MODELING WIND SLABS WITH THE SNOWPACK MODEL INTERNATIONAL SNOW SCIENCE WORKSHOP 2026, WHISTLER, CANADA

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ABSTRACT: Computer simulations of snowpack stratigraphy and stability are increasingly being used to assist avalanche forecasting. These models make information about the snowpack continuously available, even in remote locations where observations are sparse. This approach has proven useful for widespread and long-lived avalanche problems such as persistent weak layers or wet snow avalanche problems. Wind slabs on the other hand, are harder for computer models to predict, since their formation can depend on localized terrain features that may not be resolved by the spatial resolution of the forcing data. Additionally, the weak layer formed by a wind-slab problem is often short-lived, which makes model validation challenging. As a result, wind slab problems have not been well represented in the SNOWPACK model. However, the SNOWPACK model has seen continuous development over recent years to calculate snow erosion by wind based on surface snow properties, and to derive snow transport rates. Here we present new and improved functionality to describe the formation of wind slabs with the SNOWPACK model, based on these recent model developments. We describe how densification through wind can be modeled using the redeposit mode, and how this mode is used in an advanced wind redistribution scheme. We show how the new redistribution scheme, in combination with virtual slopes, can be applied to model the formation of wind slabs. Lastly, we implemented changes to the drift index to yield a more realistic wind slab indicator for forecasters. This refined index can be calculated for each individual slope aspect, providing some generalized information about the aspects where wind slabs are likely to be found. These developments mark a small but important step forward in the use of snow models in avalanche forecasting.

KEYWORDS: Snow, Wind, Modeling, SNOWPACK, AWSOME.

1. INTRODUCTION

Detailed snow stratigraphy models such as the Swiss SNOWPACK model (Bartelt et al. 2002; Wever et al. 2015) are increasingly being used to assist avalanche forecasting. This has proven to be useful for wet snow problems (Wever et al. 2016; Bellaire et al. 2017; Mitterer et al. 2013) as well as persistent slab problems (Herla et al. 2024; Schweizer et al. 2023; Richter et al. 2019). However for wind slab prediction, there has been little progress since the formulation of the drift index (Lehning et al. 2000). There are several plausible explanations. The most pragmatic is that contrary to persistent weak layer detection, which requires investigation of the snow cover by manual snow profiling, wind slab formation can be reasonably well detected from surface properties, as well as from recent wind speed and direction. These provide a quick first order approximation of the likely occurrence of wind slabs. Assessing wind induced instabilities with models is challenging because, contrary to persistent weak layer problems, the wind-induced instabilities are typically short lived, and minor model errors may therefore lead to erroneous detection. Added to that is the fact that the physical formation processes are challenging to capture in a 1-dimensional model without a high-resolution representation of the atmospheric boundary layer.

Wind transport of snow consists of creep, saltation and suspension. Creep, the rolling and sliding of particles is thought to be of minimal contribution, and therefore usually neglected (Vionnet et al. 2014). Saltation occurs when wind overcomes the forces of gravity and cohesion, causing snow grains to be lifted from the surface and bounce around. Suspension, in contrast, consists of smaller particles that are transported over larger distances with little or no contact with the surface (Melo et al. 2024; Vionnet et al. 2014). The processes of particle ejection, transport, and deposition break down snow grains into smaller rounded grains, thereby increasing the density of the snow once deposited (Sommer et al. 2017). Wind slabs develop where the transport capacity of the flow decreases, such as on lee slopes and in terrain depressions.

Modeling the physics of suspension requires simulation of the atmospheric boundary layer. SNOW-

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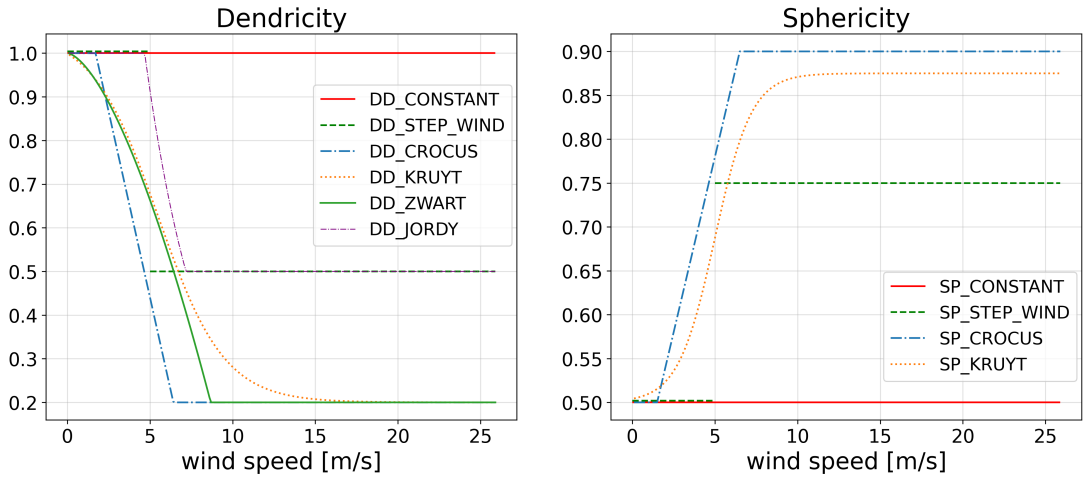


Figure 1: Parameterizations of new snow dendricity and sphericity in SNOWPACK, as a function of wind speed. Our parameterization (SP_Kruyt) is a continuous function for both dendricity and sphericity. (Note y–axis limits)

PACK (Lehning et al. 2002; Wever et al. 2015), a one-dimensional, physically-based snowpack model that simulates the evolution of a layered snowpack by solving the energy balance equations along a vertical column, does not allow for explicit modeling of the suspension. SNOWPACK therefore parametrizes saltation, and uses this as a proxy for total transport (Lehning et al. 2008). Since the largest snow particles, that carry most of the mass, remain mostly close to the surface, this further justifies focusing on saltation only (Wever et al. 2023).

This paper aims to present some of the recent developments in the SNOWPACK model with regards to the influence of wind on the snow cover. In the following, we will discuss some key features of the model that relate to wind, and explain recent changes and the motivation behind them.

2. SNOWPACK MICROSTRUCTURE PARAMETERS

In SNOWPACK, the microstructure of the snow is prognostically described by grain size, bond size, and shape parameters dendricity and sphericity, with grain type being diagnostically derived from those. Sphericity and dendricity have values between 0 and 1. Dendricity describes the degree to which a snow grain retains the branched, dendritic structure characteristic of freshly fallen snow crystals. It is important to note that in SNOWPACK, dendricity can only decrease. Sphericity on the other hand defines how rounded the grain is, with a value of 1 indicating perfectly rounded, compact snow grains, and a sphericity closer to 0 indicating faceted crystals. Sphericity can both decrease and increase, primarily driven by temperature and temperature gradients.

In previous versions of SNOWPACK, the dendricity and sphericity of freshly fallen snow used to be tied to the setting for density parameterization. We have replaced this intrinsic coupling between new snow density scheme and new snow microstructure settings, by introducing the configuration keys *DD_PARAMETERIZATION* and *SP_PARAMETERIZATION* [2]. Figure 1 shows the options for these settings, as well as their values as a function of wind speed during snowfall. [3]

3. NEW SNOW DENSITY

The density of freshly fallen snow is modeled separately from its microstructural parameters. Several different parameterizations exist for the initial density. Most of them contain a dependency on wind speed and air temperature, while some include other parameters such as relative humidity, wet-bulb temperature or snow surface temperature.

Figure 2 shows several common parameterizations for new snow density in SNOWPACK, plotted as a function of wind speed and air temperature. If specified in the literature, the red box indicates the measurement data that the parameterization was based upon. This is the case for the parameterizations LEHNING_NEW (Lehning et al. 2002) and

[2] Commit: d098dbbf24e42c608510c4f29530822e239d0eb1 on https://gitlabext.wsl.ch/snow-models/snowpack on 17-6-2026

[3] The step function is the default value in case no DD_- or SP_PARAMETERIZATION is specified, which ensures backward compatibility.

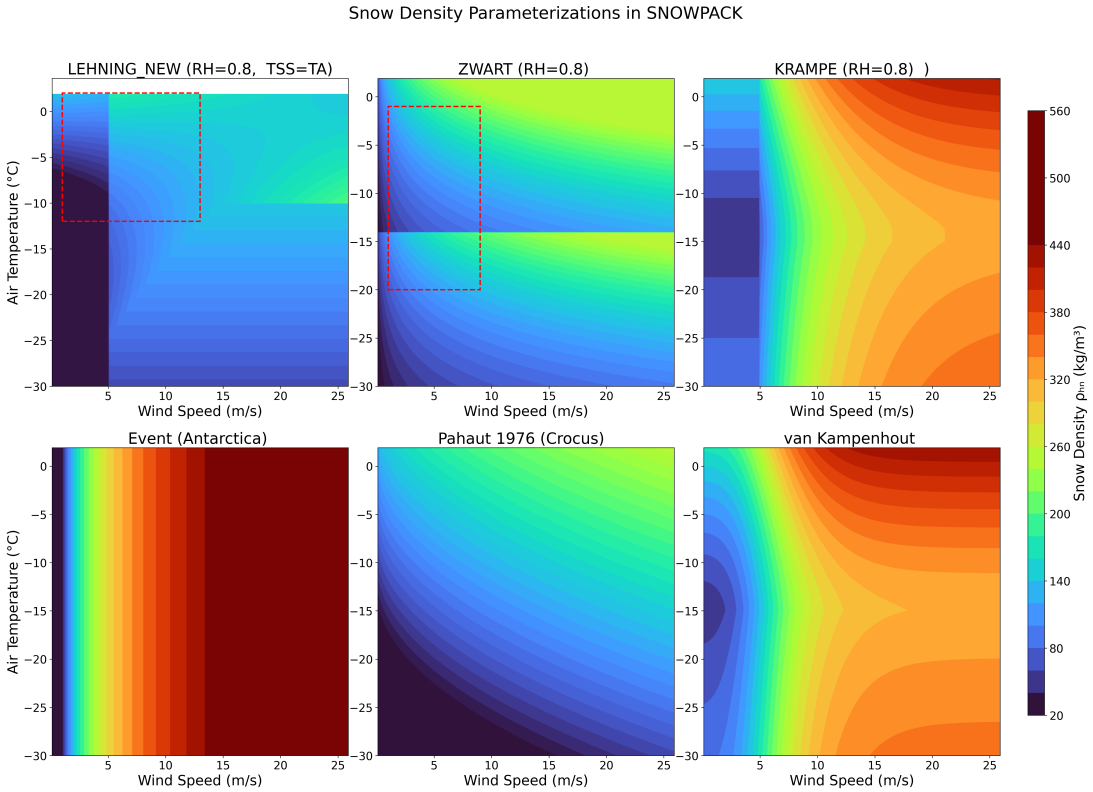


Figure 2: Parameterizations for new snow density in SNOWPACK. The red dotted boxes indicate the range of measurement data that formed the basis for the fit.

ZWART (Zwart 2007), 2 of the most commonly used parameterizations. Given the limited range of the data, Lehning et al. 2002 suggest to apply an upper limit of 150kg m^{-3} to their parameterization. [4] While most of these new snow density parameterizations were developed based on data from the Alps, observations in Norway's snow profile database regobs.no suggest new snow densities above 250 kg m^{-3} are common. This motivated exploring the use of several parameterizations developed specifically for polar regions: Groot Zwaaftink et al. (2013) investigated snow deposition on the Antarctic Plateau; Van Kampenhout et al. (2017) developed a density parameterization for polar snow in the CESM model, while Krampe et al. (2021) combined the parameterizations of Van Kampenhout et al. (2017) and Liston et al. (2007) to form a new one. All these have since been included in the SNOWPACK model, where the *HN_DENSITY_PARAMETERIZATION*s KRAMPE and VANKAMPENHOUT have been given maximum densities of 450 kg m^{-3}. As can be seen in Figure 2, these new additions allow for significantly higher densities of new snow under windy conditions.

[4] In the previous version of SNOWPACK, all new snow densities (except EVENT) were capped at 250 kg m^{-3}. In the current version, this cap has been increased to 450 kg m^{-3} for the parameterizations KRAMPE and VANKAMPENHOUT.

4. EROSION AND REDEPOSITION

Wind influences the snow density not only during snowfall events, but also during periods with high wind speeds and no precipitation. As long as there is snow available with densities low enough to erode, sufficient wind speed (friction velocity exceeding the threshold friction velocity) can initiate saltation, and drifting snow-compaction can occur. Keenan et al. (2021) implemented such a compaction routine into a dedicated polar version of SNOWPACK, and showed it was able to replicate compaction observed in Antarctica. In SNOWPACK, drifting snow occurs once the friction velocity $u*$ exceeds the snow threshold friction velocity u_{*th}. The friction velocity is calculated from the wind speed and the snow's roughness length, while the threshold friction velocity depends on the snow's microstructural properties and is defined by Lehning et al. (2000) as

$$u_{*th} = \sqrt{\frac{A\rho_i g r_g (SP+1) + B\sigma N_3 \frac{r_b^2}{r_g^2}}{\rho_a}} \quad (1)$$

where ρ_i and ρ_a are the densities of ice and air,

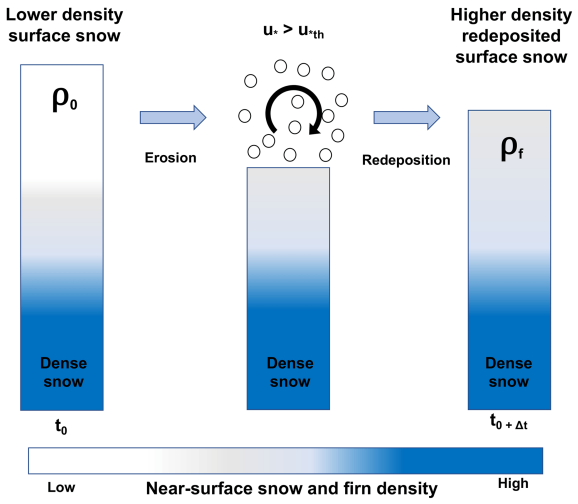


Figure 3: The process of erosion and redeposition of snow, leading to densification. Figure from Keenan et al. 2021.

respectively; r_b and r_g are the bond- and grain radius; SP is the sphericity[0,1], N_3 is the model coordination number, σ is the reference shear strength set to 300 Pa, and A and B are parameters for which several values are found in literature. Lehning et al. (2000) originally mention them as 0.018 (A) and 0.0135 (B), based on the work of Schmidt (1980). Clifton et al. (2006) suggest $A = 0.046$ and $B = 0.00345$ based on wind tunnel experiments. Finally Lehning et al. (2008) suggest $A = 0.02$ and $B = 0.0015$, the values found in the current version of SNOWPACK.

Once the condition for drifting snow $u* > u*_{th}$ is met, the total horizontal mass flux of saltating particles is calculated following Sørensen (2004) or Doorschot et al. (2002). This is then translated into an erosion mass flux by dividing by an ill-defined horizontal length scale L, which can be interpreted as an upwind fetch length over which the snow particles have been eroded (Keenan et al. 2023), or as a tuning parameter (Wever et al. 2023). If the timestep-integrated erosion mass flux is greater or equal than the mass of the top element of the snow cover, this top element is eroded. Depending on SNOWPACK's setting for *SNOW_EROSION*, this eroded mass can either be removed from the snowpack entirely (*SNOW_EROSION*=FREE) or redeposited (*SNOW_EROSION*=REDEPOSIT) using a higher density following the *redeposit* scheme introduced by Keenan et al. (2021). This scheme, schematically represented in Figure 3, was developed for Antarctica. To improve this scheme's applicability outside of Antarctic snow climates, some modifications were made. Keenan et al. (2021) used the event-based densities for redeposited snow proposed by Groot Zwaaftink et al. (2013). Antarctica however, is characterized by relatively few snowfall events, interspersed with many strong wind events. In our testing, intermittent snowfall with continuous wind speeds led to frequent switching between the event-based snow compaction and normal snowfall events. This produced many thin layers with strong density differences. To prevent this, the routines were adjusted so that the redeposit scheme can use the same parameterizations as those used for new snow density described in Section 3. By using the same density parameterization for both new snowfall as well as redeposited snow (through setting *DENSITY_REDEPOSIT*=PARAMETERIZED) this frequent switching between different densities is prevented. This results in more homogeneous densities in case of intermittent snowfall with strong winds, while still compacting the snow as intended.

5. SNOW REDISTRIBUTION

As a one-dimensional model, SNOWPACK is not able to simulate wind transport between grid cells. To overcome this limitation, Lehning et al. (2008) introduced the concept of virtual slopes. The user can specify a number of virtual slopes within a single simulation, most commonly four representing the cardinal aspects North, East, South and West. The option *SNOW_REDISTRIBUTION* then allows snow to be transported from the windward virtual slope to the leeward virtual slope, given the threshold friction velocity of the top layer is exceeded (for erosion criteria see the previous section). This process is schematically represented in Figure 4. In the original implementation of this redistribution mechanism, the snow was redeposited on the lee slope with the same density as it had before being eroded, thereby neglecting the process of compaction through saltation. In the latest release, the options for the setting *SNOW_REDISTRIBUTION* have been extended to include the new ADVANCED setting, which invokes the same redeposit scheme as described in the section 4..

5.1. *Interplay between redeposition and redistribution*

The two processes described here of *SNOW_EROSION*=REDEPOSIT and *SNOW_REDISTRIBUTION* share the same mechanism w.r.t. densification through drifting snow, but they differ in the way they are applied. *SNOW_EROSION*=REDEPOSIT leads to wind compaction on the same slope (either the main

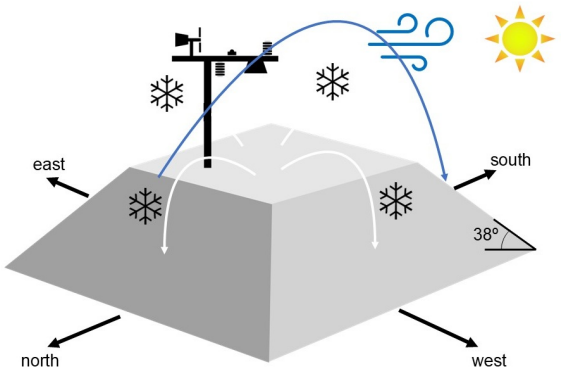


Figure 4: Schematic representation of virtual slopes. The flat slope in the center represents the main slope of the simulation, while the four inclined slopes at the cardinal aspects N,E,S,W represent four virtual slopes.

slope or a virtual slope), while *SNOW_REDISTRIBUTION*=ADVANCED deals with the wind compaction of snow that is transported from one virtual slope to another. Depending on the user settings, these can interact in different ways, depicted schematically in Figure 5.

6. DRIFT INDEX

The drift index proposed by Lehning et al. (2000) quantifies wind-transported snow and serves as a proxy for wind slab formation. Over the years, this index has become a tool that is relied on in forecasting centers. It takes the drifted snow of the last 24 hours, and transforms it into a hypothetical slab depth in cm/24h. In order to transform the flux of drifting snow to a slab depth, some assumptions have to be made w.r.t. the deposition density and slope length. Most notably, the density used to calculate a deposition depth is set to an unrealistically low 77 kg/m^3, leading to high values for the drift index. While the experienced user can interpret these values, they do not represent actual slab depths. Furthermore, the index sums the eroded snow over all virtual slopes to calculate one, aspect-independent index. We present an improved index by making the slab density a configurable parameter, so the user can select a more realistic wind slab density (typically 200-350 kg/m^3). Furthermore, the drift index is now calculated per aspect, which gives the user an overview of the aspects where wind slabs can be expected to form. Note that the new index is defined as the aspect where the snow is deposited, opposite of where it was eroded from. Figure 6 shows an example of this drift index.

7. DISCUSSION

This work has presented new and updated functionality with regards to the way wind affects the snow cover simulated by SNOWPACK. It should be noted that this is written from a perspective of SNOWPACK being forced with data from a weather model, as this allows the simulation of the future state of the snow cover. It does not aim to be complete, since there are several settings that have not been discussed, such as the other settings for *SNOW_EROSION*: FREE, VIRTUAL and HS_DRIVEN. The latter is especially useful when forcing with data from weather stations where snow depth is measured.

Modeling the physical processes dominating wind transport of snow is difficult without a coupled model of both surface processes and boundary layer processes. Models such as CRYOWRF (Sharma et al. 2023) or Meso-NH/Crocus (Vionnet et al. 2014) provide such a coupling and allow for a more physically accurate simulation of three-dimensional transport processes. For the purpose of avalanche forecasting, these models may not be well suited, since they require very high resolutions and substantial computing power. The simplifications in SNOWPACK allow for an approximation of these processes that may be more applicable to the avalanche practitioner.

However, these approximations/simplifications introduce some limitations. For example, wind transport in SNOWPACK is described solely by steady-state saltation, and ignores suspension and sublimation. Keenan et al. (2021) notes that the poorly constrained fetch length L, which is used to convert mass fluxes in a 1D model to eroded mass, can be considered as a way to include both suspension and saltation in the simulations. Indeed Lehning et al. (2008) call this fetch length ”a scaling parameter without physical meaning”. However, this parameter does have significant effect on both the eroded mass as well as the value of the drift index, and it is unclear what constitutes a sensible value. Sublimation too, is not taken into account. While the contribution of sublimation to the mass balance varies significantly by snow environment, its contribution can be significant, especially in colder and drier locations (Robinson et al. 2026; MacDonald et al. 2010).

The original motivation for the redeposit scheme comes from Antarctic research (Keenan et al. 2021), where large, homogeneous slopes are

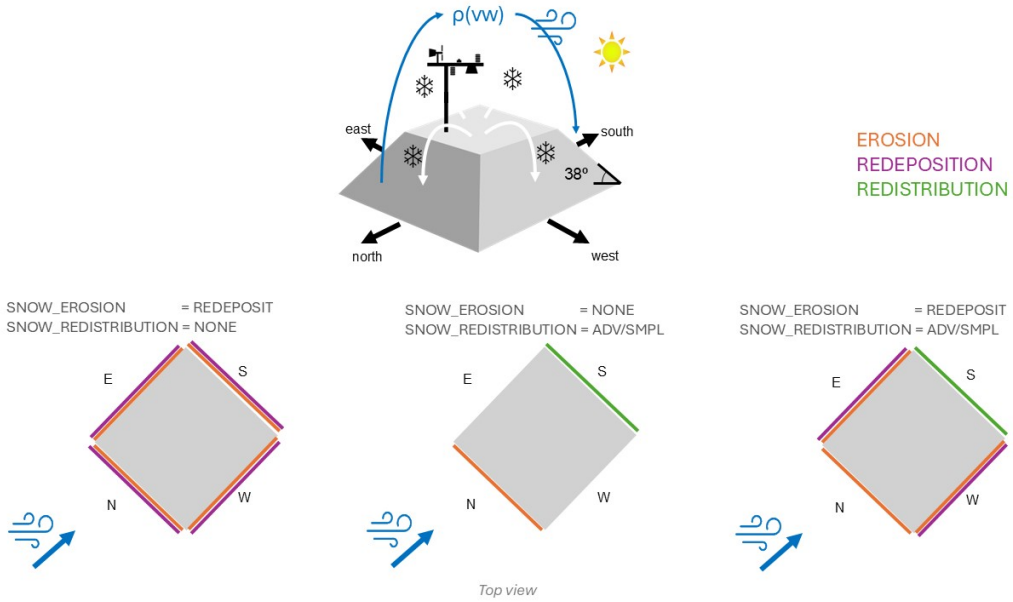


Figure 5: The interplay of the setting SNOW_EROSION and SNOW_REDISTRIBUTION on four virtual slopes. In case there is no SNOW_REDISTRIBUTION, SNOW_EROSION occurs on all four virtual slopes (L). SNOW_REDISTRIBUTION, when engaged, affects the windward slope where it erodes snow, and the leeward slope, where that same snow is deposited. Should both SNOW_EROSION and SNOW_REDISTRIBUTION be activated, then the situation on the right occurs, where the snow from the windward side is redistributed to the lee side, and the other virtual slopes that are neither windward nor leeward, are treated under the erosion scheme.

commonplace. In such a context, the assumption that all eroded snow is redeposited seems plausible (and in fact this is assumed in the formulation of the transport rate, which assumes steady-state saltation (Melo et al. 2024)). In avalanche forecasting, we generally deal with topography that is more complex and the assumption that the same amount of snow is deposited as is eroded breaks down. This is partly an issue of scale, and partly a consequence of using a one-dimensional model to simulate two dimensional snow transport. In SNOWPACK, the processes of wind compaction at the same slope (SNOW_EROSION=REDEPOSIT) and wind transport between virtual slopes (SNOW_REDISTRIBUTION) are treated as strictly separate processes. In reality these may occur simultaneously at the same slope, and the balance between the two depends on terrain parameters that are not captured at the scale of our forcing data (assuming NWP data at the km scale). This is a consequence of the abstractions made in the modeling. As always, care should be taken to interpret model results within the context of the abstractions made. Future measurement campaigns will hopefully provide data to parameterize a split between the two processes on the same slope. Similarly, we hope to collect data from snowdrift measurements to assist in the tuning of parameters such as fetch length. The various suggestions for parameters A and B in equation 1 could also benefit from better calibration data.

Another shortcoming in the current implementation of wind redeposition is the use of routines for new snow when dealing with older, wind drifted snow. As a consequence, grain size, dendricity and sphericity of redistributed and redeposited snow are now 'reset' and treated as new snow, disregarding their microstructure before being eroded. This is a significant simplification. Keeping track of the microstructure throughout erosion and deposition would require substantial redesign of the code however, and is therefore left for the future.

8. CONCLUSIONS

Wind slab problems remain one of the more difficult avalanche problems to represent with one-dimensional snowpack models because their formation depends on highly variable wind transport processes and local terrain effects generally not captured by the forcing data. We present updates to the treatment of wind–related processes in SNOWPACK, including an updated new snow routine, wind-induced densification, and advanced wind redistribution between virtual slopes. We present an improved drift index that provides

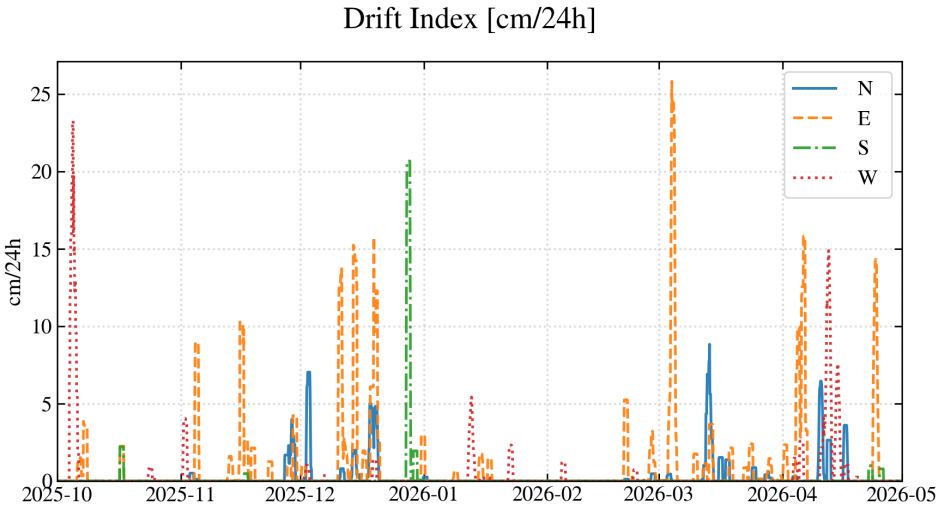


Figure 6: Example of the modified drift index from a location in south-central Norway. The wind slab density in this simulation is set to 350 kg/m^3, and the fetch length is set to the default 70 m. Both these settings have significant influence on the value of the drift index.

aspect-specific information and more realistic estimates of slab depth. Together, these developments allow the model to better represent the formation of dense wind-deposited snow and provide forecasters with more relevant information about potential wind slab problems.

However, our approach remains a simplified representation of inherently three–dimensional processes and does not take into account suspension and sublimation. Further validation against field observations and dedicated snowdrift measurements will therefore be essential. While wind slab forecasting will continue to rely heavily on field observations and expert interpretation, the presented developments move SNOWPACK closer to providing useful, operationally relevant guidance on the timing, location, and magnitude of wind slab formation.

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