EVALUATION OF SNOWPACK METAMORPHISM AND MICROSTRUCTURE IN A CANADIAN CONTEXT: A CASE STUDY FOR SNOW STABILITY ASSESSMENT
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ABSTRACT: The snow thermodynamic multi-layer model SNOWPACK was developed in order to address the risk of avalanches by simulating the vertical geophysical and thermophysical properties of snow. Risk and stability assessments are based on the simulation of the vertical variability of snow microstructure (grain size, sphericity, dendricity and bond size) as well as snow cohesion parameters. Previous research has shown a systematic bias in the grain size simulations (equivalent optical grain size) over several areas in northern Canada. In order to quantify the simulated biases in snow grain size, snow specific surface area (SSA), was measured using a laser-based system measuring snow albedo through an integrating sphere (InfraRed Integrating Sphere, IRIS) at 1310 nm. Optical grain size was retrieved from the SSA measurements in order to be compared to the optical equivalent grain radius simulated by SNOWPACK. Measurements were taken from two consecutive field campaigns during the 2013-2014 and 2014-2015 winters in the Canadian Rockies to quantify the bias. The two study plots selected are located at Glacier National Park, BC and Jasper National Park, AB. Profiles of density and stratigraphic analysis were completed as well as grain size (IRIS) profiles, combined with a snow micropenetrometer (SMP). Density analysis showed good agreement for the simulated values. Instabilities predicted by SNOWPACK were observed by SMP resistance variation. The optical grain size analysis showed systematic overestimation of the modeled values. Bias was mainly driven by temperature gradient which in turn was site dependent. A more climate oriented parametrization of the microstructure would be a great improvement for stability assessment in future release.

KEYWORDS: Snow grain, SNOWPACK, avalanche, model, stability, metamorphism.

1. INTRODUCTION

Avalanches are important and recurrent phenomena in many mountainous regions in Canada (Jamieson and Stethem, 2002). Schneizer et al, (2003) identified 5 major contributing factors: terrain, new snow, wind, temperature and snow stratigraphy conditioning avalanche occurrence. Any vertical discontinuity between the snow layers creates weak areas that will determine the risk of an avalanche as well as its type (McClung and Schaefer, 1993). Recent developments in the comprehension of the snow physical properties and metamorphism led to the development of the numerical formulation of one-dimensional physical snow models, including Crocus (Brun et al., 1992) and SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002). The SNOWPACK model has been tested in Canada in several studies (Bellaire et al., 2011; Côté et al., 2016; Smith et al., 2008). It has been pointed out that microstructure had to be improved for an overall performance of the model (Bellaire et al. 2011). Other research underlined the uncertainties regarding grain size and bond (Langlois et al. 2012, Lundy et al. 2001). Metamorphism equation were mainly developed using empirical lab measurements and the physics used in SNOWPACK have not been extensively validated due to the complexity of measuring such variables (lack of reference data). The initial size of the crystals is set constant by the model so any variability in the precipitation diameter and form are not well represented.

With the difficulties to measure and define with repeatability traditional grains metrics (size and form) (Domine et al., 2006; Taillandier et al., 2007), optical diameter (dopt) has become a new standard for grain characterisation. Dopt can be estimated from Kokhanovsky and Zege (2004) as dopt=6V/S where V is the average volume and S is the surface of grains. The relationship with snow specific surface area (SSA) is than dopt=6/(ρ_ice
SSA). Since grain size and shape affects the spectral reflectance of the snow (Domine et al., 2006; Picard et al., 2009) in the near infrared domain, it is possible to derive SSA and thus Dopt from snow albedo. Recent methods using reflectance at 1300 nm with a laser mounted on integrating spheres (Domine et al., 2006; Montpetit et al., 2012) provided precise measurements which are used in this paper for the validation of the metamorphism physics in SNOWPACK for two climate regions in Canada. The objectives of this paper are to 1) compare visually measured snow grain type and size with the InfraRed Integrating Sphere (IRIS) developed by our group (see details in Methods Section); 2) validate simulated Dopt from SNOWPACK using IRIS measurements; 3) evaluate the Structural Stability Index formulated by SNOWPACK by measuring snow resistance from a snow micropenetrometer (SMP); 4) evaluate simulated density with SMP measurements; and 5) discuss the errors and stability for two different climatic zones of Canadian avalanche terrain.

2. SNOWPACK MICROSTRUCTURE CALCULATIONS

For all its calculations, SNOWPACK take meteorological data as input. Those parameters are air temperature (K), relative humidity (%), wind speed (m s-1) and direction (Degree), incoming solar radiation (W m-2), downwelling longwave radiation (W m-2) and precipitation (kg m-2). The model than calculates bulk properties (e.g. snow water equivalent (SWE), depth) and the properties of the different layers and their microstructures (grain size, grain shape, dendricity and sphericity). The stability assessment calculated by the model is based on those parameters. These parameters are mainly affected by the temperature and the temperature gradient in dry conditions, or volumetric water content and snow temperature from empirical equations for melt. Wet metamorphism was not evaluated in this study. The dendricity and the sphericity represent the form of the grains and both are varying from 0 to 1. Those parameters define what type of grains are present in a layer.

Two different algorithm are used to describe metamorphism. First, in the absence of a significant temperature gradient (less than 5 K m-1) the growth rate given the sphericity of the grains is defined as:

\[ \dot{r}_g(T,t) = \text{sp} \left( A_t + \frac{A_2}{r_g} \right) e^{\Delta \left( T_0 - T \right)} \]

(1)

where \( T \) is the temperature in K, \( t \) represents the time in seconds, \( \text{sp} \) is the sphericity, \( r_g \) the grain radius in m, \( T_0 \) is the reference temperature 273.15 K and \( A_1 \) (m s-1), \( A_2 \) (m2 s-1) and \( A_3 \) (K) are coefficients. These coefficients were set empirically using measured data for the rate of change of the grain size with a high degree of sphericity. When snow reaches a full faceted state (i.e. sphericity =0), the growth rate is stopped and stability is reached.

When a temperature gradient is over 5°K m-1, a semi-empirical model is used for kinetic grain growth (Baunach et al., 2001). This model is gradient dependent and assumes cubic grains of length \( r_g(0) \). Two axes are allowed to grow as plates, while the other axis is fixed. The length of the growing axis is defined as grain size. The temperature gradient metamorphism growth rate is then calculated as:

\[ \dot{r}_g(t) = \frac{a^2(t)J_L(t) + \Delta \\frac{\Delta J}{L}}{2 f_{gg} r_{gg}} \]

(2)

where \( a \) represents a constant lattice, \( \Delta J_L \) represents the intra layer water vapor flux in kg m-2 s-1, \( \Delta J_{L2L} \) represents the layer to layer water vapor flux (kg m-2 s-1) and both are dependent on the temperature gradient, \( \Delta z \) is the thickness of the layer in m, \( f_{gg} \) is a geometrical factor, \( \rho_i \) is the density of pure ice (917 kg m-3), \( r_g(0) \) is the initial grain size in m before kinetic growth and \( r_g(t) \) is the actual grain size (m) at time \( t \). This model is based on cold lab experiments for the optimization of the different constants.

The SNOWPACK model implemented an empirical model for optical equivalent grain size given the dendricity \( d \), sphericity \( \text{sp} \) and grain size \( g_s \) (Vionnet et al., 2012):

\[ D_{opt} = \begin{cases} 10^{-4}[d + (1-d)(4-s)] & \text{dendritic} \\ g_s \times \max(1-s) \times \max(4.10^{-4} \frac{g_s}{2}) & \text{nondendritic} \end{cases} \]

(3)

For the dendritic case only the state of decomposition and the level of sphericity is used for dopt conversion of grain size. The nondendritic equation is driven by the grain size and the level of sphericity. Note that a fully rounded grain \( (s=1) \), no conversion factor is applied so grain size is equal to Dopt.
3. SNOWPACK STRUCTURAL STABILITY INDEX

Many stability equations are available within the SNOWPACK model (Jamieson and Johnston, 1998; Lehning et al., 2004; Schweizer et al., 2006). The most relevant for this research is the SSI (Schweizer et al., 2006) which take the vertical microstructure variability to calculate a stability index. This index adjusts the Sk38 (Jamieson and Johnston, 1998) value that are solely based on snow strength and stress. The SSI is defined as:

\[ \text{SSI} = \text{SK38} + \Delta R^* + \Delta E^* \]

With,

\[ \Delta R^* = \begin{cases} 0 & \text{if } \Delta R \geq 1.5 \text{ mm} \\ 1 & \text{if } \Delta R < 1.5 \text{ mm} \end{cases} \]

\[ \Delta E^* = \begin{cases} 0 & \text{if } \Delta E \geq 0.5 \text{ mm} \\ 1 & \text{if } \Delta E < 0.5 \text{ mm} \end{cases} \]

where \( \Delta R^* \) is the vertical difference of hand hardness and \( \Delta E^* \) is the vertical difference in the traditional grain size of two adjacent layers. This index is calculated for the entire layers simulated by the model but only the lowest value is taken into account since it is the weakest location and slab failure has more chances to happen at this depth.

Schweizer et al. (2006) categorized the stability as poor when SK38<0.45 and SSI<1.32, the stability as fair when SK38<0.45 and SSI≥1.32 and good stability when SK38≥0.45.

4. STUDY SITES

Two study sites are evaluated in this study. They are located in western Canada in the Glacier National Park (GNP) and in the Jasper National Park (JNP) (fig. 1). The study site at GNP is on Mount Fidelity, a meteorological station used for avalanche forecast. Mount Fidelity has a transitional climate and is warmer than JNP with important precipitation throughout the year. This site generally promotes an equilibrium metamorphism and thus rounding of the grains. The JNP site was located at Marmot Basin ski resort. A weather station was installed in an undisturbed area. Snow profile were also conducted within this area. The cold climate at this study site promotes kinetic growth and faceting of the grains.

Fig. 1: Location of the Fidelity site in Glacier National Park (GNP) and the Marmot Basin site in Jasper National Park (JNP).

5. METHOD

5.1 Snow measurements

Vertical profiles were measured at both study sites. Three snowpits were dug at the GNP and two were dug at the JNP site. Geophysical properties were measured for each profile: density, temperature and layering. SSA was measured using the InfraRed Integrating Sphere (IRIS), developed by our group (Montpetit et al., 2012) following the approach of Gallet et al. (2009). All measurements were done near the weather stations with which the SNOWPACK simulation were driven. The site at the Fidelity station (GNP) was flat and data at Marmot Basin (JNP) were taken on a 25° slope facing North East.

Simulated snow height by the model was adjusted to compare the measurement on the field and the different layers simulated by the model. The modelled interfaces \( z_i^{mod} \) were stretch according to Lehning et al., (2001):

\[ z_i^{mod} = z_i^{mod} \frac{z_i^{obs}}{z_i^{mod}} \]

Where \( z_i^{obs} \) and \( z_i^{mod} \) represent respectively the total observed and modelled snow heights. The \( i \) index represents the simulated layers boundaries from 0 to \( nM \). All measurements were compared to the corresponding corrected layers height.

SMP measurement were conducted next to every snowpits in the GNP site. No SMP profiles were
made at the JNP because of mechanical issues with the instrument. SMP profiles were collected 5 times at each snowpit, and the best of 3 profiles were averaged to evaluate changes in resistance between the layers which was used to qualitatively validate the SSI values from the simulation.

6. RESULT AND DISCUSSION

The profile at GNP were conducted on the first 200 cm of the 350 cm total snow depth and the profiles at JNP where conducted all the way through 180 cm total depth. The different profiles at the two different sites highlighted the dominant metamorphic processes anticipated (Fig. 2). The high variability of crystal size due to the kinetic metamorphism at the JNP was well identified by the Dopt measurements. The grain shape at this site also confirmed the presence of a high temperature gradient during the winter. The smaller and round grains at the GNP site really contrasted with JNP. This site showed a highly stable and rounded environment. The Dopt observed at there was constant between 0.25 and 0.3 mm except for the decomposing snow at the surface.

Alongside Dopt measurements, snow density profiles were made using snow cutters. Two profiles of 80 cm were conducted on March 25th and one of 250 cm on the 26th. Values ranged from 91 to 260 kg m\(^{-3}\) for the first 80 cm and a maximum of 450 kg m\(^{-3}\) for the deeper snowpit. Density values at the JNP site ranged from 90 to 517 kg m\(^{-3}\). Maximum density was attributed to the presence of a melt freeze crust.

The density profiles of each site were compared to the values from the SNOWPACK simulations. A good agreement was found between the simulated and the measured densities (Fig. 4). A non-linear relation was observed where low density values are overestimated by the model and higher values underestimated. The JNP site showed more variability in the densities than the GNP site which could be explained by the highly dynamic metamorphism present at JNP.
Despite the underestimated density values, the results showed good agreement between the measured and simulated density values ($R^2=0.76$). Since SNOWPACK simulation of hand resistance was linked to density and grain type, it was considered to be well simulated. This was important because this element is crucial for the SSI equation and was not thoroughly addressed by this study.

The simulated Dopt by SNOWPACK resulted in two different profiles. Smaller rounded grains were simulated for GNP and bigger grains with faceting for JNP. Comparison between the simulated data and the measured Dopt demonstrated a clear overestimation on both site (Fig. 4). Episode of cold temperature seemed to have increased the overall values in the GNP simulation. Three distinct shifts in the simulated Dopt were present but were not verified on the measured data. A different trend was observed for the JNP site. A lower difference between simulated and measured Dopt was observed for high values. Generally, the values simulated for this site was increasing from top to bottom were expected for a highly kinetic environment.

The grain size error can have different effect on the interpretation of the SSI. A constant error of the simulated data would not affect the difference between the adjacent layers thus the stability index would not be affected. On the contrary, if the error would be size dependent, large difference between layers would be exacerbated. Transferring the values from the traditional grain size to Dopt for SSI evaluation revealed to be a hard task if not impossible. In fact, sphericity and dendricity were not measured on the field because those metrics are hardly measurable while central for the conversion (Eq.3). The large difference between the conversion of highly faceted crystals and rounded ones makes it difficult to track the grain size error measured using Dopt. From that perspective, it becomes clear that the Dopt error is clearly dependent on the sphericity and thus is linked with the dominant metamorphism present on the site. Consequently, the SSI values of two sites with distinct metamorphism could behave differently and not performed as well on both.

7. CONCLUSION

In this study we presented an evaluation of the snow grain optical diameter (Dopt) simulated by the SNOWPACK model in two Canadian sites with avalanche problems (different climates). Vertical profiles of Dopt as well as geophysical properties were measured. The characteristics of the main metamorphism processes present at each site was observed in the snow geophysical properties. Comparison with SNOWPACK simulation showed systematic overestimation with different degree in regard with the metamorphic process that was dominant. The conversion equation from grain size to Dopt by the model was identified as one of the main source of incertitude. The conversion is governed by two microstructure parameters, sphericity and dendricity, which could not be measured on the field. Furthermore, sphericity, which is highly affected by metamorphism, changes the conversion equation depending on its level. Thus, the Dopt error depends on the main type of metamorphism. This incertitude prevented us evaluating the grain size bias, hence the evaluation of SSI was not completed thoroughly. Since this stability index is based on the difference in grain size, the climate type and main metamorphism should be address before implanting this as a stability tools for the Canadian forecasters.

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