On modelling the formation and survival of surface hoar in complex terrain

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ABSTRACT: Surface hoar crystals form on the snow surface during cold nights. Cloudless sky, humid air and low to moderate wind speeds are required meteorological preconditions. When buried by subsequent snowfall, surface hoar crystals can form a weak snowpack layer often associated with snow avalanches. For avalanche forecasting, knowledge about the spatial distribution of surface hoar is therefore of great importance. We investigate if spatial variations of surface hoar in mountainous terrain can be modeled based on terrain characteristics using an ensemble of 1800 simulated topographies, covering a wide range of characteristic length scales. We modeled distributed radiation over this set of topographies using a detailed radiation balance model. Relative humidity was assumed to be favorable for surface hoar formation. Based on a series of cold laboratory experiments, we derived a sky view factor threshold associated with the minimum longwave radiative cooling necessary for surface hoar formation. As a first approach, we further assumed that surface hoar only survives on shaded slopes. Finally, we used a wind sheltering factor to simulate the destruction of surface hoar by wind. Applying these three simple thresholds to our spatial radiation modeling, our results show that the spatial distribution of surface hoar is greatly affected by large-scale terrain roughness and sun elevation angle. Spatial correlation ranges for surface hoar, on the order of several hundred meters, were closely related to the typical width of topographic features. Furthermore, correlation ranges of surface hoar decreased with increasing sun elevation angle. Overall, the modeled spatial patterns of surface hoar were in line with previously published spatial field observations, suggesting that simple terrain parameters can very well be used to describe the predominant surface hoar layer patterns in complex topography. A practical implication of our work is that large-scale field studies can be optimized by carefully considering the underlying topography and the time of the year.

KEYWORDS: Surface hoar, spatial variability, complex terrain characteristics, avalanche forecasting.

1 INTRODUCTION

Surface hoar crystals can cover the moutains in a sparkly blanket. These crystals form on the snow surface during cold cloudless nights when due to longwave (LW) radiative cooling the snow surface becomes colder than the air, resulting in the deposition of water vapour on the snow surface. While the meteorological preconditions for surface hoar formation, which also include humid air and low to moderate wind speeds (e.g. Colbeck, 1988; Hachikubo and Akitaya, 1997, 1998; Stössel et al., 2010), are relatively well understood, less is known about the evolution and survival of surface hoar crystals on the snow surface, for instance due to the influence of wind or incident solar radiation (Stössel et al., 2010; Shea and Jamieson, 2011).

Once buried by subsequent snowfall, surface hoar can form a weak snowpack layer which can remain hazardous for weeks or even months (e.g. Paulcke, 1938). Knowledge on the spatial distribution of surface hoar prior to burial is therefore of great relevance to avalanche forecasting. To assess snow stability within a forecasting region, avalanche forecasters need to characterize the spatial distribution of weak snowpack layers. This is usually done based on a few point observations, in combination with meteorological data from stations, weather forecasts and the personal experience of the forecaster. This process is extremely time consuming and can be somewhat subjective. Furthermore, field observations are often not possible during periods of high avalanche hazard.

In this study, we therefore investigate if the spatial distribution of surface hoar in mountainous terrain can be modeled using simple terrain characteristics. Results presented here build upon previously published work (Helbig and van Herwijnen, 2012), where we investigated the formation and survival of surface hoar solely based on incoming and outgoing radiation fluxes. Since previous field observations showed that surface hoar is mostly destroyed by wind and by incident shortwave (SW) radiation (e.g. Feick et al., 2007; Shea and Jamieson, 2011),

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we now included the impact of wind on the spatial distribution of surface hoar by incorporating a simple sheltering factor for wind in complex terrain.

2 METHODS

2.1 Radiation modelling and topographies

We used a detailed surface radiation balance model (Helbig et al., 2009, 2010) to compute distributed incident radiation over a set of random topographies, which were characterized by two length scales: a typical width ξ and a typical height σ of the topographic features (for more details see Helbig and Löwe, 2012). Our random topographies had a fixed domain size of 3km and fixed grid size of 30m. The domain-averaged slope angle ζ of each 3x3km^2 topography was 31°, chosen to focus on slopes were dry snow slab avalanches typically release (e.g. van Herwijnen and Heierli, 2009). By keeping the domain-averaged slope angle constant but varying the characteristic length scales of topographic features in the grid, we created an ensemble of 1800 topographies covering a broad range of terrain characteristics (see Table 1 in Helbig and van Herwijnen, 2012). Furthermore, by varying the sun elevation angle θ_e between 10° and 90° in steps of 10°, we investigated a large range of sun incidence angles, relevant for different seasons and various geographical locations. Note that we used a constant sun azimuth angle.

2.2 Thresholds for surface hoar formation and survival

We investigate surface hoar formation and survival by using three simple terrain based thresholds: 1. a sky view factor threshold for LW radiative cooling, 2. a shading index for incident SW radiation and 3. a sheltering threshold for wind. We assume relative humidity and light winds to be favourable for surface hoar formation in all places at all times.

First, regarding surface hoar formation, we approximate the necessary water vapour flux toward the snow surface (deposition) by means of a sky view factor threshold required for sufficient LW radiative cooling at the surface. The sky view factor is an appropriate parameter for LW radiative cooling since in mountainous terrain, outgoing LW radiation is directly influenced by the surrounding terrain as it reduces the amount of sky seen from the surface. The sky view factor F_{sky} is the proportion of the flux falling on an inclined surface from the visible part of the sky to that received from an unobstructed hemisphere. Based on two series of cold laboratory measurements, we derived a threshold value of $F_{sky} \geq 0.65$ for a minimum temperature difference between the snow surface and the air of 4 °C necessary for surface hoar formation (for details see Helbig and van Herwijnen, 2012).

Second, regarding surface hoar survival, we assumed that surface hoar can only survive in shaded areas, i.e. we applied a direct beam SW radiation threshold of zero W/m^2. This threshold conforms well with previous field observations showing that surface hoar usually survived on shaded slopes (e.g. Feick et al., 2007; Lutz and Birkeland, 2011; Shea and Jamieson, 2011). One might argue that our direct beam radiation threshold of zero W/m^2 is too restrictive since surface hoar has been observed to survive on slopes with incident SW radiation (e.g. Feick et al., 2007; Hachikubo and Akitaya, 1998; Lutz and Birkeland, 2011; Shea and Jamieson, 2011; Stössel et al., 2010). However, we note that shaded grid cells still receive appreciable diffuse SW radiation from the sky and reflected radiation from the surrounding terrain.

Third, we included a threshold to describe surface hoar survival in wind sheltered areas during large-scale wind events. We therefore computed a wind sheltering factor by simplifying the approach presented by Winstral et al. (2002). A grid cell is defined as sheltered when the maximum slope between the grid cell of interest and all the grid cells up to the boundary grid cell in a specified wind direction did not exceed 5° or 20°. We chose two shelter angles in order to account for weak and strong winds.

3 RESULTS AND DISCUSSION

By applying the above outlined thresholds on terrain characteristics and distributed SW radiation fluxes of our set of simulated topographies, we obtained five databases for spatially distributed grid cells with surface hoar. We created five additional databases for spatially distributed grid cells with potential avalanches by only including surface hoar grid cells with a slope angle of at least 30°. Thus, we obtained ten databases (see Figure 1 for examples):

1. A set of spatially distributed grid cells with surface hoar (threshold one and two)
2. A set of spatially distributed potential avalanche grid cells (threshold one, two and slope angle $\zeta \geq 30°$)
3. Two sets of spatially distributed grid cells with surface hoar after a weak and a strong northerly wind event (threshold one, two and three)
4. Two sets of spatially distributed potential avalanche grid cells after a weak and a strong northerly wind event (threshold one, two, three and slope angle $\zeta \geq 30°$)

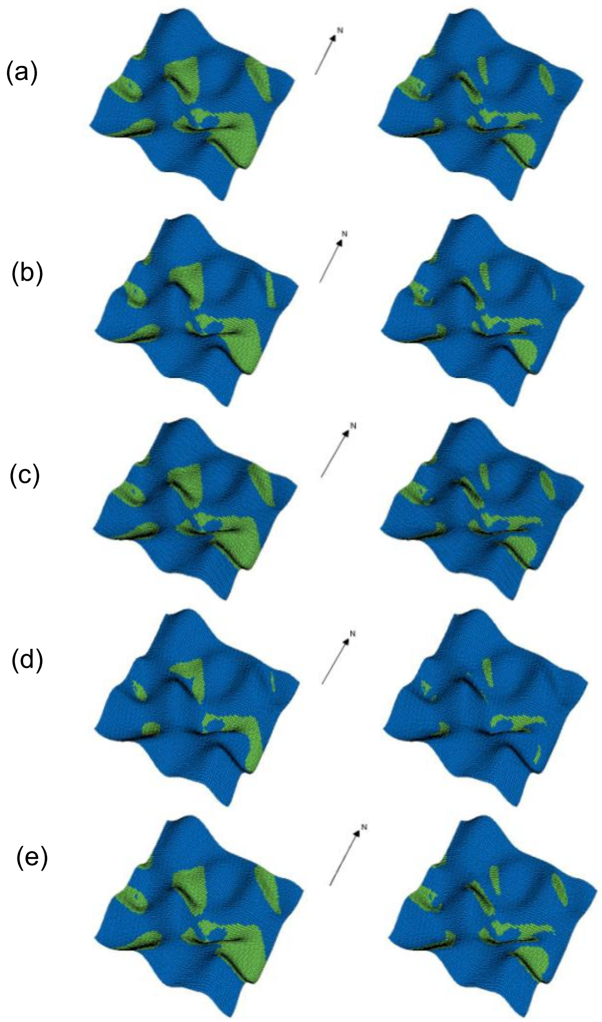

Figure 1. Spatial distribution of (left) surface hoar and (right) potential avalanche grid cells for one topography with a typical width of topographic features ξ of 500 m, a typical height of topographic features σ of 182 m and a sun elevation angle θ_e of 20°. (a): Without wind, (b): Weak northerly wind, (c) Weak southerly wind, (d) Strong northerly wind, (e) Strong southerly wind.

5. Two sets of spatially distributed grid cells with surface hoar after a weak and a strong southerly wind event (threshold one, two and three)
6. Two sets of spatially distributed potential avalanche grid cells after a weak and a strong southerly wind event (threshold one, two, three and slope angle $\zeta\geq30°$)

3.1 Applying thresholds for sky view factor and solar shading

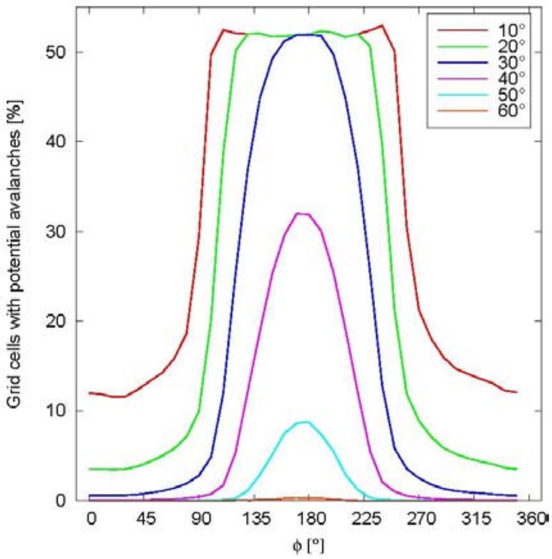

Figure 2. Mean percentage of potential avalanche grid cells for all topographies as a function of slope azimuth angles ϕ for different sun elevation angles θ_e with $\phi=0$ being a south facing slope and ϕ counted counterclockwise. Potential avalanches are defined here as grid cells with surface hoar and a slope angle $\zeta\geq30°$. Note that the number of potential avalanche grid cells is shown in 10° intervals as percentage of the total number of topographic azimuth angles per interval.

By analyzing omnidirectional semivariograms of the first database, where we only applied the sky view factor and horizon shading thresholds, we found spatial correlation ranges for low to intermediate sun elevation angles to be closely related to the typical spacing between topographic features of our random topographies (Helbig and van Herwijnen, 2012). This is in line with field observations showing that spatial correlation ranges were closely related to the typical size of basins in the study area (Borish et al., 2010). Interestingly, we found spatial correlation ranges on the order of several hundred meters, which compares well to previously found ranges from field campaigns (e.g. Borish et al., 2010; Schweizer and Kronholm, 2007). Thus, the spatial distribution of surface hoar is greatly affected by large-scale terrain roughness, i.e. the typical width of topographic features ξ in a study area. We further found that the correlation ranges decreased with increasing sun elevation angle (Helbig and van Herwijnen, 2012), suggesting that field measurements taken at different times throughout the season cannot directly be compared.

For avalanche forecasting the predominant terrain aspects covered by surface hoar are of great interest. The distribution of topographic azimuth angles of potential avalanche grid cells (second database) showed that surface hoar mostly survived on northerly oriented slopes (Figure 2; Helbig and van Herwijnen, 2012). The narrower distributions with increasing sun eleva-

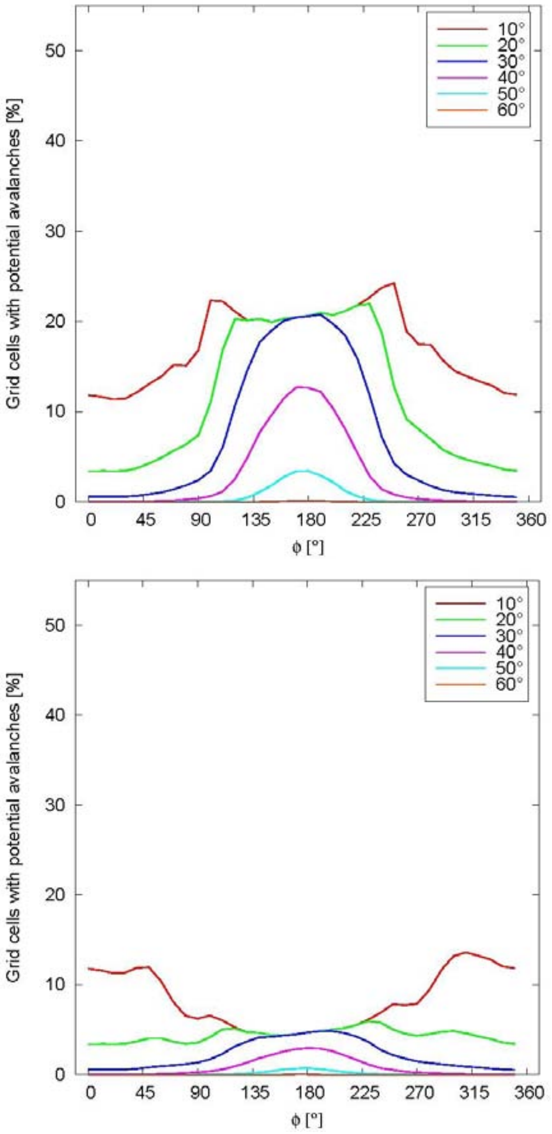

Figure 3. As Figure 2 but including wind sheltering for a northerly wind event. (top): Weak wind (shelter angle of 5°), (bottom): Strong wind (shelter angle of 20°).

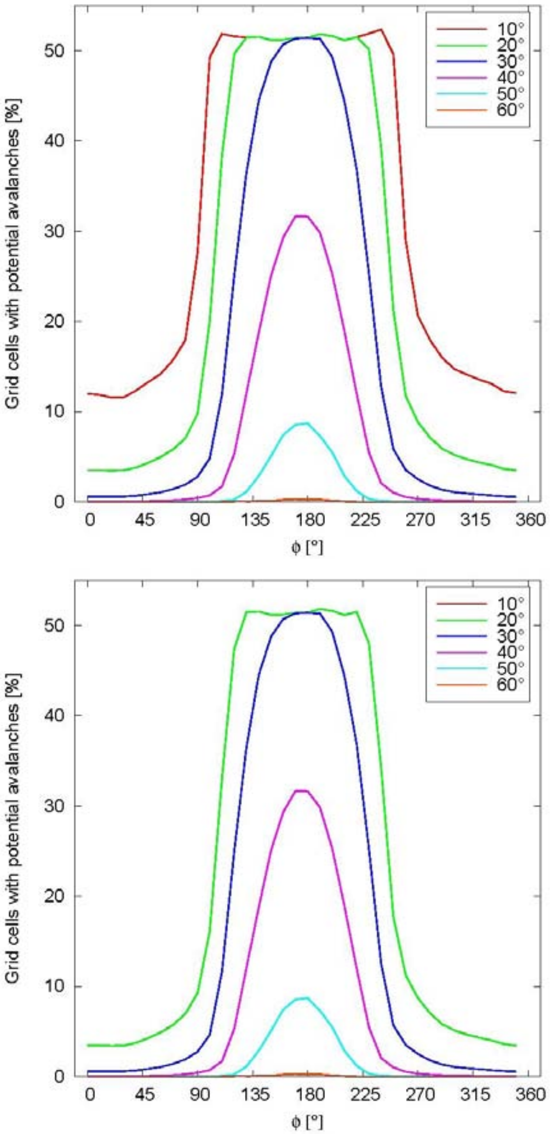

Figure 4. As Figure 3 but with a southerly wind event. (top): Weak wind, (bottom): Strong wind.

tion angle are a result of self shading of slopes, because horizon shading becomes less important for larger sun elevation angles. Note that in Figure 2 to 4 we averaged over the 200 realisations of each σ, ξ combination as well as over all σ, ξ combination per sun elevation angle.

3.2 Applying thresholds for sky view factor, solar shading and wind sheltering

We analyzed the impact of destruction of surface hoar by wind on our spatial fields by including two wind sheltering factors for weak and for strong winds, and two wind directions. One wind direction corresponded to the sun azimuth angle (south) and one in the exact opposite direction (north). Note that since we used random topographies with uniform topographic azimuth distributions, the directions given here do not correspond to real compass directions (see Helbig and van Herwijnen, 2012).

For the northerly wind events, we found that the overall number of potential avalanche grid cells was greatly reduced (Figure 3). The decrease was largest for the lowest sun elevation angle of 10° and mainly affected grid cells with a northerly aspect. However, for the strong northerly wind event, even easterly and westerly oriented grid cells were affected (Figure 3, bottom).

Under the influence of southerly wind events, the topographic azimuth distributions with potential avalanches were not altered much compared to those without wind (Figure 4). Indeed, for a weak southerly wind event the distributions remained unchanged, while for a strong southerly wind event the distribution for θ_e=10° collapsed with the one for θ_e=20°. This result is not surprising since our wind sheltering factor was essentially computed in the same way as horizon shading. Thus, a wind event from a given direction can roughly be modelled as computing horizon shading with a sun azimuth angle corresponding to the wind direction and a sun elevation angle corresponding to the wind sheltering threshold.

Finally, note that the spatial correlation ranges from omidirectional semivariograms did not change substantially under the influence of wind [not shown].

4 CONCLUSIONS

With this study, our aim was to answer the question if simple terrain characteristics can be used to model the spatial distribution of surface hoar in complex, alpine terrain. Thus, we chose a systematic approach that would not be feasible with field observations. We analyzed spatial distributions of surface hoar by means of distributed radiation balance values on a large ensemble of random topographies covering a wide variety of typical terrain characteristics.

Our results show that by using simple terrain thresholds for surface hoar formation and survival, we were able to reproduce observed spatial surface hoar patterns in complex terrain. We found spatial correlation ranges to be on the order of several hundred meters, comparing well to previously found ranges from field campaigns (e.g. Borish et al., 2010; Schweizer and Kronhom, 2007). For typical sun elevation angles for mid-latitude winter months, spatial correlation ranges were closely related to the typical width of topographic features. While incorporating the destruction of surface hoar by wind had little effect on the correlation ranges, our results show that wind can have a substantially effect on the topographic azimuth distributions of grid cells with surface hoar.

The accuracy of the threshold values we applied is perhaps somewhat uncertain. Nevertheless, once more detailed studies are performed we can easily incorporate new threshold values. Since our approach is strikingly simple, we believe it can provide a new avenue for a more statistical approach to avalanche forecasting.

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