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Interactive comment on "Meteorological, elevation, and slope effects on surface hoar formation" *by* S. Horton et al.

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We thank the reviewer for these helpful and constructive comments that significantly improved our manuscript. The reviewer's comments are in italics, followed by our response.

General comments

This manuscript aims at identifying the influence of meteorological and terrain factors (elevation, slope angle and aspect) on surface hoar formation. In the Columbia Mountains of British Columbia at Glacier National Park and around the town of Blue River three layers of surface hoar were spatially analyzed. Additionally, the snow cover model

SNOWPACK was driven with meteorological data from the numerical weather prediction model GEM-LAM in 2.5 km horizontal resolution to simulate the spatial surface hoar formation on virtual slopes during that period. Even though the model could not accurately reproduce surface hoar crystal size on south-facing slopes it was able to simulate surface hoar over different elevation bands where surface hoar formed under warm humid air, light winds and cold surface temperatures. The authors conclude that a coupled weather-SNOWPACK model chain could benefit avalanche forecasters by predicting surface hoar on a larger horizontal scale and over varying elevation bands.

The manuscript presents a step towards forecasting surface hoar formation on a regional scale which is of great use for avalanche forecasters. The authors validate large-scale simulated surface hoar layers with various field campaigns. The investigation took place under a high-pressure period in Canada which is one specific meteorological condition. Other terrain parameters than elevation, slope angle and aspect were not included in the study. However, limited sky view variations can also lead to spatially varying LW surface cooling. I would suggest clarifying both limitations in the article. Overall, the manuscript is well written and I suggest this manuscript be published with the minor corrections listed below.

Since surface hoar formation is a complex process, we agree highlighting model limitations is important. We have clearly stated the two suggested limitations throughout our revised manuscript in the abstract, methods, results, and conclusions, namely:

1. The study was limited to specific meteorological conditions
2. The model was limited to simplified terrain (e.g. no sky view effects)

To address the first limitation we have expanded our analysis of meteorological data to cover an entire season (6 months) instead of one high-pressure period. However, we still acknowledge the field verifications are limited to a specific high-pressure period.

The second limitation could be addressed by adding complexity to the model. For example, sky view effects could be modelled with GIS software (e.g. Lutz and Birkeland, 2011), and local wind and radiation effects could be modelled with Alpine3D. However, our interest was to model simple terrain features over a coarser spatial scale to reflect the large scales used by regional avalanche forecasters (i.e. general aspect and elevation bands). In our revised manuscript we make our intentions clearer and state our model is limited to simplified terrain.

Specific comments

1. *Fig. 10: What were the terrain slope angles at the field sites presented in Fig. 10? How much sky view factor did they have and what is the median elevation of the grid points within the 10 km radius compared to the elevations of the field sites? To summarize, how similar were the field site slope terrain parameters compared to the virtual 30 slopes which do not have surrounding terrain? It might be that SNOWPACK does not exaggerate radiation effects on surface hoar, but that the radiation effects on surface hoar at the field sites simply weren't that comparable.*

   Matching field observations with SNOWPACK runs on virtual slopes is indeed difficult. We have expanded our description of the field sites and model configuration, as well as acknowledged the limitations of comparing field and model data.

   Several terrain parameters were recorded during the field campaigns including subjective estimates of sky view factor and wind exposure. These are described in greater detail in the methods (Sect. 2.1), and briefly restated in the results (Sect. 3.3.3). The slope angles of the field sites ranged between 20 and 30° (median of 28°), and so the virtual slopes at 30° may have more radiation effects in some cases. Our grid point selection method is described in more detail in the

   caption of Fig. 10 and clarifies that we only used grid points and field sites at treeline elevations.

   To summarize, we admit that it was difficult to isolate the effects of a single terrain parameter in the field (e.g. slope aspect), and so we made our conclusion more broad: "Factors affecting surface hoar formation on slopes were highly variable and thus difficult to model by only accounting for slope incline and aspect".

2. *Abstract: Along my previous comment, I would maybe soften the abstract a bit. Furthermore, I would add "during a high-pressure period" somewhere, e.g. in Line 7. If not I think your statement that the moisture content had the largest impact is misleading the reader with regards to previously found large impacts as light winds, certain net radiation amount or a certain difference in surface and air temperature.*

   We have softened our abstract, particularly the interpretation of meteorological effects. Our original presentation of meteorological effects was misleading because we did not perform a proper sensitivity analysis, and therefore should not have ranked the importance of inputs. We have re-written our interpretation of meteorological data in Sect. 3.1 to discuss the weather conditions associated with modelled surface hoar growth, and how they impact the distribution of layers. We do not rank the importance of each input. Accordingly, the abstract now gives a broader statement: "Modelled surface hoar growth was associated with warm air temperatures, high humidity, cold surface temperatures, and low wind speeds."

   The abstract also acknowledges that observations were limited to "a period of high pressure" and the modelling was done for "simplified terrain".

3. *p. 1869, Line 26-28: Mott et al. (2011) observed that in wind-exposed areas turbulent fluxes considerably contributed to snow melt sometimes outperforming net radiation. Since wind-exposure seem necessary I suggest to check if the*

referred slopes were indeed wind-exposed. In the study of Mott et al. (2011) they are also referring to net radiation (net shortwave and longwave radiation) instead of direct solar radiation.

We used a subjective ordinal scale to rate the wind exposure of each field site, which is now described in the methods. Most below treeline and treeline elevations sites were sheltered by sparse vegetation, while most sites at alpine elevations had greater wind exposure. Since our sites reported in Fig. 10 were at treeline elevations, they would have been exposed to some moderate winds. We acknowledge that wind exposure may explain some variations between field sites in Sect. 3.3.3.

We also corrected our description of Mott et al. (2011).

Technical comments

1. *1858, Line 25 and p. 1862, Line 15-16: replace sublimate with deposit. The transition from solid into gas is called sublimation. However, for surface hoar formation water vapour deposits onto the snow surface.*

   Changed as suggested.

2. *p. 1861, Line 23: air or surface temperature, please specify.*

   Air temperature specified.

3. *p. 1866, Line 15-16: Do you mean "Radiation forecasts [..]" ?*

   Yes, now corrected to "radiation forecasts".

4. *p. 1869, Line 17-18: Fig. 10f does not show data from 10 February but from 4 February. Fig. 10g is not described.*

   References to Fig. 10 have been corrected.

5. *p. 1870, Line 2-4 and Line 25-27: Terrain shading is not caused by limited sky view, but generally describes shadows cast by surrounding topography during low sun elevation angles. The sky view factor determines e.g. how much diffuse sky radiation a surface receives and how much LW cooling it experiences during nights. I suggest to change e.g. Line 2-4 to: [..] radiation absorption "by the surface", snow melt, terrain and vegetation shading, and local sky view effects from topography and vegetation.*

   Changed as suggested.

6. *Fig. 1: Please include a description for the locations of field campaigns around Blue River or/and a description for the inset showing Blue River and GNP.*

   A description of the inset map has been added to the caption.

7. *Fig. 9: Please add the region from where data is shown, e.g. "[..] (1800 to 2200 m) in GNP." Maybe mention that the modelling is again done with the HRDPS/SNOWPACK model.*

   The study region and model details have been added to the caption.

8. *Fig. 10: I think the words "with" and "without" allocated to the symbols in the caption were meant to be the other way round. There is a sun crust on south slopes.*

   Symbol descriptions have been corrected.

Interactive comment on The Cryosphere Discuss., 9, 1857, 2015.