MODELLING SPATIAL SNOW DRIFT PATTERNS USING WIND FIELDS AND NEGATIVE OPENNESS

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ABSTRACT: We present first results of a newly developed 2-layer snow drift model for alpine terrain, which provides snow drift modelling at very high temporal and spatial resolution (15 minutes and <= 100 m, respectively). It is based on a statistical-empirical snow drift point model, the lateral distribution is done via a topographic parameter. The model is coupled to the snow cover model SNOWGRID and furthermore driven with gridded meteorological input data of the Integrated Nowcasting Model INCA. Due to the simple approach with only a few parameters required, this new snow drift model is computationally very efficient, easily adaptable to other domains and applicable for operational use on large domains. The snow drift model was developed firstly for modelling historical storm events in Tyrol, Austria, to estimate extreme additional snow loads due to snow drift and take them into account for avalanche risk management and planning. For this purpose the model was used in analysis mode and the modelled snow drift patterns represent a maximum potential of snow drift in complex terrain. Currently, the methodology is implemented into the operational snow cover model SNOWGRID of ZAMG (Zentralanstalt für Meteorologie und Geodynamik, Austria) producing a high resolution snow drift forecast for future applications by avalanche warning services and other users.

KEYWORDS: patterns of snow drift, maximum potential of snow drift, SNOWGRID, operational snow drift forecast.

1. INTRODUCTION

Snow drift, the snow transport due to wind, plays an important role for the snowpack's structure and its temporal and spatial development, especially in complex terrain. Mainly it adds a load of snow to some areas and erodes it elsewhere, thereby increasing shear stress. Therefore snow drift has a strong impact on the snowpack's stability and is thus a crucial factor regarding avalanches. Pomeroy (1989), for example, already described major principles regarding physical and processed-based models of snow drift and Pomeroy and Gray (1990) designed a useful semi-empirical saltation model adapted to flat terrain. Numerical simulations of snow transport in alpine terrain followed, e.g. by Bernhardt et al. (2010), Doorschot et al. (2001) and Gauer (1998, 2001). The numerical model chain Safran-Crocus-Mepra was developed to forecast snow drift with regard to avalanche danger (Coléou et al., 2009; Durand et al., 2004, 2005; Guyomarc'h et al., 2009). The Swiss SLF, as another example, also provides snow drift forecast in alpine terrain for operational use by their snow drift index (DI) (Lehning et al., 2000; Lehning and Fierz, 2008). The DI is based on simulations of the one-dimensional momentum, mass- and energy-balance model SNOWPACK, which allows a detailed representation of the layered snow structure (Lehning et al., 1999). Such high resolution operational models require lots of observation/measurement data of weather and snow conditions, which are sometimes not available at a sufficient spatial resolution, especially in mountainous regions. Moreover, their computational effort is high due to the detailed treatment of snow microstructure and internal physical snowpack processes.

We focused on developing an operationally usable and spatially distributed snow drift model, which doesn't require much input data while covering the main process for the considerable local to regional snow drift quantities, which are also crucial for avalanche formation. Our primary goal was to model extreme snow drift events to represent patterns of maximum potential of snow drift. As in terms of avalanche-danger mapping and land-use planning, extreme scenarios based on a correct assessment of snow redistribution in the avalanche-release zones are an essential factor. Furthermore, the quality of the snow cover model SNOWGRID (Olefs et al., 2013) should be improved via an operationally usable snow drift algorithm.

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2. METHODS AND MODEL DESCRIPTION

The snow drift model presented here was developed in two steps, which also represent the two main program steps of the final model algorithm. Firstly, a statistical-empirical snow drift point model focuses on the process of saltation. Secondly, an algorithm follows, which accounts for the lateral redistribution of the drifted snow by the use of a topographic parameter. Both steps are explained shortly in the following chapters.

2.1 *STEP 1 - snow drift point model*

Snow drift

Snow drift is a very complex process depending on several meteorological parameters (e.g. precipitation or wind), the topography, and the existing snowpack, all of which may vary substantially over short distances and times. The properties of the uppermost layers of a snowpack (e.g. hardness, density, grain types, liquid water content) are key conditions for the occurrence of snow drift. The driving factor of snow drift is the wind speed, which is directly acting on the snow surface, called friction velocity u*. In the literature three basic mechanisms regarding snow drift can be outlined: creeping, saltation and suspension of snow particles (Gauer, 1998). If the friction velocity u* exceeds the snow density depending threshold u_{th}*, snow particles are pulled out of the snow cover. Firstly, it comes to a particle movement across the surface over a horizontal distance of several centimeters. Secondly, another process called saltation starts. It is still predominant near the surface, but it has a greater horizontal range. This transport describes the bouncing of particles along the surface in ballistic trajectories. Thirdly, suspension derives from saltation and extends the blowing snow upwards from the top of the saltation layer via turbulent diffusion. The distinction between saltation and suspension at a single point is not easily made, because there exists an overlapping region of both processes. Additionally, it requires detailed information about vertical profiles of wind, turbulence and stability conditions, which mostly are not available for a large model domain. In case of a full physical-based multilayer snow drift model all three aspects of snow drift should be taken into account. For our purposes, we picked out the process of saltation, partly mixed with small scaled suspension. Saltation indicates measureable snow transport, has a high local transport rate (Doorschot, 2002) and is therefore, also determinable in point measurements of snow height.

Measurements and model data

The statistical-empirical snow drift model is based on a combined dataset of measurements and model data. The measurements were taken from 16 sites located in alpine terrain of Tyrol and Salzburg, both Austria. The station owners are the Tyrolean Avalanche Warning Service (Lawinenwarndienst Tirol) and the ZAMG (Zentralanstalt für Meteorologie und Geodynamik), respectively, spanning an altitudinal range from 1,600 to 3,100 m. To ensure high quality data in terms of model development the used variables wind speed, wind direction, air temperature and snow height should originate all from the same measurement spot, which was mostly the case. However, due to limited availability of high quality data in complex terrain, some of the selected measurement sites have separate “wind stations” and “snow stations”. In that case the former represents an automatic weather station (AWS) recording wind speed and wind direction at a wind exposed position. The latter is located in a wind-sheltered area, in the vicinity of the wind station, where temperature and snow height (ultrasonic or laser height sensor) are measured. If the two measurement sites were separated in a “snow station” and a “wind station”, the difference in altitude between them must not be greater than 100 m and their location has to be topographic comparable. The measurement data used is covering the periods October until May 2014/15, 2015/2016, for some stations also for 2012/13, and had a temporal resolution of either 10, 15 or 60 minutes. After a detailed raw data processing (quality check, deletion of erroneous data and periods with frozen gauge, etc.) hourly averages of the measurement data were calculated.

Additionally, 1-hourly point data of snow height (analysis data) was extracted from the operational snow cover model SNOWGRID (Olefs et al., 2013) of ZAMG (Zentralanstalt für Meteorologie und Geodynamik) for each of the measurement sites. SNOWGRID is a two-layer model with a spatial resolution of 100 m and a temporal resolution of 1 hour based on calculations of 15 minutes.

Automated selection of snow drift periods

As we tried to keep our approach of modelling snow drift simple and empirically based, we used historical snow drift data for our model development. In order to define periods of snow drift an algorithm was developed, based on the comparison of measurement and model data. In the course of that working process, some problems and uncertainties became apparent, due to capturing the lateral phenomenon of snow drift from point measurements. Even with high quality data and representative measurement sites, small scale topographic effects as well as preliminary snow patterns and snow conditions (mainly snow structure and density) led to both, snow erosion and accumulation, at the same individual measurement station. In addition, snow mass transports of both signs occurred with no clear correlation to wind speed or wind direction. However, the mass of snow itself, that is lifted in the air, was good determinable with point measurement data.

Therefore, we took the lifted mass of snow as our definition of drifted snow and made no distinction between snow accumulation and snow erosion at this point which is why the snow drift amount itself in this first step is unsigned. We only considered periods without solid precipitation to exclude wind affected snow distribution during snowfall events.

A comparison between measured and modelled snow height was made and periods with a change in measured snow height, which are not resulting from precipitation, melting or settling processes where extracted in order to capture only the net snow drift effect. For these periods (Δt) the net snow drift amount (physical dimension: drifted snow height per time, e.g. cm/h) was calculated with

$$snowdrift\ amount_{\Delta t} = abs\ \left(abs\ (snowheight^{\Delta t}{}_{meas}) - \ abs(settling^{\Delta t}{}_{model})\right) \quad (1)$$

The results were evaluated using the following criteria:

- The snow drift amount has to be at least 5 cm per hour. Smaller values are considered to lie in the range of measurement uncertainty.
- The measured friction velocity u* has to exceed a threshold u_{th}* depending on the actual snow density.

Linear regression model

To obtain a point model for the snow drift amount, a statistical model was fitted to the measured snow drift amount (=predictor) and meteorological measurements as well as topographic variables (=regressors). For more information about obtaining a suitable regression model see Winkelmann and Boes (2006). Thereby several types of linear regression models were tested, as snow drift often is assumed to be proportional to the square or the cube of wind speed (e.g. Pomeroy and Gray, 1990; Gauer, 1998). In order to find the most suitable regression type we also varied different combinations of regressor variables. After a detailed validation of the model assumptions and a quality check a linear relationship between the snow drift amount and the friction velocity u* showed the best results (Equation 1). The friction velocity was calculated from the measured wind speed (measurement height varied between 2 m and 10 m above the ground) with the assumption of a neutral logarithmic velocity profile and a roughness length of 2 mm, which is a typical threshold for drift over a fresh snow surface (Lehning and Fierz 2008).

$$snow\ drift\ amount = c \cdot u^{*} \quad (2)$$

Table 1 shows the calculated snow drift amounts, using a snow density of 120 kg/m³. A plausibility check as well as a sensitivity analysis was made for the snow drift point model, which both showed satisfying results.

ff @ 2m [m/s]	snow drift amount [cm/h]
~ 4	5
> 5 - 8	7
> 8 - 10	9
> 10 – 12	10
> 12 – 14	12
> 14 – 16	13
> 16 – 18	15
> 18 - 20	17
> 30	25

Table 1: Wind speed (ff) and calculated snow drift amount based on a snow density of 120 kg/m³.

This way we developed a snow drift point model which calculates the mean net snow drift amount in a 100x100m grid cell using wind speed and snow density solely. The model is driven with gridded meteorological input data of INCA. The central European multivariable analysis and nowcasting system INCA was especially developed for use in mountainous terrain and is described in detail in Haiden et al. (2011). Required snow data is provided by the snow cover model SNOWGRID (Olefs et al., 2013) of ZAMG (Zentralanstalt für Meteorologie und Geodynamik). As already mentioned the snow drift amount is unsigned, as it represents the mass of snow that can be lifted up into the air depending on the current wind and snow conditions. This calculation represents the first step of the snow drift model algorithm, the lateral redistribution of that drifted snow amount follows in step 2.

2.2 STEP 2 - lateral snow drift redistribution

Topographic openness

In step 2 the lateral redistribution of drifted snow based on the 100m-gridded DEM of SNOWGRID and a topographic parameter, namely the negative openness (Hanzer et al., 2016; Yokoyama et al., 2001) was implemented. The negative openness describes the exposure of a grid cell to the surrounding ones within a specified radial limit. The negative openness varies between 0 and 3.15 rad, whereas values < 1.57 rad represent convex areas, values > 1.57 concave areas, a negative openness of 1.57 rad represents a flat area compared to the surrounding topography. The negative openness turned out to be the most suitable topographic measure for the lateral redistribution, by representing the wind exposure and therefore the occurrence of snow drift which cannot be explained by high values of measured wind speed and/or the sea level of a grid cell solely. We define 1.47 rad as the threshold, separating a donor from an acceptor cell of the snow drift. Hence calculated snow drift amounts of all grid cells with a negative openness <= 1.47 radian were eroded (donor cells) and handed over to surrounding acceptor cells (negative openness > 1.47 rad).

Scheme of lateral snow drift redistribution

In the following, the scheme of this new snow drift model is described.

(1) For each of the 100 m grid cells a snow distribution cell type, acceptor (A) or donor (D) cell, is determined via the negative openness threshold. In order to consider the ability of different surface types to store a specific snow amount, which cannot be eroded, we determine a snow holding capacity (Frey and Holzmann, 2015) based on land use categories from the CORINE 2012 dataset (data source: Umweltbundesamt GmbH - data.umweltbundesamt.at). The two layers of the model are represented by an old snow layer and a new snow layer, both are an output of the snow cover model SNOWGRID (Olefs et al., 2013).

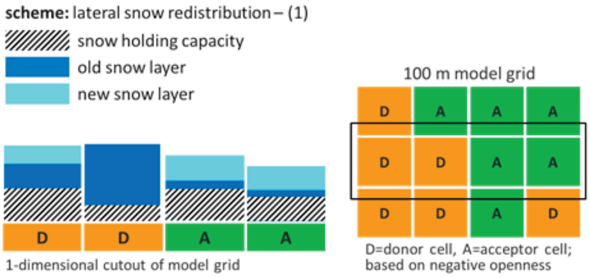

Figure 1: Donor (D) and acceptor (A) cells of snow drift with individual snow holding capacities (hatched boxes) and blue colored total snow cover (old snow layer, new snow layer).

(2) The mean snow drift amount of the grid cell is calculated for each grid cell (Equation 2) depending on wind speed and snow density of the new snow layer and/or the old snow layer.

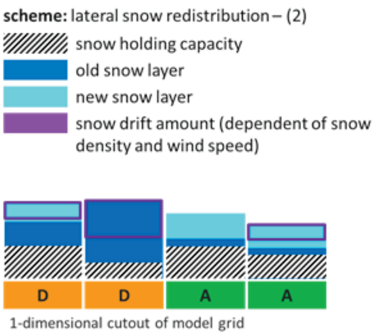

Figure 2: Grid cells with calculated snow drift amounts for each cell (purple frames).

(3) Donor cells redistribute their snow drift amount partly to surrounding acceptor cells, which number can vary between 1 and 8. If there is no acceptor cell adjacent to the donor cell, the snow amount is divided by 8 and redistributed temporary to the 8 surrounding donor cells. This amount is not accumulated there rather than stored temporary as an additional snow drift amount, which is transported further in the next timestep. In case of an acceptor cell, the snow drift amount remains on that cell.

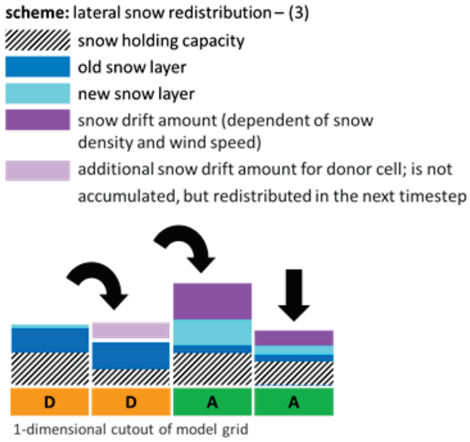

Figure 3: Redistribution of snow drift amounts (purple colored boxes)

3. RESULTS

3.1 *Current application*

The snow drift model presented here was developed within a project co-financed by the Forest and Technical Service of Torrent and Avalanche Control Tyrol (WLV). It was primarily designed to model storm events in Tyrol, Austria. The main goal was estimating extreme additional snow loads due to snow drift and take them into account for avalanche risk management and planning. For this application the model was used in “analysis mode” driven by historical INCA data. To study extreme snow drift events, high quantities of erodible snow were used as an initial condition (great amount of old snow and 72h new snow sum for a return period of 150 yrs for the new snow layer). The modelling was conducted for 12h- and 24h-storm events. Settling and melting processes of the snow cover were included; no precipitation was assumed during the storms. This way maps of the 12h- and 24h-sums of net snow drift were computed, which represent patterns of maximum potential snow drift in Tyrol, Austria.

3.2 *Future application*

The snow drift model is currently implemented into the snow cover model SNOWGRID (Olefs et al., 2013). Firstly, to improve the operational forecast of the snow cover and its spatial distribution by considering snow drift effects. Secondly, high resolution operational snow drift forecasts based on forecast data for different applications by avalanche warning services and other users are planned.

Figure 4 is an example for the operational snow drift forecast with SNOWGRID: It shows a 3D-map of the 24h-net-snow-drift-amount for the mountain range north of Innsbruck, Tyrol. The modelling includes settling and melting of the snow cover and is based on actual snow and meteorological conditions. Red pixels are representing net snow erosion and blue pixels net snow accumulation during the 24 hours interval.

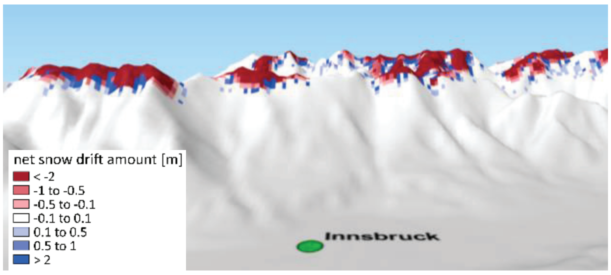

Figure 4: Operational 24h-net-snow drift forecast with SNOWGRID.

4. CONCLUSION AND OUTLOOK

This new 2-layer snow drift model is based on empirical-statistical snow drift data and provides snow drift at very high temporal and spatial resolution (15 minutes and <= 100 m, respectively) for alpine terrain. It includes melting and settling effects in the snow cover and considers snow density increase due to wind influence. The model covers the bulk effect of snow drift, which is important regarding avalanche formation. Due to its simple empirical-based design the model only requires a few parameters in contrast to snowpack models including the complex physical snow (drift) processes. It is, therefore, computationally very efficient, easily adaptable to other domains and applicable for operational use on large domains (e.g. 400 x 700 km with 100 m grid cell size - roughly 28 million points).

Initially the main focus was on the development of an individual application in analysis mode. Due to convincing performance, now several tests and improvements for the operational high resolution forecast are planned. The full implementation into SNOWGRID (Olefs et al., 2013) will be continued. Thereby the next steps will be the consideration of sublimation of the drifted snow and a decreasing snow drift amount as a function of the distance from the grid cell where the amount originates. Furthermore the implementation of donor and acceptor cells based on sectors of wind direction will be conducted, as well as a detailed spatial verification for selected snow drift periods based on high resolution laser scan data of the snow cover.

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