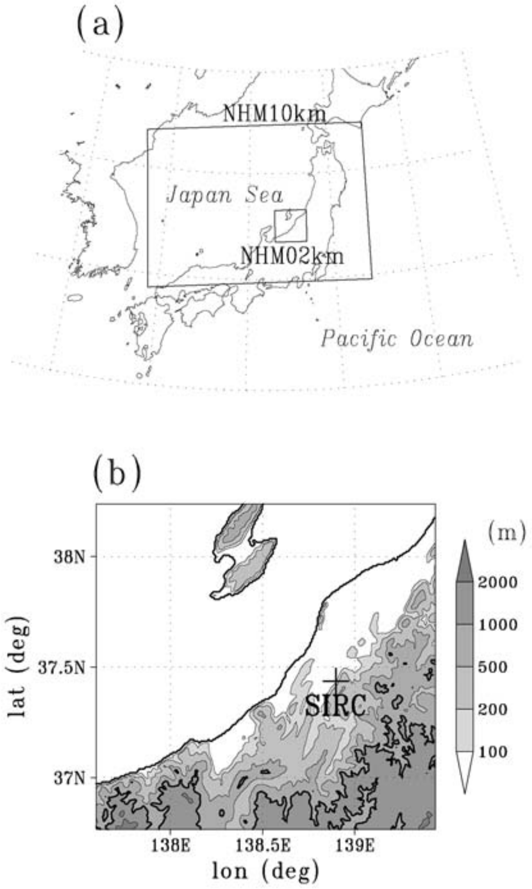

**Fig. 2** Experimental domain of NHM. (a): location map of NHM10km and NHM02km and (b): topography of NHM02km. The cross mark in (b) indicates the position of the Snow and Ice Research Center (SIRC).

land surface is considered; it is assumed that the land surface is covered exclusively by grass. In the snowfall region, whether the land surface is covered by snow or not is thought to be important from the viewpoint of the energy budget at the surface. Feedback from the snow cover model to NHM is necessary to treat the snow cover as the lower boundary in NHM. This improvement will be made in future work.

First, a 33-hour forecast run of NHM10km was carried out twice daily at the initial times of 0000 and 1200 UTC (Coordinated Universal Time), i.e., 0900 and 2100 JST (Japan Standard Time), respectively. The end times of each forecast run were 0900 UTC (1800 JST on the next day) and 2100 UTC on the next day (0600 JST on the day after the next day). Then, a 30-hour forecast run of NHM02km was conducted. The initial data of NHM02km were supplied by the output of NHM10km at forecast time 03 (that is, 3 hours after the initial time; hereafter, FT=03). Therefore, the initial times of NHM02km were 0300 UTC (1200 JST) and 1500 UTC (0000 JST on the next day). The end time was the same as that of NHM10km. Taking the spin-up time for 7 hours into account, forecast data for 24 hours from FT=10 to 33 were used for the analysis. The output interval of the predicted data was one hour. In addition, continuous data from 0100 JST 1 December 2005 to 0000 JST 1 January 2006 were obtained by successively connecting twice-daily 12-hour forecasts from FT=10 to 21.

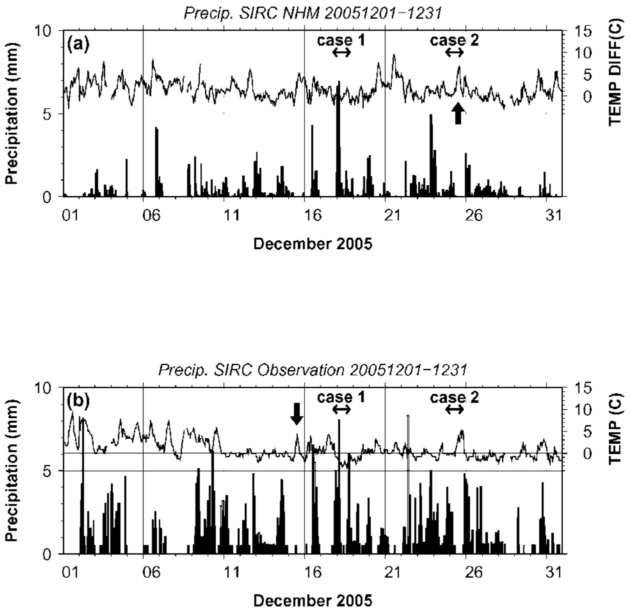

**Fig. 3** Hourly atmospheric data at SIRC. (a): precipitation simulated by NHM02km (bar) and temperature difference between the simulation and the observation (line), and (b): observed precipitation (bar) and temperature (line). The output of NHM02km at the nearest grid point to SIRC is selected in (a).

### 3.2 Results

**Fig. 3** shows the precipitation and the temperature at SIRC for one month. Following the manner in which the snow disaster forecasting system is utilized for forecasting at a target point, the values at the nearest grid point of NHM02km from SIRC were plotted as the simulated results. NHM reproduces, to some extent, the timing of precipitation. However, the precipitation amount of NHM is much smaller than that of the observation throughout the period, with few exceptions. The total precipitation simulated by NHM is 225 mm, whereas the observed precipitation is 583 mm. The simulated temperature variation shows a tendency towards overestimation (**Fig. 3a**). In our experiment, the forecasting result of NHM has a tendency to underestimate the cloud amount (figures not shown), which results in an underestimate of surface precipitation and an overestimate of surface temperature.

The daily precipitation amount simulated by NHM on 18 December (27 mm) was the largest in the experiment and relatively close to the observed daily precipitation (37 mm). At this time, the simulated temperature also corresponded well to the observed temperature (the daily-averaged temperature difference was about 0.1 K on 18 December). The horizontal distributions of the precipitation at 0300 JST on 18 December are shown in **Fig. 4**. The corresponding observed precipitation is retrieved from a radar-echo composite map obtained from the JMA radar network (for the sake of simplicity, the JMA radar network is referred to as "radar," and the radar-echo composite map, as a "radar map"). Both in the NHM prediction and the radar map (**Figs. 4a**, **4b**, respectively), the precipitation areas are aligned from northwest to southeast over the sea, and precipitation, occurring primarily over land, is dominant in the mountains. NHM successfully predicts both the distribution and the amount of precipitation at this time. It should be noted that NHM predicts heavy precipitation around 36.8° N, 138.6° E, which

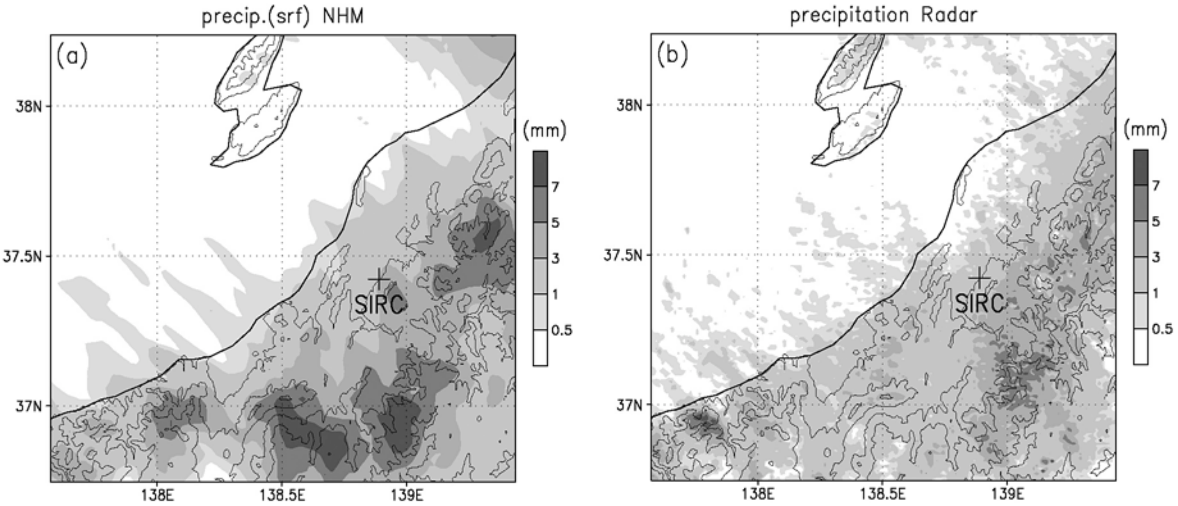

**Fig. 4** Horizontal distribution of the preceding hourly precipitation at 0300 JST on 18 December 2005. (a): result of NHM02km and (b): radar map.

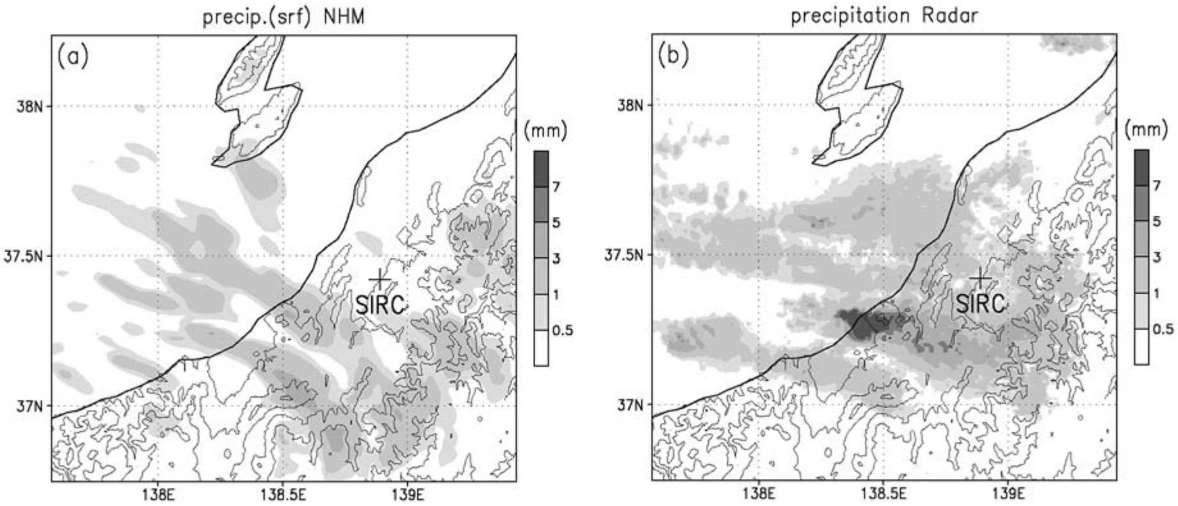

**Fig. 5** Same as Fig. 4 but at 2100 JST on 24 December 2005.

does not appear on the radar map. This disagreement is thought to be caused by a radar problem. In general, the radar cannot observe clouds over the higher mountains because the radar beam passes over the top of the clouds. Therefore, precipitation derived by the radar might be underestimated in the mountains.

NHM did not exactly reproduce the horizontal distribution of precipitation at 2100 JST on 24 December (**Fig. 5**). In this case, the basic structure of the snowfall area, which is linear with a width of about 20 km, is in good agreement with the observed structure; however, a heavy snowfall area (around 37.3° N, 138.4° E) does not appear in the simulation. In addition, since the running direction of the simulated precipitation is from northwest to southeast but from west to east on the radar map, the snowfall area over land shifts southward compared with that on the radar map. The precipitation amount of NHM at SIRC was found to be smaller than that of the observation at around this time. Even if the basic structure of snow clouds is reproduced in NHM, the occurrence of inconsistency in the spatial pattern might result in a large difference at a certain point.

**Fig. 6** shows the total precipitation from 1 to 31 December. NHM underestimates the amount of precipitation near the coast from 37.0° N to 37.4° N and from 138.2° E to 138.7° E. The monthly precipitation of NHM averaged in the domain is about 240 mm, which is small compared with the observed precipitation of 430 mm. The underestimation may be attributed to problems related to sea and land surface processes, cloud parameterization, and initial and boundary data. These are the most important points for improving NHM. It is noteworthy that the radar cannot be used to observe the mountainous region of Niigata. Therefore, the observed precipitation might be underestimated near the southern and southeastern edge of the domain. Considering a validation method for the prediction results is also important for improving NHM. Using surface observation would be the most appropriate method of validation at present.

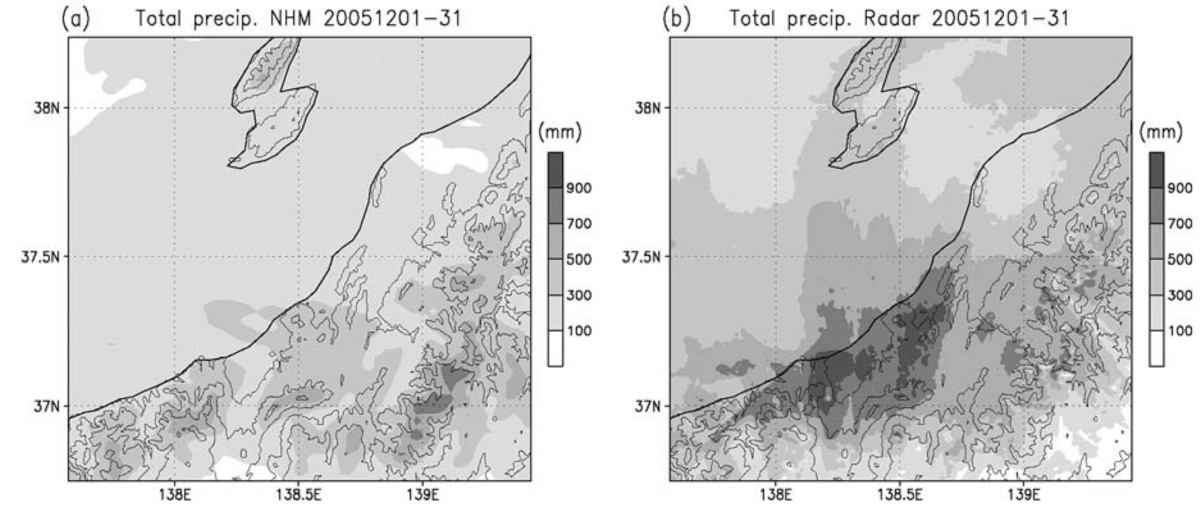

**Fig. 6** Accumulated precipitation from 0100JST on 1 December 2005 to 0000JST on 1 January 2006. (a): simulation of NHM02km and (b): radar map.

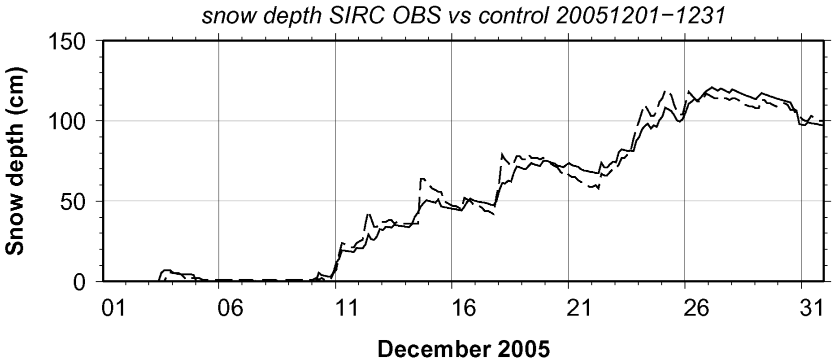

**Fig. 7** Snow depth at SIRC in December 2005. The solid line denotes the simulated snow depth by SNOWPACK, whereas the dashed line denotes the observed snow depth.

## 4. NOWCASTING EXPERIMENT OF THE PHYSICAL PROPERTIES OF SNOW COVER BY SNOWPACK

SNOWPACK is a one-dimensional snow cover model. SNOWPACK includes the realistic dynamics and thermodynamics of snow cover in the governing equations, diagnosing the time evolution of the physical properties of the snow cover, such as snow temperature, density, water content, and type, using meteorological data. The snow type is categorized by the diagnosed dendricity, sphericity, and grain size of each layer in the snow cover. By using the finite-element method, SNOWPACK can represent even fine structures in the snow cover, such as a thin ice layer.

### 4.1 Experimental design

A SNOWPACK run is based on the meteorological data observed every one hour from the snow and weather observation site at SIRC. The input data of SNOWPACK are the temperature, relative humidity, wind speed, precipitation, and downward shortwave and longwave radiation at the surface. All of the input data, except precipitation, are instant values, whereas precipitation is an accumulated value for the preceding one hour. Considering that the catch efficiency of the precipitation gauge declines in winter, the observed precipitation was corrected with the formulation of Yokoyama et al. (2003) using the observed wind speed. It is presumed that precipitation occurs as snow below 0.5℃ and as rain above this temperature (Yamaguchi et al., 2006). The density of new snow is set at 130 kg $m^{-3}$. The calculation period is from 0100 JST 1 December 2005 to 0000 JST 1 January 2006. The output interval of the data is three hours. The snow depth automatically observed from the SIRC snow and weather observation site is used for validation of the simulated snow depth. The simulated snow type and snow density are compared with the results of snow pit observations at SIRC on 20, 25, and 30 December 2005.

### 4.2 Results

The time evolution of the snow depths at SIRC is shown in **Fig. 7**. SNOWPACK reproduces the observed snow depth with slight differences, particularly at rapid increases and at the diminishing stage. Diminishing snow depth is generally caused by melting and/or densification, and these are connected with the snow type of the snow cover. **Fig. 8** depicts the simulated snow types as four categories. Metamorphism of snow is generally categorized into three types: equitemperature, wet snow, and temperature gra-

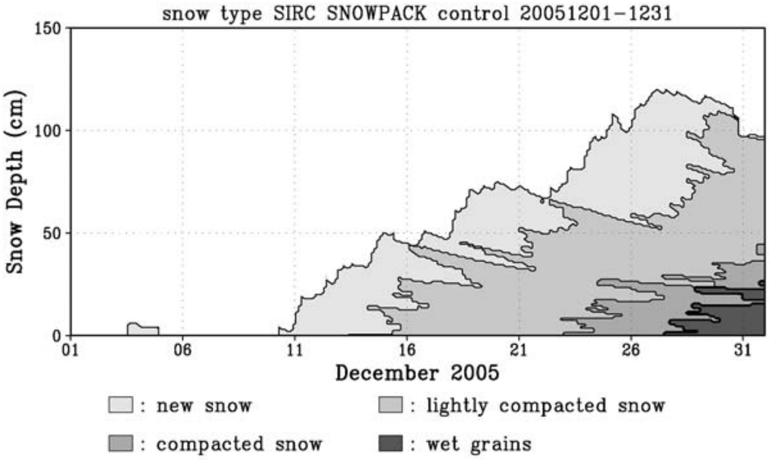

**Fig. 8** Simulated snow type at SIRC by SNOWPACK in December 2005.

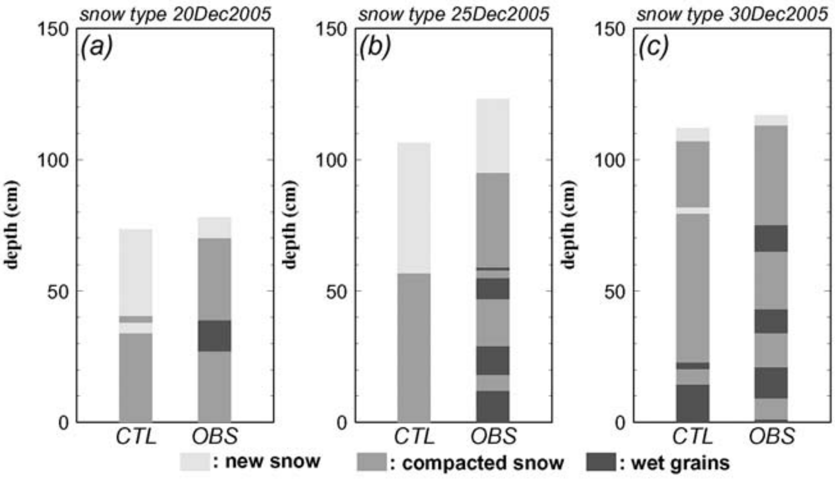

**Fig. 9** Simulated (CTL, left bar) and observed (OBS, right bar) snow type on (a): 20 December, (b): 25 December, and (c): 30 December 2005. Because of the difficulty in distinguishing between lightly compacted snow and compacted snow on the basis of the observation, they are both shown as compacted snow.

dient. The wet grain layer and compacted snow layers are formed by wet snow metamorphism and equitemperature metamorphism, respectively. The process of equitemperature metamorphism is well simulated in SNOWPACK. For example, new snow near the surface on 14 December undergoes metamorphic development into lightly compacted snow at 45 cm on 16 December and into compacted snow at 25 cm on 24 December. This layer contains liquid water (figures not shown) because it is exposed to high air temperature at the snow surface on 15 December (indicated by the downward arrow in **Fig. 3b**). Therefore, the layer finally changes into wet grain at 20 cm on 27 December after the grain size of the layer becomes larger.

Vertical profiles of snow types are compared in **Fig. 9**. Obviously, the simulated snow types are different from those observed. The wet grain layers in the middle of the snow cover do not appear in the simulation. In addition, the simulation shows fewer layers of compacted snow than the observation. In SNOWPACK, calculation of shear strength at a layer is based on the type of metamorphism at the target layer by the formulation of Jamieson and Johnson (2001) and Yamanoi and Endo (2002). Therefore, failure in determining the type of metamorphism could be a problem in the prediction of avalanches. In particular, methods of eliminating underestimates of wet grain layers, which are potentially weak layers in surface avalanches, need to be developed. For the formation of a wet grain layer in the snow cover, it is necessary that meltwater is supplied to the layer by penetration and/or by lateral transport. The penetration process can be improved by adopting the concept of unsaturated hydraulic conductivity in the snow cover (that is, the process in which water penetrates from the upper layer to the lower layer through an unsaturated layer). Suitably expressing lateral transport in SNOWPACK is difficult because SNOWPACK is a one-dimensional model. To represent lateral transport, a two- or three-dimensional model must be developed.

On the other hand, underestimating compacted snow seems to be an observational problem. New snow and compacted snow in SNOWPACK are classified according to their sphericity and dendricity; the criteria used for observations are different. Moreover, the observed snow type is subjective and varies from one observer to another. This is, however, not a serious problem for the prediction of avalanches, because the snow type change from new snow to compacted snow occurs under the same metamorphic process (equitemperature metamorphism). The shear strength at a layer is determined only by the density of the layer in the cases of new snow and compacted snow.

## 5. FORCASTING OF PHYSICAL PROPERTIES OF SNOW COVER BY A COMBINATION OF NHM AND SNOWPACK

In this section, the influences of the prediction error of NHM on the result of SNOWPACK are discussed. Two cases were chosen for the experiment in December 2005: from 1900 JST on 17 to 1900 JST on 18 December (case 1) and from 1900 JST on 24 to 1900 JST on 25 December (case 2) (see **Fig. 3**). First, a SNOWPACK run was performed on the basis of the observation data at SIRC from 1 December to the end time of each case (hereafter, this run is called a control run). Then, using the output of the control run at the initial time of each case as the initial conditions, the SNOWPACK run was performed on the basis of the forecast data at the nearest grid point of NHM02km from SIRC from the initial time to the end time of the case (this run is called a forecast run). The diagnosed snow depth and snow density of the forecast run were compared with those of the control run.

The snow depth and the snow density simulated by the forecast run are shown in **Fig. 10**. In case 1, the simulated depth for 24 hours is within a difference of 10 cm compared with the result of the control run. The vertical profile of the density of the forecasting run also reproduces the result of the control run with slight differences at around 40 cm. Both the precipitation and temperature simulated by NHM are in good agreement with the observation in this case (see **Figs. 3a, 4**). The forecasted results, therefore, correspond to the control run as a whole. The slight differences between the density profiles are caused by the erroneous melting water at the surface due to an overestimate of the downward shortwave radiation of NHM in this case (figures not shown here).

In case 2, the depth increase until 04 JST on 25 December is not suitably reproduced, although the depth decrease after 04 JST is consistent with the control run (**Fig. 10b**). The underestimate of the depth increase is caused by an underestimate of the precipitation at the former part in case 2 (**Fig. 3**). The underestimate occurs as a result of inconsistency of the horizontal distribution of the cloud, as previously mentioned (see **Fig. 5**). The snow density of the forecasting run below 85 cm has a similar profile to that of the control run, but the local minima at around 60 cm and 70 cm in the

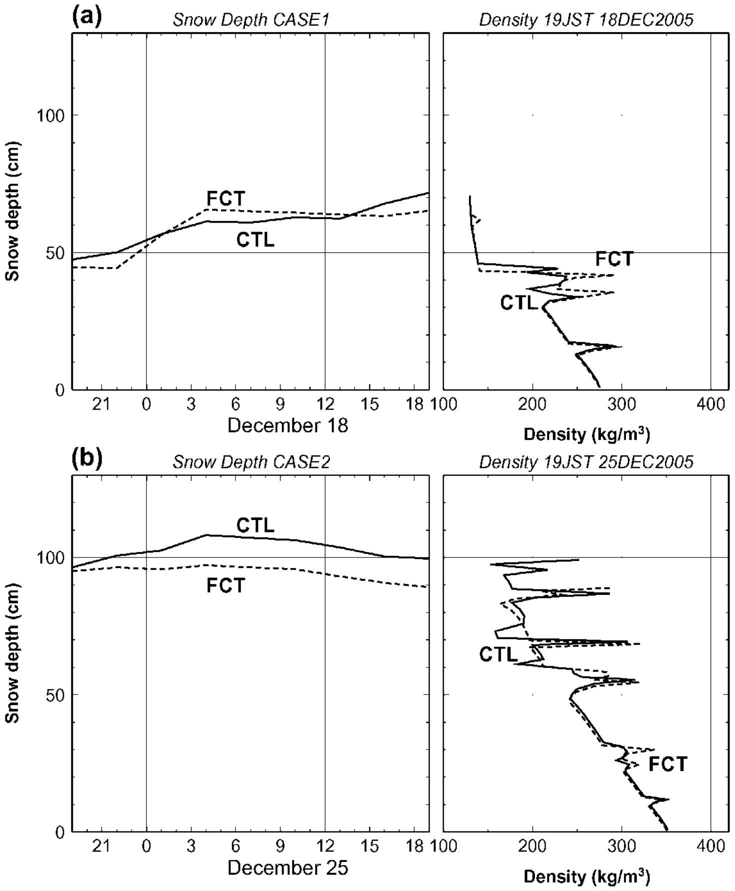

**Fig. 10** Variation in snow depth (left panels) and snow densities at the final state in the SNOWPACK forecast run (right panels) of (a): case 1 and (b): case 2. The solid and dotted lines denote the results of the control run (CTL) and the forecast run (FCT), respectively.

control run are not reproduced. As indicated by the upward arrow in **Fig. 3a**, the air temperature simulated by NHM on 25 December is much higher than the observed temperature (~7℃). As a result, the erroneous melting water due to the overestimate of the air temperature of the forecasting run seems to smooth the density profile in this case.

According to the results of cases 1 and 2, prediction error of the precipitation affects the layer near the snow surface, while overestimate of the air temperature could influence the deeper layer in the snow cover through erroneous melting water, especially in the warmer temperature range (~0℃). Yamaguchi et al. (2007) revealed that much snowfall occurs at about 0℃ in the Niigata region. Therefore, accuracy of the temperature as well as of the precipitation must be considered for improving NHM.

## 6. CONCLUSIONS

A snow disaster forecasting system has been developed at SIRC. The system was designed to predict various types of snow disasters a few days before their occurrence. In this study, we investigated the performance of numerical weather prediction by NHM and the numerical snow cover model SNOWPACK in the Niigata region, selecting the events of December 2005 as the case for the experiment.

NHM reproduces snowfall events at suitable timing but reproduces less precipitation in most of the events. In particular, it tends to underestimate precipitation near coastal areas. Due to the high population density near the coast, there is more infrastructure in the area; thus, it is important to correct underestimate of the precipitation. The snowfall processes of NHM should be improved for better prediction. Moreover, the validation method of prediction also poses certain problems. The JMA radar network cannot reach over and behind higher mountainous areas in the Niigata region. Surface observation is useful for validation, but there are few observatories in mountainous areas. Methods of evaluating the results of simulation need to be examined.

SNOWPACK suitably reproduced the snow depth in December 2005, but the snow type was not consistent with that shown by snow pit observation. In particular, underestimating the wet grain layer could be a significant problem in avalanche prediction. The penetration and/or the lateral transport processes of meltwater should be represented suitably in the snow cover model. Moreover, there are two problems to be considered.

1. In this study, the observed precipitation is assumed to be rain when the air temperature is above 0.5℃ and snow below this temperature. However, this assumption should change with various atmospheric conditions, including those in the upper air. It is unrealistic to fix this value, but it is difficult to evaluate the threshold temperature at present. The heat energy applied to snow cover is different for rain and snow even if their temperatures are the same. The threshold temperature of 0.5℃ is also related to correction of precipitation because it is assumed that the catch efficiency of the precipitation gauge changes at this temperature (Yokoyama et al., 2003) and thus, the total precipitation itself can fluctuate depending on the threshold.
2. New snow density is assumed to be 130 kg $m^{-3}$ in this study. However, the density depends strongly on the atmospheric conditions. According to Kajikawa (1989), it depends on the air temperature and the wind speed. In reality, the value is changeable and difficult to observe. New snow density is closely connected to the densification process.

NHM separately outputs the amounts of rain, snow, and graupel. By combining the precipitation information in NHM with the observation, the former issue might be resolved. As for the latter issue, distributions of temperature and wind predicted by NHM might be useful.

The forecasting experiment of the physical properties of the snow cover was performed by combining NHM and SNOWPACK. The results of the forecast run indicated that the snow depth was underestimated when NHM did not suitably reproduce the snow cloud and that the density profile was smoothed when NHM overestimated the air temperature. Taking into consideration the fact that much snowfall occurs at about 0℃ in the Niigata region (Yamaguchi et al., 2007), an accurate prediction of temperature and precipitation is required for prediction by SNOWPACK. Data assimilation techniques, such as nudging, the Kalman filter method, and three- or four-dimensional variational analyses, are potential solutions for improving the prediction of NHM.

## ACKNOWLEGEMENTS

We are grateful to the staff of the Numerical Prediction Division and Meteorological Research Institute of JMA for the utilization of NHM in this study. We are also grateful to Michael Lehning, the Swiss Federal Institute for Snow and Avalanche Research, for his useful advice with regard to the application of SNOWPACK in Japan. Two anonymous reviewers also gave us valuable comments. The snow disaster forecasting system was developed by all the researchers at the Snow and Ice Research Center. This study is supported by a research project of the National Research Institute for Earth Science and Disaster Prevention entitled "Development of a snow disaster forecasting system."

## REFERENCES

Bartelt, P. and M. Lehning, 2002. A physical SNOWPACK model for the Swiss avalanche warning Part I: Numerical model. *Cold Regions Science and Technology*., **35**, 123-145.

Hirashima, H., K. Nishimura, S. Yamaguchi, A. Sato, and M. Lehning, 2006: Avalanche forecasting in a heavy snowfall area using the SNOWPACK model. *Proceedings of 2006 International Snow Science Workshop*, Telluride, Colorado, 54-62.

Ikawa, M. and K. Saito, 1991: Description of a nonhydrostatic model developed at the Forecast Research Department of the MRI. *Technical Reports of the Meteorological Research Institute*, 28, 238pp.

Jamieson, J. B. and C. D. Johnson, 2001: Evaluation of the shear frame test for weak snowpack layers. *Annals of Glaciology*., **32**, 59-68.

Kajikawa, M., 1989: Relationship between new snow density and shape of snow crystals. *Seppyo*, **51**, 178-183, in Japanese with English abstract.

Lehning, M., P. Bartelt, B. Brown, and C. Fierz, 2002a: A physical SNOWPACK model for the Swiss avalanche warning Part III: Meteorological forcing, thin layer formation and evaluation. *Cold Regions Science and Technology*, **35**, 169-184.

Lehning, M., P. Bartelt, B. Brown, C. Fierz, and P. Satyawali, 2002b: A physical SNOWPACK model for the Swiss avalanche warning Part II:

Snow microstructure. *Cold Regions Science and Technology*, **35**, 147-167.

Nishimura, K., H. Hirashima, K. Kosugi, T. Kobayashi, T. Sato, and A. Sato, 2004: Forecasting of snow and ice on roads. *Proceedings of 2004 Cold Region Technology Conference*, Wakkanai, **20**, 122-127, in Japanese.

Saito, K., T. Fujita, Y. Yamada, J.-I. Ishida, Y. Kumagai, K. Aranami, S. Ohmori, R. Nagasawa, S. Kumagai, C. Muroi, T. Kato, H. Eito, and Y. Yamazaki, 2006: The operational JMA nonhydrostatic mesoscale model. *Monthly Weather Review*, **134**, 1266-1298.

Sato, A., M. Ishizaka, M. Shimizu, T. Kobayashi, Y. Nohguchi, K. Nishimura, S. Nakai, S. Yamaguchi, K. Iwamoto, T. Sato, O. Abe, K. Kosugi, and S. Mochizuki, 2003: Forecasting system of snow and ice disaster. *Proceedings of 2003 Cold Region Technology Conference*, Kushiro, **19**, 786-789, in Japanese.

Sato, A., M. Ishizaka, M. Shimizu, T. Kobayashi, K. Nishimura, S. Nakai, T. Sato, O. Abe, K. Kosugi, S. Yamaguchi, K. Iwamoto, and M. Lehning, 2004a: Construction of snow disaster forecasting system in Japan. *Snow Engineering V*, Ed. P. Bartelt, E. Adams, M. Christen, R. Sack, and A. Sato, A. A. Balkema, Rotterdam, pp 235-238.

Sato, T., K. Iwamoto, S. Nakai, K. Kosugi, M. Nemoto, and A. Sato, 2004b: Areal prediction of blowing snow and its resultant visibility change. P*roceedings of 2004 Cold Region Technology Conference*, Wakkanai, **20**, 332-337, in Japanese.

Sato, T., K. Kosugi, and A. Sato, 2004c: Development of saltation layer of drifting snow. *Annals of Glaciology*, **38**, 35-38.

Yamaguchi, S., O. Abe, S. Nakai, and A. Sato, 2007: Recent snow cover fluctuations in the mountainous areas of Japan. *Glacier Mass Balance Changes and Meltwater Discharge*, Ed. P. Ginot and J. E. Sicart, IAHS Publ., 318, IAHS Press, Wallingford, pp. 116-125.

Yamaguchi, S., H. Hirashima, M. Ishizaka, A. Sato, and M. Lehning, 2006: A study of snow cover structures in 2005/06 winter season using a numerical snow cover model. *Proceedings of 2006 Cold Region Technology Conference*, Sapporo, **22**, 44-48, in Japanese.

Yamaguchi, S., A. Sato, and M. Lehning, 2004: Application of the numerical snowpack model (SNOWPACK) to the wet-snow region in Japan. *Annals of Glaciology*, **38**, 266-272.

Yamanoi, K. and Y. Endo, 2002: Dependence of shear strength of snow cover on density and water content. *Seppyo*, **64**, 443-451, in Japanese with English abstract.

Yokoyama, K., H. Ohno, Y. Kominami, S. Inoue, and T. Kawakata, 2003: Performance of Japanese precipitation gauges in winter. *Seppyo*, **65**, 303-316, in Japanese with English abstract.