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A simple snow-cover model for avalanche warning in Japan

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Abstract

This paper describes a simple snow-cover model (SSCM) that was developed primarily to evaluate the hazard to traffic posed by snow avalanches. The SSCM requires only air temperature and precipitation or snow depth as input data, and we simplified the physical processes that affect the snowpack in the model. Snow pit observations and the calculation for avalanche cases were carried out to verify the SSCM output. The SSCM was able to reproduce the change in the snowpack properties fairly well. Further, the snow stability index, which shows the ratio of shear strength to shear stress in the snow, indicated that the SSCM can be used to provide a reliable estimate of avalanche hazard.

1. Introduction

Avalanche-prone locations in Japan range from small roadside slopes to mountain ski resorts. The most common avalanche type that affects roads in winter are dry-snow slab and dry loose snow avalanches, which are usually caused by the release of a new snow

layer that accumulated during a heavy snowfall over a short period. Recently, many avalanches have occurred along the national road network, not only in the snowy region along the Sea of Japan, but also in the region of Tohoku on the Pacific coast. Although the latter is typically seen as a region that is less affected by snowfall, since 2010 it has experienced heavy snowfall events generated by cyclones that developed rapidly along the south coast of Japan. In particular, during February 2014 a record-breaking snowstorm caused the historical maximum snow depth of 114 cm at Koufu, Yamanashi and nearly 100 avalanches were recorded (Izumi et al., 2014).

Full-depth avalanches occasionally develop from pre-existing cracks and/or folds in the snow cover. However, no clear warning signs of impending slope failure are evident prior to the release of dry-snow slab and dry loose snow avalanches. At present, Japanese road administrators monitor the snow avalanche hazard only by measuring snowfall amounts. However, this simple method is not always able to estimate avalanches precisely, as additional factors such as the existence of weak layers in the snowpack and slope angle are involved in avalanche release.

Sophisticated snow-cover models, such as SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002) and Crocus (Brun et al., 1989, Vionnet et al., 2012), consider numerous physical processes, which are carefully reviewed by Morin et al. (2019). Both models require various meteorological inputs, including downward short- and longwave radiation. However, the currently available datasets generated by the Global Spectral Model and provided by the Japan Meteorological Business Support Center have a 20-km grid spacing and are updated every 6-hours. They are far from satisfactory because snow properties are very sensitive to weather conditions and can change rapidly. These limitations can be overcome by using the precipitation and surface air temperature

products available from the Japan Meteorological Agency (JMA) on a 1-km grid, which are updated every hour.

In this study, we have developed a simple snow-cover model (SSCM) that requires only air temperature and precipitation or snow depth data as inputs. The model is intended to describe grain type, temperature, and density profiles, as well as evaluate the avalanche hazard. The physical processes incorporated into the SSCM were greatly simplified. Therefore, the simulation requires only limited computing power and allows the user to generate numerous simulations within a short period over a wide area and at small grid scales.

In this paper, we provide an outline of our SSCM. Although it has been developed aiming for the operational avalanche warning, we use the observed meteorological data and the performance of the model is verified by comparing with snow pit observations and previous avalanche incidents.

2. Data and study methods

2.1 Model description

The process used to generate the avalanche warnings, including the estimate of snowpack properties simulated by the SSCM, is shown schematically in Fig. 1. The calculations are run from two to three days before the snowfall and the outputs are the snow properties from the snow surface to the base of the newly fallen snow every hour. The only inputs to the model are air temperature and precipitation or snow depth. The hourly snowfall amount is added to the snowpack as a new layer and its temperature is set to the air temperature. In the present study, we assume rainfall did not occur during

the study period. Other snowpack properties (e.g., snow density, thickness, grain type, and shear strength from the surface to the bottom) are estimated for each layer. Then, by considering the slope angle, the snow stability index (SI: the ratio of shear stress to the snow's shear strength) is estimated.

Our model estimates the possibility of an avalanche being released during a storm or over a couple of days following a snowfall. This is because the potentially weak layers are located mostly within or just below the newly accumulated snow. This differs from other detailed models, such as SNOWPACK and Crocus, in which the simulations are carried out for the entire depth of the snow cover.

Ideally, the snow temperature should be obtained by solving the heat transfer equation. However, in this study, in order to make all the processes as simple as possible, we applied the procedures shown below. Since we use hourly snowfall to set one layer, the thickness of each layer is supposed to be fairly small. Thus, the snow temperature at time i and depth j , $T_s(i, j)$ ($^{\circ}\text{C}$), can be set using the approach by Suizu (2002) that considers each layer and its adjacent layers at one time step before using Eq. (1), as follows:

$$\begin{aligned}
 T_s(i, j) &= \frac{(T_a(i-1) + T_a(i))}{2} & j = 1 \\
 T_s(i, j) &= \frac{(T_s(i-1, 1) + T_s(i, 1) + T_s(i-1, 2))}{3} & j = 2 \\
 T_s(i, j) &= \frac{(T_s(i-1, j-2) + T_s(i-1, j-1) + T_s(i-1, j))}{3} & \text{for } j \geq 3
 \end{aligned} \tag{1}$$

The precipitation amount, given as input p in kg m^{-2} , is converted to the new snowfall depth H_0 (m) according to the new snow density ρ_0 in kg m^{-3} :

$$\rho_0 = \begin{cases} 54 & \text{for } T_a \leq -2 \text{ }^{\circ}\text{C}, \\ 79 + 12.5 T_a & \text{for } T_a > -2 \text{ }^{\circ}\text{C} \end{cases} \tag{2}$$

Equation (2) was developed by Suizu (2002) based on the observations of Endo et al.

(2002) and Kajikawa (1989), where T_a is the air temperature.

Except for the surface layer, the snow density is derived from viscous compression theory. The density of a layer at time i is derived from that at $i - 1$ and the overburden pressure caused by the snow layers above. Endo et al. (2004) derived the relationship between the viscosity coefficient and the density based on several observations made by Kojima (1967), Nakamura (1988), Kajikawa and Ono (1990), Yamanoi and Endo (1998), and others. The viscosity coefficient η (Pa s) is defined as follows:

$$\eta = \begin{cases} C_1 \rho^a & \text{for } \rho \leq 200 \text{ kg m}^{-3} \\ C_2 \exp(k\rho) & \text{for } \rho > 200 \text{ kg m}^{-3} \end{cases} \quad (3)$$

where C_1 is $1.78 \exp(-0.0958 T_s)$, C_2 is $3.44 \times 10^6 \exp(-0.0958 T_s)$, and a and k are 3.69 and 0.0253, respectively. Using the above procedures, temporal evolution of the thickness H of each snow layer can be obtained.

We classified the grain type using the scheme of Saito and Enomoto (2003). This scheme uses the effective temperature gradient g_t , which was introduced by Yamazaki (2001), to identify the point where depth hoar (DH) begins to form, and g_t is defined as follows:

$$g_t = \begin{cases} \Gamma f(T_s) & \text{for } \Gamma \geq 10 \text{ } ^\circ\text{C m}^{-1} \\ 0 & \text{for } \Gamma < 10 \text{ } ^\circ\text{C m}^{-1} \end{cases} \quad (4)$$

Here, $\Gamma = \frac{\partial T_s}{\partial z}$ is the temperature gradient, and,

$$f(T_s) = \frac{D_v(T)\delta(T)}{D_v(T_0)\delta(T_0)} \cong 1 + 0.073T_s + 0.00197T_s^2 + 0.0000187T_s^3$$

(5)

D_v is the diffusion coefficient of water vapor and δ is the differential coefficient of saturated vapor density with respect to temperature. Both decrease as temperature

decreases. The time integral G_t of g_t can be expressed as:

$$G_t(t + \Delta t) = G_t(t) + g_t \Delta t \quad (6)$$

Based on G_t and the snow density ρ , the grain type can be classified as decomposing and fragmented precipitation particles (DF), rounded grains (RG), faceted crystals (FC), or DH (Fig. 2). Grain types and their characteristics can be found in the International Classification for Seasonal Snow on the Ground (Fierz et al., 2009).

When the grain type is classified as precipitation particles (PP) or DF or RG, the shear strength of snow can then be calculated as follows (Yamanoi and Endo, 2002):

$$\sigma_A = 9.40 \times 10^{-4} \rho^{2.91} \quad (7)$$

where σ_A is in Pa.

If instead the grain type is classified as FC or DH, the shear strength is set as follows (Abe et al., 2005):

$$\sigma_B = 3.91 \times 10 \exp(10^{-2} \rho) \quad (8)$$

where σ_B is expressed in Pa.

Consequently, the shear strength of the snow differs significantly depending on whether G_t is greater than 29 ($^{\circ}\text{C cm}^{-1} \text{ h}$) or not, and whether the grain type is hoar or not, even for a given snow density. Thus, to bridge the gap between Eq. (7) and Eq. (8), we added Eq. (9) to our calculation procedures:

$$\sigma = -\frac{G_t - 19}{39 - 19} (\sigma_A - \sigma_B) + \sigma_A \quad \text{for } 19 < G_t < 39 \text{ (}^{\circ}\text{C cm}^{-1} \text{ h)} \quad (9)$$

where σ is also expressed in Pa.

Finally, the snow stability index (SI_j) can be calculated as:

$$SI_j = \frac{\sigma}{(\sum_{j=1}^n \rho_j H_j g) \sin \theta} \quad (10)$$

where θ is the slope angle, ρ_j is the snow density of the layer at the depth j , and H_j is

the snow thickness over the depth j .

Perla (1977) reviewed 80 avalanche cases and found that the average SI value was 1.66, with a standard deviation of 0.98; the minimum value was 0.19, and the maximum value was 6.4. He also concluded that $SI < 1.5$ is critical for avalanche release. Further, Sommerfeld (1984) suggested that $SI \leq 1.5$ is the threshold for avalanche risk. In Japan, Hirashima et al. (2006, 2008) indicated that an SI threshold of 2 was appropriate for evaluating avalanche susceptibility.

2.2 Observed data and avalanche incidents for model evaluations

Eight snow pit observations were carried out at Mikuni Pass and two at Kiritachi Pass, in Hokkaido (Fig. 3). An example of snow pits at Mikuni Pass (1600 JST 28th January 2013) is shown in Fig. 4. Meteorological elements were measured every 10 minutes at an automatic weather station (AWS) operated by the Hokkaido Regional Development Bureau (RDB), Ministry of Land, Infrastructure, Transport and Tourism (MLIT). The snow pit observations were performed approximately 10 m from the AWS; snow temperature, density, and grain type were measured every 10 cm. Further, the shear strength of the snow was observed directly using a shear frame near the bottom, and also indirectly every 10 cm via snow hardness measurements using a push–pull gauge. In the latter case, the values obtained were converted into shear strength following Yamanoi et al. (2004), who derived the following relationship:

$$\sigma = 0.0180S^{1.18} \quad (11)$$

where S (Pa) is snow hardness and σ (Pa) is the shear strength. Evaluations were also carried out for other nine pit observations.

On February 5–6, 2018, a stationary cyclone delivered a large amount of snow to the

mountain passes of Hokkaido. At Notsuka Pass (Fig. 3; 522 m above sea level), an avalanche was released at around 1600 JST on February 5 and blocked the highway for 20 hours. Meteorological data collected at the AWS station by the Hokkaido RDB, which is 1.4 km away and 60 m higher than the avalanche site, showed nearly 40 cm of new snow had accumulated over the preceding two days and the air temperature was in the range -8 to -5 °C, as shown in Fig. 5. We also calculated SI values using the SSCM for 12 other avalanche events in Japan listed in Fig. 3.

3. Results

Fig. 4 shows the SSCM outputs for Mikuni Pass as well as the observed data. Overall snow heights often vary over distances of meters even on fairly flat terrain (Lehning et al., 2001). In fact, observed snow height at 10 m away from Mikuni AWS was 0.27 m, while simulated one based on the AWS data was 0.48 m. Thus, we stretched the SSCM profile linearly to compensate for the snow depth differences according to Lehning et al. (2001) and Lundy et al. (2001); modeled and measured snow heights were each assigned a unit height and a normalization of depth is performed. Then, the profile parameters were compared. Further, in Table 1, four agreement scores, namely, the mean bias (observed value – model value), root mean square error (RMSE), Pearson's correlation coefficient, and Willmott and Wick's index of agreement (Willmott and Wicks, 1980) were obtained for the snow temperature, density, and shear strength (Lundy et al., 2001). The agreement scores for the grain types were calculated as the simple average over the number of observed layers (Lehning et al., 2001).

Although the simulated temperatures in Fig. 4 (a) are around 2 °C lower than the

observations, the general trend from the surface to the bottom is similar. Thus, Pearson's correlation coefficient was high as shown in Table 1 (a). From the surface to 0.2 of the normalized depth, the difference in the density was within 100 kg m^{-3} (Fig. 4 (b)). Although the deviation becomes larger near the bottom, the agreement score for the total snow height was acceptable (Table 1 (a)). The shear strength values obtained from both the observations and SSCM in Fig. 4 (c) showed good agreement. Particularly the calculated values corresponded well with the values measured using the shear frame. As shown in Table 1 (a), all of the scores were reasonably well reproduced. Our pit observations showed DF between 0.4 and 1.0 of the normalized depth range. This layer represents the snow that fell on January 25 and changed to DF over the observation period. However, this layer remained as PP in the SSCM run. Below this layer, FC appeared both in the observations and the SSCM simulation. We calculated normalized distances which are the measure of agreement for the combinations of basic grain types according to Lehning et al. (2001). A score of "1" indicates perfect agreement and "0" stands for no agreement. Score in Table 1 (a) was satisfactorily high.

In addition to the example shown in Fig. 4 and Table 1 (a), other ten observations at Mikuni and Kiritachi were compared with the SSCM (see Table 1 (b)). All of the scores for the snow temperature, shear strength, and grain type were reasonably high, as was the case in Table 1 (a). In fact, they are similar to, or even better than, the scores obtained using the SNOWPACK model by Lundy et al. (2001) and Hirashima et al. (2004). On the other hand, the score for the density was lower than the others. The SSCM often outputs a lower density than the observations, probably reflecting the lower snow temperature simulation (as shown in Fig. 4). However, the bias in Table 1 (b) was not large and did not have a significant effect on the shear strength, which is key for the snow avalanche

warnings.

The SSCM calculation for the avalanche released at Notsuka Pass around 1600 JST on February 5 is shown in Fig. 5. As the depth of PP increased on February 4, the SI decreased rapidly. Then, although it increased gradually, the SI fell again due to the snowfall in the afternoon of February 5. When the SI dropped below 2.5, the avalanche was released; the model was able to accurately simulate the avalanche danger.

We also calculated SI values using the SSCM for 12 other avalanche events listed in Fig. 3 and the obtained SI values are summarized in Table 2. The minimum SI value was 0.9, and the maximum was 4.9, with an average of 2.4 and a standard deviation of 1.1. These are closely comparable with the values in the review by Pelra (1977).

4. Discussion and conclusions

We developed an SSCM in this study that can reproduce, within reasonable accuracy, the changes in snowpack properties that follow a large snowfall, and is therefore suitable for use as an avalanche warning tool. However, room for improvement remains.

Firstly, as shown in Fig. 4 (a), although the overall trend of the snow temperature calculated by the SSCM agreed well with the observations and the correlation coefficients were high, the simulated temperatures were generally lower than the observations. Consequently, the model tends to simulate a lower snow density because, as shown in Eq. (3), snow viscosity is a function of snow temperature. In fact, the values of bias in Table 1 are larger than those reported by Lundy et al. (2001) and Hirashima et al. (2008). As described before, we calculated the snow temperature simply following Eq. (1) without applying the heat transfer equation, and it might cause the differences. However, the

SNOWPACK model, which incorporates the above process as well as the heat balance on the snow surface, also occasionally simulated systematic differences from the surface to the base (Lundy et al., 2001). In particular, large deviations were recognized near the surface. Thus, this issue is left for future consideration.

Secondly, as shown in Fig. 4 (d), the snowfall on 25th January changed to DF in the observations but remained as PP in the SSCM run. This suggests that the viscous compression process as well as the snow temperature calculation should be improved.

When we applied the SSCM to the avalanche incidents in Table 2, the calculated SI values were similar to those reported by Pelra (1977). It suggests the suitability of the SSCM for use as an avalanche warning system, although the model has not been combined with meteorological forecasts at this stage. The system should also consider the effect of wind over complex topography. Wind causes snowdrift and non-uniform snow can accumulate, which sometimes increases the avalanche risk. In fact, in Table 2, the SI for avalanche case 6 at Notsuka Pass is apparently larger than the values suggested by Sommerfeld (1984) and Hirashima et al. (2006, 2008). In our calculation, we input the meteorological data from the Notsuka AWS station, which is located on the lee side of the mountain, but the wind speed was probably much higher near the avalanche release area and this is likely to have caused greater snow accumulation. The effect of snow drifts should thus be incorporated into the model to make it more precise.

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Supplements

Table S1: Main morphological grain shape classes.

References

- Abe, O., Mochizuki, S., Yamaguchi, S., Hirashima, H., Sato, A., 2005: Shear strength of depth hoar snow layers. *Cold Region Technology Conference Proceedings*, **21**, 249–252, (in Japanese).
- Bartelt, P., Lehning, M., 2002: A physical SNOWPACK model for the Swiss avalanche warning Part I: numerical model. *Cold Regions Science and Technology*, **35**, 123–145.
- Brun, E., Martin, E., Simon, V., Gendre, C., Coleou, C., 1989: An energy and mass model of snow cover suitable for operational avalanche forecasting. *J. Glaciology*, **35**(121), 333–342.
- Endo, Y., Kominami, Y., Yamanoi, K., Niwano, S., 2002: Calculation method of hourly snowfall and initial snow density using the visco-elastic deformation. *Seppyo*, **64**, 3–13 (in Japanese with English abstract).
- Endo, Y., Kominami, Y., Yamanoi, K., Takeuchi, Y., Murakami, S., 2004: Calculation method of snow depth and density from precipitation data. *Seppyo*, **66**, 17–25 (in Japanese with English abstract).
- Fierz, C., Armstrong, R., Durand, Y., Etchevers, P., Greene, E., McClung, D.,

- 276 Nishimura, K., Satyawali, P., Sokratov, S., 2009: The International Classification
277 for Seasonal Snow on the Ground. *In: Tech. Doc. Hydrol.*, **83**. UNESCO, Paris, pp.
278 80.
- 279 Hirashima, H., Nishimura, K., Yamaguchi, S., Sato, A., Lehning, M., 2006: Evaluation
280 of snow stability index in a snow cover model for avalanche accidents. *Cold
281 Region Technology Conference*, **22**. 26-30. (in Japanese)
- 282 Hirashima, H., Nishimura, K., Yamaguchi, S., Sato, A., Lehning, M., 2008: Avalanche
283 forecasting in a heavy snowfall area using the snowpack model. *Cold Reg. ci.
284 Technol.*, **51 (2-3)**. 191-203.
- 285 Izumi, K., Kawashima, K., Iyobe, T., Matsumoto, T., 2014: Characteristics of avalanche
286 accidents caused by heavy snowfall in mid-February 2014. *Department of Grants-
287 in-Aid for Scientific Research Report*, 111–118 (in Japanese).
- 288 Kajikawa, M., 1989: Relationship between the density of new snow and snow crystal
289 form. *Seppyo*, **51**, 178–183 (in Japanese with English abstract).
- 290 Kajikawa, M. Ono, N., 1990: Relationship between the compactive viscosity of new
291 snow and the shape of snow crystals. *Seppyo*, **52**, 283–287 (in Japanese with
292 English abstract).
- 293 Kojima, K., 1967: Densification of Seasonal Snow Cover. *Physics of Snow and Ice*, part
294 1, ed. Oura, Sapporo, Inst. Low Temp. Sci., Hokkaido Univ., 929-952.
- 295 Lehning, M., Fierz, C., Lundy, C., 2001: An objective snow profile comparison method
296 and its application to SNOWPACK. *Cold Regions Science and Technology*, **33**,
297 253–261.
- 298 Lehning, M., Bartelt, P., Brown, B., Fierz, C., Satyawali, P., 2002: A physical
299 SNOWPACK model for the Swiss avalanche warning Part II: Snow microstructure.

- 300 *Cold Regions Science and Technology*, **35**, 147–167.
- 301 Lundy, C., Brown, R., Adams, E., Birkeland, K., Lehning, M., 2001: A statistical
 302 validation of the snowpack model in a Montana climate. *Cold Regions Science and*
 303 *Technology*, **33**, 237–246.
- 304 Morin, S., Horton, S., Techel, F., Bavay, M., Coléou, C., Fierz, C., Gobiet, A.,
 305 Hagenmuller, P., Lafaysse, M., Ližar, M., Mitterer, C., Monti, F., Müller, K., Olef,
 306 M., Snook, J. S., van Herwijnen, A. and Vionnet, V. , 2019: Application of physical
 307 snowpack models in support of operational avalanche hazard forecasting: A status
 308 report on current implementations and prospects for the future. *Cold Regions*
 309 *Science and Technology*, **170**, 237–246.
- 310 Nakamura, H., 1988: Studies on the Settlement Force of Snow as a Generation
 311 Mechanism. *Report of the National Research Center for Disaster Prevention*, **41**,
 312 361-385.
- 313 Perla, R. 1977: Slab avalanche measurements. *Canadian Geotechnical Journal*, **14**,
 314 206-213.
- 315 Saito, Y., Enomoto, H., 2003: Development and application of snow cover model
 316 simulation., *Annual Report on Snow and Ice Studies in Hokkaido*, **22**, 33–36 (in
 317 Japanese).
- 318 Suizu, S., 2002: Calculation model for stability index of snow for dry surface snow
 319 avalanche derived by heavy snowfall. *Seppyo*, **64**, 15–24 (in Japanese with English
 320 abstract).
- 321 Sommerfeld, R. A., 1984: Instructions for using the 250 cm² shear frame to evaluate the
 322 strength of a buried snow surface., *U.S. For. Serv. Res. Note RM-446*, 1-6.
- 323 Vionnet, V., Brun1, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E. and

- Willemet, J.-M., 2012: The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2, *Geosci. Model Dev.*, **5**, 773–791.
- Willmott, C. J., Wicks, D.E., 1980: An empirical method for the spatial interpolation of monthly precipitation within California. *Phys. Geogr.* **1**, 59-73.
- Yamanoi, K, Endo, Y., 1998: Measurement of the compactive viscosity coefficient of wet snow. *Preprints of the 1998 Conference Japanese Society of Snow and Ice*, 86.
- Yamanoi, K., Endo, Y., 2002: Dependence of shear strength of snow cover on density and water content. *Seppyo*, **64**, 443–451 (in Japanese with English abstract).
- Yamanoi, K., Takeuchi, Y., Murakami, S., 2004: Estimate of snow stability index using “Push Pull Gauge”. *Seppyo*, **66**, 669–676 (in Japanese with English abstract).
- Yamazaki, T., 2001: A one-dimensional land surface model adaptable to intensely cold regions and its applications in Eastern Siberia. *J. Meteor. Soc. Japan*, **79**, 1107–1118.

Figure Captions

Table 1. Statistical analysis of the simulated and observed snowpack parameters for (a) the Mikuni-Pass, Hokkaido at 1600 JST 28th January 2013, and (b) the Mikuni Pass in January 2013 and the Kiritachi Pass in February 2013 and March 2014.

Table 2. Data for the 12 avalanches mentioned in the text. Events 1–9 occurred in Hokkaido; events 10–12 occurred in Honshu. The altitudes of events 8 and 12 correspond to the avalanche release points; for other events altitudes correspond to the elevations where the roads were covered with debris. SI values are obtained from the SSCM simulations.

Fig. 1. Schematic diagram of the simple snow cover model (SSCM).

Fig. 2. SSCM classification of snow type. Here, T_a ($^{\circ}\text{C}$) is air temperature, ρ (kg m^{-3}) is snow density, and G_t ($^{\circ}\text{C m}^{-1} \text{ h}$) is the time integral of the effective temperature gradient introduced in Eq. 6.

Fig. 3. Location of the study sites showing (★) snow pit observations in Table 1 and (●) avalanche cases in Table 2.

Fig. 4. Properties of the snow layer measured (solid line) and calculated by the SSCM (dashed line) using the data from the Mikuni AWS at 1600 JST 28 January 2013. Measured and modeled snow heights (0.27 and 0.48 m, respectively) are each

assigned a unit height. Profiles of (a) snow temperature, (b) density, (c) shear strength converted from snow hardness, and (d) grain types are shown. Square in (c) indicates the shear strength (measured using a shear frame) and the symbols in (d) follow the International Classification for Seasonal Snow on the Ground (Fierz et al., 2009). The descriptions of each symbols are shown in Supplementary materials.

Fig. 5. Time series of air temperature, snow depth, snowfall at Notsuka Pass AWS, and SI calculated using the SSCM for February 1–5, 2018.

Table 1. Statistical analysis of the simulated and observed snowpack parameters for (a) the Mikuni-Pass, Hokkaido at 1600 JST 28th January 2013, and (b) the Mikuni Pass in January 2013 and the Kiritachi Pass in February 2013 and March 2014.

(a) The Mikuni Pass (1600 JST 28th January 2013)

	n	Bias	RMSE	r	d
Snow temperature	6	2.6 °C	3.0 °C	0.9	0.7
Density	6	68.5 kg m ⁻³	85.8 kg m ⁻³	0.7	0.5
Shear strength	6	539.2 Pa	872.7 Pa	0.9	0.7

	n	Score
Grain types	6	0.9

(b) All cases for the Mikuni pass and the Kiritachi pass

	n	Bias	RMSE	r	d
Snow temperature	48	1.6 °C	2.6 °C	0.8	0.8
Density	48	38.2 kg m ⁻³	53.5 kg m ⁻³	0.6	0.6
Shear strength	46	39.4 Pa	507.2 Pa	0.6	0.7

	n	Score
Grain types	50	0.9

Table 2. Data for the 12 avalanches mentioned in the text. Events 1–9 occurred in Hokkaido; events 10–12 occurred in Honshu. The altitudes of events 8 and 12 correspond to the avalanche release points; for other events altitudes correspond to the elevations where the roads were covered with debris. SI values are obtained from the SSCM simulations.

No.	Location	Release altitude (m)	Debris runout altitude (m)	Release date	SI
1	The Sekihoku Pass		844	1100 JST 14th January 2004	2.5
2	Wakkanai		12	1845 JST 13th February 2008	0.9
3	The Notsuka Pass		423	1700 JST 19th February 2010	3.4
4	Bekkari		55	0330 JST 24th January 2011	2.0
5	The Mikuni Pass		1147	0300 JST 11th December 2012	3.4
6	The Notsuka Pass		522	1600 JST 5th February 2018	1.9
7	The Kiritachi Pass		259	1500 JST 24th January 2020	1.4
8	Pinneshiri	527		1200 JST 1st February 2020	1.3
9	The Notsuka Pass		522	0800 JST 6th March 2020	4.9
10	The Sekiyama Pass		670	0955 JST 15th February 2014	2.9
11	Ooisawa		400	0655 JST 9th February 2014	2.8
12	Okudaisen	758		1200 JST 31th December 2010	1.4

Fig. 1. Schematic diagram of the simple snow cover model (SSCM).

Fig. 2. SSCM classification of snow type. Here, $T_a(^{\circ}\text{C})$ is air temperature, ρ (kg m^{-3}) is snow density, and G_t ($^{\circ}\text{C m}^{-1} \text{ h}$) is the time integral of the effective temperature gradient introduced in Eq. 6.

Fig. 3. Location of the study sites showing (★) snow pit observations in Table 1 and (●) avalanche cases in Table 2.

Fig. 4. Properties of the snow layer measured (solid line) and calculated by the SSCM (dashed line) using the data from the Mikuni AWS at 1600 JST 28 January 2013. Measured and modeled snow heights (0.27 and 0.48 m, respectively) are each assigned a unit height. Profiles of (a) snow temperature, (b) density, (c) shear strength converted from snow hardness, and (d) grain types are shown. Square in (c) indicates the shear strength (measured using a shear frame) and the symbols in (d) follow the International Classification for Seasonal Snow on the Ground (Fierz et al., 2009). The descriptions of each symbols are shown in Supplementary materials.

Fig. 5. Time series of air temperature, snow depth, snowfall at Notsuka Pass AWS, and SI calculated using the SSCM for February 1–5, 2018.

Supplement

Table S1 displays the main morphological classes of grain shapes. The IACS (the International Association of Cryospheric Sciences) working group defined main grain shape classes are classified by using either a symbol or a unique two-letter upper case abbreviation code.

The characteristics of snow types are as shown below.

PP is for classifying the first, usually short lived, stage of seasonal snow on the ground.

DF has characteristic shapes of precipitation particles still recognizable; often partly rounded.

RG is rounded, usually elongated particles.

FC is solid faceted crystals; usually hexagonal prisms.

DH is hollow skeleton type crystals; usually cup-shaped.

SH is striated, usually flat crystals; sometimes needle-like.

Table S1. Main morphological grain shape classes. (Fierz et al., 2009)

Class	Symbol	Code
Precipitation Particles	+	PP
Decomposing and Fragmented precipitation particles	/	DF
Rounded Grains	●	RG
Faceted Crystals	□	FC
Depth Hoar	^	DH
Surface Hoar	∨	SH