Annals of Glaciology 38 2004

Application of the numerical snowpack model (SNOWPACK) to the wet-snow region in Japan

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ABSTRACT. The snow-cover model SNOWPACK was applied to the wet-snow areas of Japan. Simulated variations of snow type, snow depth and weight, profiles of snow density, temperature and liquid-water content were compared with snow-pit measurements. The snow-depth simulation during early winter agreed with the measurements, but the differences between the simulation and the measurements increased during the course of the melt season. These differences were caused by underestimation of the energy balance at the snow surface, mainly that regarding sensible-heat flux during the melt season. The underestimation was caused by the implicit numerical treatment of the heat-transport equation. Consistent with the underestimation of snowmelt, simulated metamorphosis of compacted particles into melt forms was slower than the change shown by the measurements, and faceted snow particles, which constitute a snow type not actually found in the study area, sometimes appeared in the model. The inaccurate melt treatment also influenced simulated densities, which were larger than the measurements at small densities, while they were smaller than the measurements at large densities. Greater accuracy was achieved when an empirical compressive viscosity formulation for wet snows in Japan was introduced. A new version of SNOWPACK, with an accurate treatment of melt processes, is available.

INTRODUCTION

Numerical models are useful tools to simulate snowpack characteristics and to forecast snow avalanches. The snow-cover model SNOWPACK developed by the Swiss Federal Institute for Snow and Avalanche Research (Bartelt and Lehning, 2002; Lehning and others, 2002a,b) is one of the most valid models and has been used to forecast snow-cover development and help estimate the associated avalanche danger. It may have practically contributed to reducing the number of avalanche disasters (Lehning and others, 1999; Bartelt and Lehning, 2002). The model uses meteorological parameters as input, and as output provides predicted snowpack characteristics.

Japan has heavy snowfalls on the Sea of Japan coast, and many snow disasters occur each winter. To mitigate the risk of snow disasters, especially snow avalanches, the variations of snowpack characteristics need to be forecast. However, no study of the application of SNOWPACK to these areas has been performed. The most important difference between Switzerland, where SNOWPACK was developed, and the southern parts of Japanese areas with a seasonal snow cover is that snow deposited in these areas is predominantly wet due to the formation and percolation of meltwater even during the coldest part of the winter. Consequently, snow covers with completely different characteristics develop. The purpose of this paper is to apply SNOWPACK to heavy- and wet-snowfall areas. We present validation studies and suggestions for model improvements.

TEST SITES

Two test sites were chosen for application of the SNOWPACK model. They are located on the Sea of Japan coast, Japan's heaviest-snowfall area. One of the study sites was the Nagaoka Institute of Snow and Ice Studies (NISIS) (37°25′ N, 138°53′ E; 97 m a.s.l.), where mean daily air temperature during winter (December–February) was $>2°C$ and deposited snow was wet due to the formation and percolation of meltwater throughout the winter. Another site was the Shinjo Branch, NISIS (SB) (38°47′ N, 140°19′ E; 127 m a.s.l.), where deposited snow was dry at least during the coldest period (January).

Meteorological and snow-cover data

The meteorological data obtained at both sites were air temperature, relative humidity, wind speed, incoming and outgoing shortwave radiation, net radiation (directly measured) and precipitation. Moreover, variations of snow depth and snow water equivalent (SWE) were measured. The parameters were measured automatically at 1 hour intervals. The datasets used in this study were obtained in 1997/98, 1998/99, 1999/2000, 2000/01 and 2001/02 at NISIS and in 2001/02 at SB.

Snow-pit investigations were carried out at 0900 h at 5 day intervals during 2000/01 and 2001/02 at NISIS, and at 10 day intervals during 2001/02 at SB. The elements examined in the snow-pit investigation were snow depth,

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stratigraphic factors, snow type, snow density, snow temperature and liquid-water content. Liquid-water content was measured using a dielectric probe (Denoth type). The parameters were measured at 5–10 cm intervals.

METHODS

Simulated results of SNOWPACK were compared with snow-pit measurements using the objective snow-profile comparison method (Lehning and others, 2001) and additional statistical analyses (Lundy and others, 2001).

Simulation conditions

In order to simulate snow characteristics (e.g. snow type, snow temperature, density, and liquid-water content), SNOWPACK requires the following meteorological data: air temperature, relative humidity, wind speed, shortwave radiation, snow surface temperature and/or incoming longwave radiation, and snow depth and/or precipitation (Lehning and others, 2002b).

In this study, the mass added through snowfall was determined based on the variations in measured snow depth. New-snow density (ρ_{new}) was treated as the following empirical function obtained from data gathered in the northern part of Honshu island, Japan (Kajikawa, 1989):

$$\rho_{\mathrm{new}} = 3.6V_{\mathrm{W}} - 0.2T_{\mathrm{A}} + 62\,, \quad (\mathrm{kg\,m^{-3}}) \tag{1}$$

where T_{A} is air temperature and V_{W} is wind speed.

Snow surface temperature and incoming and outgoing longwave radiation were not measured at either site, but were estimated based on the following methods: When air temperature was $<0°\mathrm{C}$, snow surface temperature was set to the air temperature; when air temperature was $>0°\mathrm{C}$, snow surface temperature was set to $0°\mathrm{C}$. Since most air temperatures were $>0°\mathrm{C}$ at both sites, we expect only a small influence on the simulation results. Incoming longwave radiation was determined using the measured net radiation and the estimated surface temperature by means of Planck's law.

Although the conventional SNOWPACK model does not require surface albedo values (Lehning and others, 2002b), each daily mean albedo estimated from incoming and outgoing shortwave measurements was introduced into the simulation in order to eliminate errors arising from the albedo estimation in this study.

Comparison algorithms

The simulated profile had much higher resolution and finer structure than did the measured profile, and differences were seen between simulated snow depth and measurements. Thus, for a quantitative comparison of measured and simulated profiles, a mapping procedure was required. We calculated agreement scores for all parameters based on algorithms described in Lehning and others (2001), but the following new equation was introduced to calculate scores for snow temperature, density and water contents:

$$S^{X}_{\mathrm{profile}} = 1\tanh\left\{\frac{1}{N}\frac{\sum_{i=1}^{N}\left|X_i^{\mathrm{obs}} - X_i^{\mathrm{mod}}\right|}{\max[1, \max(X^{\mathrm{obs}}) - \min(X^{\mathrm{obs}})]}\right\}. \tag{2}$$

Here S^{X}_{profile} is the agreement score, N is number of data, and X_i^{obs} and X_i^{mod} are a set of N predicted and measured data pairs, respectively.

Each score shows fluctuation between 1 and 0, where 1 is the maximum and 0 stands for no agreement.

A study focusing on the statistical validation of the SNOWPACK model was performed in an area having a Montana (U.S.A.) climate (Lundy and others, 2001). Similar methods were applied to the standard evaluation of SNOWPACK. In this study, the following three statistical parameters were used for discussion:

Mean deviation (D), which indicates the model's tendency towards overestimation or underestimation,

$$D = \frac{\sum_{i=1}^{N}\left(X_i^{\mathrm{mod}} - X_i^{\mathrm{obs}}\right)}{N}\,. \tag{3}$$

Root-mean-square error (RMSE), which estimates the expected magnitude of error associated with a model's prediction,

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(X_i^{\mathrm{mod}} - X_i^{\mathrm{obs}}\right)^2}{N}}\,. \tag{4}$$

Pearson's correlation coefficient (r), which indicates positive linear correlation with positive values and negative linear correlation with negative values.

$$r = \frac{\sum_{i=1}^{N}\left[\left(X_i^{\mathrm{mod}} - \mu^{\mathrm{mod}}\right)\left(X_i^{\mathrm{obs}} - \mu^{\mathrm{obs}}\right)\right]}{\sqrt{\sum_{i=1}^{N}\left(X_i^{\mathrm{mod}} - \mu^{\mathrm{mod}}\right)^2 \cdot \sum_{i=1}^{N}\left(X_i^{\mathrm{obs}} - \mu^{\mathrm{obs}}\right)^2}}\,. \tag{5}$$

Here, μ^{mod} and μ^{obs} are the means of the predicted and measured datasets, respectively. The correlation coefficient has an upper bound of 1 (perfect positive linear correlation) and lower bound of -1 (negative linear correlation).

RESULTS

Snow depth

Figure 1a–c show the snow-depth measurements and simulations for 2001/02 at NISIS, 2000/01 at NISIS and 2001/02 at SB. The simulation in 2001/02 at NISIS was in good agreement with the measurements (Fig. 1a). The snow-cover disappearance dates were 11 March in the measurements and 17 March in the simulations, and the maximum snow-depth error was 16 cm on 7 February. The snow-depth error was defined by subtracting measured snow depth from simulated snow depth. On the other hand, the simulations in 2000/01 at NISIS and 2001/02 at SB showed large differences from the measurements (Fig 1b and c). Both simulated snow depths corresponded closely with measurements before mid-February, but the snow-depth errors increased during the course of the melt season due to slower decrease of simulated snow depths. The maximum deviation between measured and simulated snow depth was approximately 60 cm at NISIS and 50 cm at SB.

Figure 2 shows the relationship between maximum snow depth and maximum snow-depth error in 1997/98, 1998/99, 1999/2000, 2000/01, 2001/02 at NISIS, and in 2001/02 at SB. It is apparent from this figure that maximum error increases with maximum snow depth when SNOWPACK is applied to wet- and heavy-snowfall areas in Japan. It is likely that snow-depth errors significantly affect snow characteristics. Thus, only simulations of snow characteristics in 2001/

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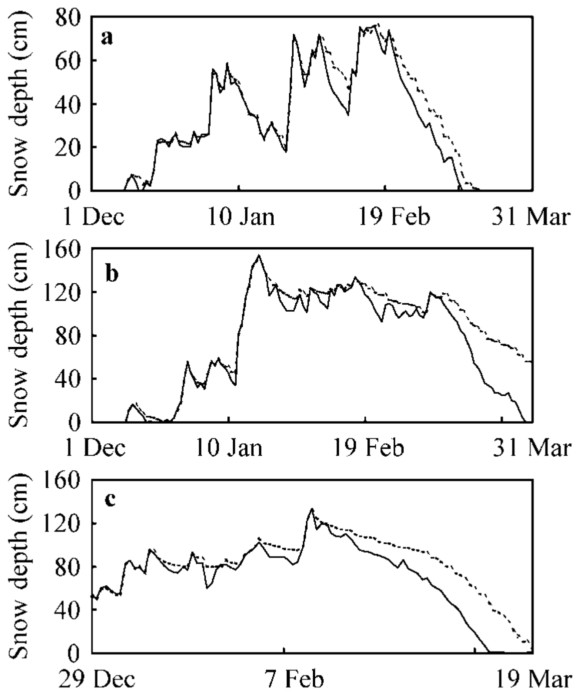

Fig. 1. Comparisons between snow-depth measurements and simulations. Solid lines indicate measurement, and dashed lines indicate simulation. (a) NISIS in 2001/02; (b) NISIS in 2000/01; (c) SB in 2001/02.

02 at NISIS were used for a detailed analysis because the simulated snow depths agreed closely with measurements.

Quantitative profile comparison

Figure 3 summarizes the individual and overall agreement scores for NISIS in 2001/02. The average total score was 0.75, which is smaller than the scores reported in the European Alps (Lehning and others, 2002b). The scores for snow temperature and snow type showed high values and small fluctuations, while those for snow density and liquid-water content showed large fluctuations (Fig. 3; Table 1). These results imply that the methods for simulating density and liquid-water content need to be improved.

In the following, detailed analyses are carried out to account for the differences between simulation and measurements.

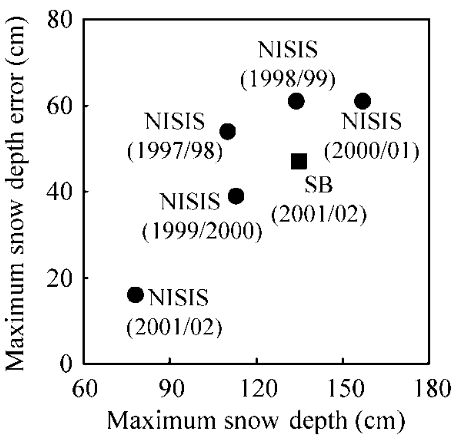

Fig. 2. Comparisons between maximum snow depth and maximum snow-depth error.

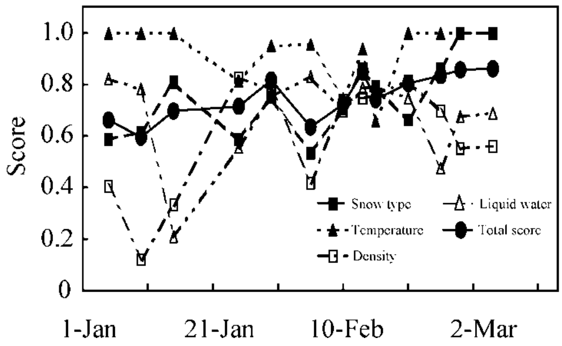

Fig. 3. Time series of individual and overall agreement scores between the measurement profile and simulations at NISIS in 2001/02.

Snow type and snow temperature

Figure 4 shows comparisons of snow-type simulations and measurements for winter 2001/02 at NISIS. Measured snow was usually wet even during mid-winter because of melt-water, and the simulation showed similar trends; that is, melt forms appeared in all seasons.

One reason for the decreasing agreement score is that the simulated speed of the change of (lightly) compacted snow into melt forms was slower than in the measurements. Another reason is that the model occasionally constructed unrealistic snow types. Faceted particles appeared on 28 December, 15 January and 25 February in the simulations, but such a snow type was never observed at NISIS during winter 2001/02.

Most of the snow-temperature measurements and simulations were 0°C. Negative temperatures were measured on only three days during the snow-pit survey, whereas seven days had negative temperatures in the simulation. Thus SNOWPACK sometimes simulated lower temperatures than those measured.

In the model, the factor of snow-grain roundness (sphericity) is treated as a function of temperature gradient (Lehning and others, 2002a). When the temperature gradient is $<5°C\,m^{-1}$, the individual snow grains' sphericity increases and their shapes become rounder. Conversely,

Table 1. Parameter scores at NISIS in 2001/02

	Average	*Maximum*	*Minimum*
Snow type	0.75	1.00	0.53
Snow temperature	0.93	1.00	0.75
Density	0.59	0.83	0.12
Liquid-water content	0.68	0.83	0.21
Total score	0.75	0.86	0.59

Table 2. Statistical measures comparing the predicted and observed snowpack parameters

	Number of samples	*D*	*RMSE*	*R*
Density	109	$-55.7\,kg\,m^{-3}$	$93.5\,kg\,m^{-3}$	0.71
Liquid-water content (% by weight)	113	−0.21%	5.00%	0.21

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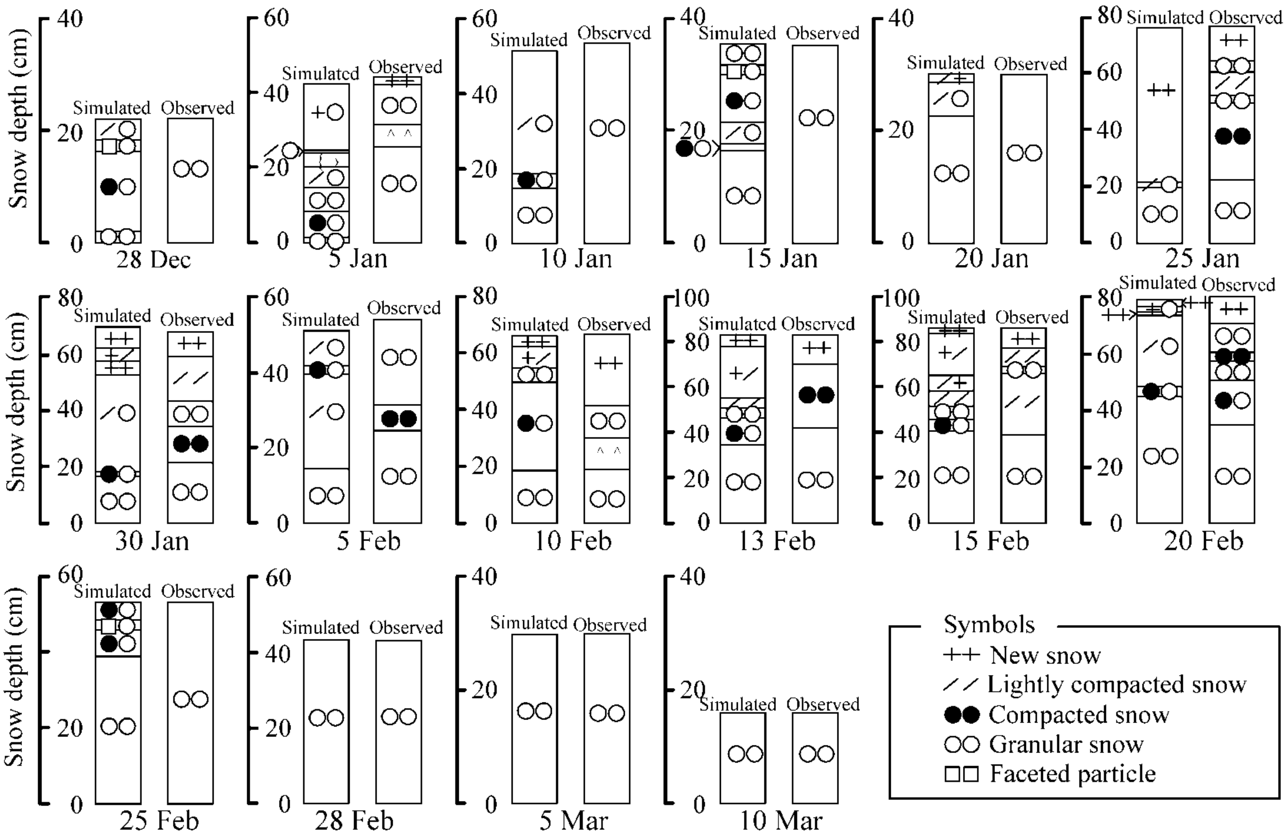

Fig. 4. Comparisons between snow-type measurement and simulations in 2001/02 at NISIS.

sphericity decreases and snow grains become more angular when the temperature gradient is $>5°\mathrm{C\,m^{-1}}$. Thus the appearance of unrealistically faceted particles is caused by the larger simulated temperature gradients associated with the lower temperatures.

Density and liquid-water content

Table 2 summarizes the results of the descriptive statistical analysis of density and liquid-water content in 2001/02 at NISIS. All measured density values and all measured liquid-water values which were not zero were used to compare with the simulations at the corresponding height.

It is apparent from the RMSE of $93.5\ \mathrm{kg\,m^{-3}}$ that SNOWPACK had difficulty predicting snow-cover density. A mean deviation (D) of $-55.7\ \mathrm{kg\,m^{-3}}$ indicates that most of the prediction error was due to underestimation of the density.

Figure 5a shows comparisons between the density measurements and simulations. It indicates that simulated densities were overestimated when they were $<200\ \mathrm{kg\,m^{-3}}$, and underestimated when $>200\ \mathrm{kg\,m^{-3}}$. These trends correspond well with the results obtained in the Montana climate (Lundy and others, 2001). One of the reasons why a larger density appeared at a small density may be the overestimation of snow depth. In the model, the amount of new snow is estimated based on the difference between simulated and measured snow depth (Lehning and others, 2002b), so overestimation of snow depth causes underestimation of the amount of new snow.

The comparison of predicted and observed liquid-water content was problematic. The simple water-transport routine employed in SNOWPACK works with a fixed volumetric residual water content of 0.025 (Bartelt and Lehning, 2002), which results in a poor description of quantitative values of layer liquid-water percentage per weight. The water-transport routine is, however, computationally effective and produces a reasonable wetting front and runoff prediction (Etchevers and others, 2004). The poor results of Table 2 with a RMSE of 5.0% have therefore to be interpreted with caution. A mean deviation (D) of −0.21% indicates that the model slightly underestimated

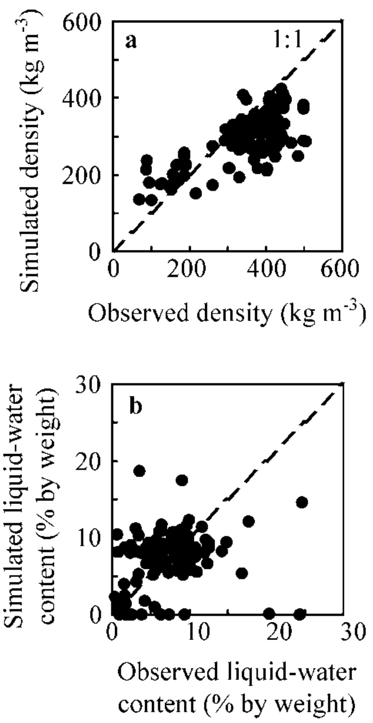

Fig. 5. Comparisons between measurement and simulation in 2001/02 at NISIS: (a) density; (b) liquid-water content.

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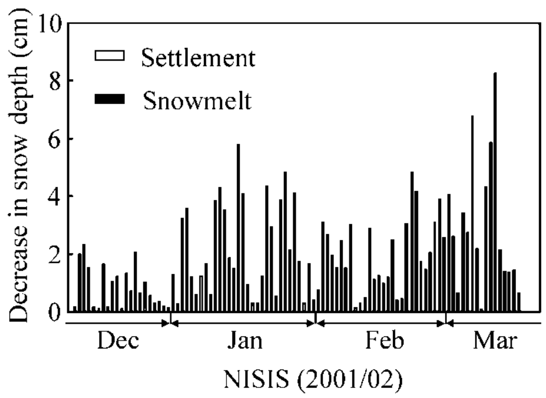

Fig. 6. Comparison between snow settlement and snowmelt in 2001/02 at NISIS.

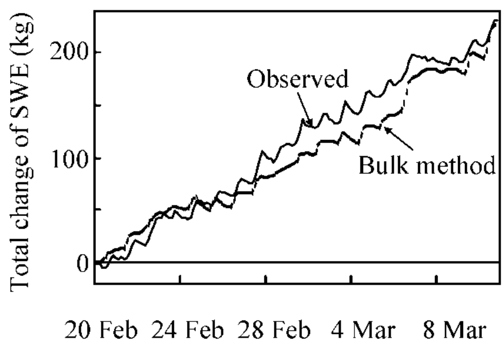

Fig. 7. Comparison of changes of snow weight between measurement and bulk method. Solid line indicates measurement, and dashed line indicates bulk method.

liquid-water content. Figure 5b shows comparisons between the measured and calculated liquid-water content. The graph and the low correlation coefficient ($r = 0.21$) suggest that there was only a very weak linear correlation. Liquid-water contents were sometimes estimated as 0% in the simulation although liquid water was detected in the measurements. These errors may be caused by the underestimation of snow temperature.

DISCUSSION

Main source of snow-depth error

Decrease in snow depth is caused mainly by two factors: snowpack settlement and snowmelt. Figure 6 shows the simulated ratio between snow-depth decrease due to snowmelt and that due to snow settlement. Snowmelt was estimated by subtracting simulated settlement from simulated snow-depth change.

The figure reveals that snowmelt was the dominant factor in the snow-depth decrease throughout the winter. It is thus inferred that snow-depth errors, which appeared at the end of winter, were caused by the underestimation of snowmelt. Therefore, in the following, we examine the surface energy balance for a melting period (20 February–10 March).

The energy balance at the snow surface can be estimated by means of the bulk method:

$$Q_e = Q_s + Q_l + Q_n\,. \tag{6}$$

Here, Q_e is the energy balance at the surface, Q_s is sensible-heat flux, Q_l is latent-heat flux and Q_n is net radiation. Q_n is measured directly, while sensible- and latent-heat fluxes are estimated using the following equations:

$$Q_s = -\alpha \rho_a c_{pa} V_W (T_A - T_S)\,, \tag{7}$$

$$Q_l = -\alpha \frac{0.622 L^{w/i} \rho_a}{P_a} V_W \left[e_s^w(T_A)\mathrm{rH} - e_s^i(T_S) \right]. \tag{8}$$

Here ρ_a is the density of air, c_{pa} is the heat capacity, T_s is snow surface temperature and P_a is air pressure. $L^{w/i}$ are the latent heat for vaporization and sublimation, respectively, $e_s^{w/i}$ is the saturation vapor pressure over water and ice, and rH is relative humidity. Assuming that the snow temperature was 0°C during this period and all of Q_e was consumed in snowmelting, the value of bulk coefficient α can be determined to fit the realistic change of SWE (Fig. 7). Its value was 2.3×10^{-3} in this study. It is emphasized that this method does not say anything about the true value of the surface heat fluxes but we have adopted a constant value of the exchange coefficient such that the decrease in snow depth and SWE becomes as large as in the observation. This becomes important in the analysis presented below.

Sensible- and latent-heat fluxes in SNOWPACK are estimated based on Monin–Obukhov similarity theory with the assumption of a neutral atmospheric surface layer (Lehning and others, 2002b). For our simulations, the value of roughness length adopted was 7.0×10^{-4} m.

Figure 8a–d show the relations between our "best-fit" bulk method and the simulation of energy balance at the snow surface, sensible-heat flux, latent-heat flux and net radiation at each hour during this period.

Table 3 summarizes the results of the descriptive statistical analysis for energy balance at the surface and each heat flux during this period. The comparison shows that on average an additional amount of −11.9 W m^{-2} would be required to reproduce the snow-mass decrease as observed. This is consistent with results obtained in the Snow Models Intercomparison Project (SnowMIP; Etchevers and others, 2004).

Figure 8a further reveals that the energy balance at the surface in the model corresponded to the measurements

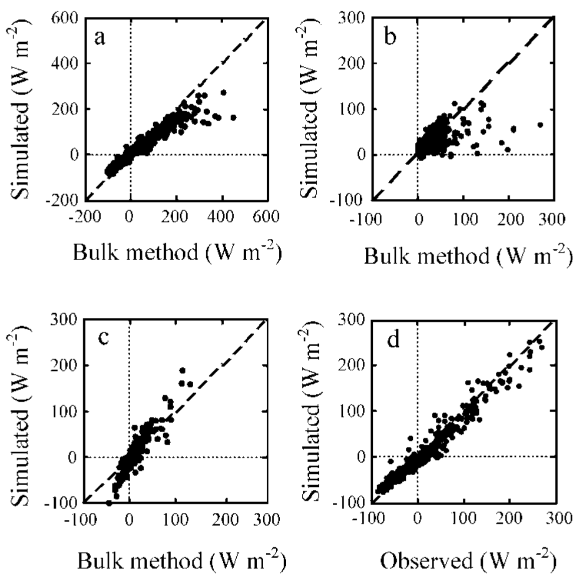

Fig. 8. Comparisons between bulk method and simulation in 2001/02 at NISIS. Net radiation was measured directly. (a) Energy balance at surface; (b) sensible-heat flux; (c) latent-heat flux; (d) net radiation.

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Table 3. Statistical measures comparing the predicted and observed heat-budget parameters

	Number of samples	D	RMSE	R
		$W\,m^{-2}$	$W\,m^{-2}$	
Energy balance	456	−11.9	38.4	0.96
Sensible-heat flux	456	−5.1	27.0	0.64
Latent-heat flux	456	−2.2	13.0	0.91
Net radiation	456	−4.6	15.2	0.98

when values were $<200\ W\,m^{-2}$, while the underestimations appeared with larger values. Although negative mean deviations (D) in both net radiation and latent-heat flux indicate that the simulations tended toward underestimation, each high correlation coefficient r (0.98 in net radiation; 0.96 in latent-heat flux) indicates accurate reconstruction. Simulated net radiation calculated from the balance of incoming and outgoing short- and longwave radiation agreed closely with the measurements because in this study the values of daily mean measured albedo were introduced into the model (Fig. 8d). Simulated latent-heat fluxes were very close to the measurements, although there was some underestimation at negative values and overestimation at large values (Fig. 8c).

On the other hand, it is apparent from the large RMSE of 27.4 $W\,m^{-2}$ and low correlation coefficient ($r = 0.64$) that SNOWPACK simulations of the sensible-heat flux did not correspond to the "best-fit" bulk method. Negative mean deviation (D) indicates underestimation of sensible-heat flux. Figure 8b reveals that most simulated sensible-heat fluxes were smaller than those independently determined by the "best-fit" bulk method, and the differences between them increased as the sensible-heat fluxes increased. This discrepancy is explained in the following way: SNOWPACK uses an implicit numerical scheme to calculate the temperature distribution (Bartelt and Lehning, 2002). This scheme adapts the surface temperature during numerical iterations to the temperature of the new time-step. Because the scheme is implicit, the surface fluxes which depend on the surface temperature, i.e. particularly the sensible-heat flux and to a smaller degree net longwave radiation and latent-heat flux, are adapted too. This scheme is correct for a non-phase-changing snow cover. However, it becomes inaccurate for a phase-changing snow cover because melt processes are treated explicitly after the temperature distribution is calculated. Therefore, when the temperature distribution of a new time-step shows temperatures $>0°C$, the temperatures are set back to 0°C and the additional energy is used to melt snow. In reality, however, the snow surface temperature stays at 0°C, and higher fluxes of heat to the snow surface are occurring than calculated by SNOWPACK because its numerical surface temperature is $>0°C$. This scheme is responsible for surface heat fluxes being underestimated for melt situations. Currently, first tests are being performed with a numerical scheme that avoids this inaccuracy. Since the error depends on the numerical calculation time-step, a sensitivity calculation has been performed with a time-step of 5 min instead of the default 15 min. The total simulated sensible-heat flux during the period became almost the same as the "best-fit" bulk method.

The values of sensible- and latent-heat fluxes in SNOWPACK depend also on the roughness length z_0; so simulations were carried out using various values of z_0 (Table 4). Although maximum snow-depth errors decreased with increases in z_0, >15 cm errors still remain even in the case of $z_0 = 2$ cm.

Improvement of compressive viscosity

Underestimations of large density seen in Figure 5a imply the possibility that snow densification was smaller than observed.

The compressive viscosity of wet snow is generally less well known than that of dry snow, and the snow cover at NISIS was usually wet throughout the winter. Although the compressive viscosity of wet snow is treated as a function of liquid-water content, which was obtained in the Swiss Alps (cf. equation (31) by Lehning and others, 2002a), it is possible that SNOWPACK is not suitable for the wet-snow zone in Japan.

Kojima (1967) found that the relation between the compressive viscosity (η) and dry densities (ρ_{dry}) can be applied to wet snow by subtracting the contribution of free water from wet-snow density having a free-water content of $<5\%$. Endo and others (2002) then described the depth and the density of hourly new snow in the wet-snow areas of Japan using the following equation:

$$\eta = 0.392\rho_{dry}^{4.1}\,. \tag{9}$$

We attempted to introduce Equation (9) in SNOWPACK, assuming that it holds when the liquid-water content is $>5\%$.

Figure 9 shows the density scores obtained through simulation using the conventional formula and Equation (9). The latter became slightly higher than the former. Therefore, the introduction of Equation (9) into SNOWPACK may be a necessary improvement when the model is

Table 4. Relationships between maximum snow-depth error (cm) and z_0

	$z_0 = 7\times10^{-4}$ m	$z_0 = 5\times10^{-3}$ m	$z_0 = 1\times10^{-2}$ m	$z_0 = 2\times10^{-2}$ m
Max. snow-depth error				
NISIS in 2001/02	16.0	14.4	12.0	10.4
NISIS in 2000/01	61.0	36.7	15.0	14.6
NISIS in 1999/2000	39.4	27.9	23.5	17.0
NISIS in 1998/99	60.7	32.8	23.6	21.8
NISIS in 1997/98	54.8	40.3	26.6	23.6
SB in 2001/02	46.5	31.5	23.0	18.9

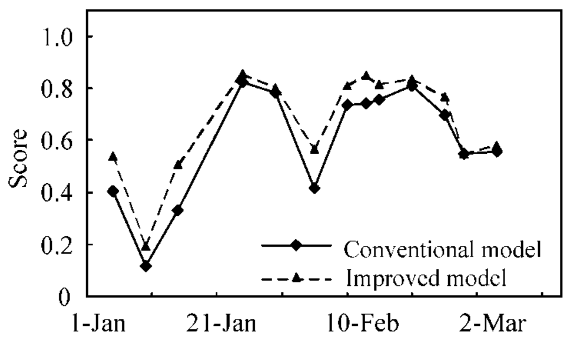

Fig. 9. Comparison of agreement score of density between conventional model and improvement model. Solid line indicates the simulation result by the conventional model. Dashed line indicates the simulation result by the improvement model with Equation (9).

applied to warm heavy-snowfall areas. However, the improvement is small compared to the absolute error. Therefore, it appears that problems in the simulation of liquid-water content (Fig. 5) cause most of the error in the wet-snow settlement simulation.

CONCLUSIONS

SNOWPACK was applied to wet snow in heavy-snowfall areas located on the Japan Sea coast. Simulation and snow-pit observations were compared, revealing the following tendencies.

The simulated snow-depth variation during early winter agreed with the observed results, whereas the differences between the simulations and observations increased as the melting season advanced. The maximum snow-depth error increased with the increase of maximum snow depth. These differences between simulation and observations are most likely caused by the implicit numerical solution of the energy equation in SNOWPACK. For frequent melt–freeze cycles, such as commonly occur during the ablation period, this solution leads to an underestimation of the sensible-heat flux. A new version of SNOWPACK, which avoids this error, is now available and results will be presented in the near future.

The overall agreement score was 0.75, which is smaller than the results obtained in the European Alps. This is again most likely because of the predominance of wet-snow dynamics in Japan, which are not completely accurate in the current version of SNOWPACK. The best score obtained was for snow temperature (0.93), and the worst was for snow density (0.59).

The speed of the change of compacted particles into melt forms in the model was slower than that shown by observations. An inaccurate snow type, faceted particle snow, sometimes appeared in the simulation results. These results may again be attributed to an inaccurate treatment of melt processes leading to a lower estimation of snow temperature in the model.

In order to improve the agreement of snow density, the compressive viscosity obtained for wet snow in Japan was introduced. This slightly improved the score.

Overall, the SNOWPACK model can predict the snow characteristics of the wet-snow areas in Japan, but improvements are needed and are currently being implemented.

Reconstruction of snowmelt is a very important factor for forecasting practical snowpack characteristics in these areas since large snowmelt takes place throughout the winter. Thus the simulation method with respect to wet-snow dynamics must be improved. Another possible source of errors not discussed here is the fact that SNOWPACK assumes neutral atmospheric stability for calculating the surface energy exchange.

This study is the first step to improve SNOWPACK to make it applicable to wet-snow areas. It has already led to an improvement of the phase-change treatment in the numerical scheme of SNOWPACK, avoiding the error of underestimating the heat flux during melt periods. This new version is currently being validated.

ACKNOWLEDGEMENTS

We would like to thank K. Nishimura of NISIS and H. Hirashima and E. Baba of the Institute of Low Temperature Science, Hokkaido University, for their useful suggestions. We are very grateful for the valuable comments by P. Etchevers and F. Pellicciotti, which helped greatly to improve the paper.

REFERENCES

Bartelt, P. and M. Lehning. 2002. A physical SNOWPACK model for the Swiss avalanche warning. Part I. Numerical model. *Cold Reg. Sci. Technol.*, **35**(3), 123–145.

Endo, Y., Y. Ohzeki and S. Niwano. 1990. [Relation between compressive viscosity and density of low-density snow.] *Seppyo*, **52**(4), 267–274. [In Japanese with English summary.]

Etchevers, P. *and 22 others.* 2004. Validation of the surface energy budget simulated by several snow models (SnowMIP project). *Ann. Glaciol.*, **38** (see paper in this volume).

Kajikawa, M. 1989. [Relationship between new snow density and shape of snow crystals.] *Seppyo*, **51**(3), 178–183. [In Japanese with English summary.]

Kojima, K. 1967. Densification of seasonal snow cover. *In* Ōura, H., *ed. Physics of snow and ice. Vol. 1, Part 2.* Sapporo, Hokkaido University. Institute of Low Temperature Science, 929–952.

Lehning, M., P. Bartelt, B. Brown, T. Russi, U. Stöckli and M. Zimmerli. 1999. SNOWPACK model calculations for avalanche warning based upon a new network of weather and snow stations. *Cold Reg. Sci. Technol.*, **30**(1–3), 145–157.

Lehning, M., C. Fierz and C. Lundy. 2001. An objective snow profile comparison method and its application to SNOWPACK. *Cold Reg. Sci. Technol.*, **33**(2–3), 253–261.

Lehning, M., P. Bartelt, B. Brown, C. Fierz and P. Satyawali. 2002a. A physical SNOWPACK model for the Swiss avalanche warning. Part II. Snow microstructure. *Cold Reg. Sci. Technol.*, **35**(3), 147–167.

Lehning, M., P. Bartelt, B. Brown and C. Fierz. 2002b. A physical SNOWPACK model for the Swiss avalanche warning service. Part III. Meteorological forcing, thin layer formation and evaluation. *Cold Reg. Sci. Technol.*, **35**(3), 169–184.

Lundy, C., R. L. Brown, E. E. Adams, K.W. Birkeland and M. Lehning. 2001. A statistical validation of the SNOWPACK model in a Montana climate. *Cold Reg. Sci. Technol.*, **33**(2–3), 237–246.