Author response to ”Meteorological, elevation, and slope effects on surface hoar formation”

June 14, 2015

Dear Editor,

We thank the reviewers for their detailed and constructive comments which we have used to revise our manuscript. We feel our manuscript has significantly improved by adopting their recommendations. The two most important changes are that we clearly state the limitations of our study and that we have changed our presentation and interpretation of meteorologoical effects.

A detailed response to each of the reviewers comments are copied below, with the original comments in italics. A marked-up version of our manuscript follows.

Thank you for overseeing the review of our manuscript.

Sincerely,

Simon Horton
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RESPONSE TO REFEREE #1

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 werent 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.

RESPONSE TO REFEREE #2

General comments

The authors of this work present research attempting to link weather, observation, and simulations for surface hoar formation. This is a very important endeavor. In general, I believe the methods to be poorly detailed and the results somewhat misleading. The authors collected a large set of field data as well as examined extensive weather data. The methods presented in Section 2 are not detailed enough to reproduce the work. More importantly, the authors present the work as a sensitivity analysis, which given the information provided is not an accurate statement.

Additionally, there are various statements in the work that elude to the importance of influence of parameters, namely, the papers major finding: moisture content of the air appears to have a larger impact (1864:8). However, no mention to how this parameter was deemed important, this type of statement must be backed up by a quantitative rigorous statistical methodology.

We agree that we misleadingly presented our weather data analysis as a sensitivity analysis. Our intent was to show how weather conditions affected when and where surface hoar formed. We feel this was important to address when mapping layers with gridded weather data. However, sensitivity analysis should measure the change in output for a given change in input. Our compilation of weather data did not systematically change the inputs, making it difficult to measure model sensitivity (e.g. sensitivity coefficients). Slaughter (2010, p. 176) demonstrate a suitable method to measure the sensitivity of modelled vapour fluxes.

To reflect the limits of our analysis, we have chosen to change our interpretation throughout the manuscript. We now present weather conditions associated with surface hoar formation, rather than stating formation was sensitive to specific inputs. Fig. 2 has been changed to boxplots to indicate that direct weather data was used, as opposed to our previous figure which may have implied the inputs were systematically changed. We removed statements suggesting moisture content of the air was the most important input, and instead report the range of values for each input that were favourable for surface hoar growth or shrinkage. Since there is a high level of interaction between the inputs, statements about relative importance would require detailed quantitative analysis. Preliminary work not included in this manuscript suggest our data set would produce similar sensitivity results to Slaughter (2010, p. 199). Our revised interpretation still provides sufficient evidence to argue that meteorological conditions caused certain regions and elevation bands to have larger/smaller modelled surface hoar.

We have also expanded our methods by adding a sub-section to clearly explain the analysis of weather data (Sect. 2.4 Analysis of meteorological data) and added details throughout the methods section to make our work reproducible.

Specific/technical comments

1. *1858:25 Vapor does not sublimate. Sublimation = solid to vapor, deposition = vapor to solid, evaporation = liquid to vapor, condensation = vapor to solid*

   Changed as suggested.

2. *1859:4 Slaughter also preformed field studies of surface hoar: http://www.ingentaconnect.com/content*

   We now cite this study in several relevant sections. The weather associated with modelled surface hoar formation in our study (Sect. 3.1 / Fig. 2) generally agrees with the weather conditions reported in this field study (e.g. Fig. 10 in Slaughter (2011)).

3. *1860: Section 2.1 Were the specific locations, aspects, sky view, etc. recorded for each site? If so, this should at least be mentioned. However, it may be appropriate to build histograms of the data so the reader can understand the distribution of the observations sites. For example, slope angles ranged from 20 to 30 degrees, was the distribution of slopes uniform or does it favor certain values.*

   The specific details of each field site were recorded, including: longitude, latitude, elevation, aspect, slope incline, and subjective ordinal scales for sky view factor, sun exposure, and wind exposure. These parameters are listed and described in our expanded methods Sect. 2.1. We qualitatively describe the distribution of these parameters, but do not present histograms.

4. *1861:7 Where does 239,152 number come? You state the simulation occurs at 393 grid points (225+168) and that data was pooled for every hour for 26 days. If this was done for 12 virtual slopes, then the total number of simulations should be (225+168)*(26*24)*12 = 2,942,784. This indicates that you are omitting a significant portion of the data, why?*

   We explain our data set size more clearly in Sect. 2.4. The analysis only considered flat field simulations, which resulted in roughly 12 times less data. We could have included simulations from virtual slopes, however many of the inputs would be repeated (e.g. air temperature, humidity, wind speed) since only radiation inputs differ on virtual slopes. We also omitted time steps when surface hoar was not present on the surface (e.g. when it was snowing), so that our analysis would focus on conditions that directly influenced the growth or shrinkage of crystals. Our revised analysis uses a similar approach, but explains the methods more clearly. We also extended the study period to cover six months (October March) to capture a broader range of meteorological conditions.

5. *1862:15 Should read "...added by deposition of water..."*

   Changed as suggested.

6. *1862:21 Why was the user-defined threshold of 3.5 m/s selected?*

   The threshold of 3.5 m/s was used for several reasons. Firstly, it is the default SNOWPACK setting, likely based on the findings of Hachikubo (2001) who measured negative sublimation rates at high speeds. We considered calibrating the threshold with our field observations, however we lacked detailed wind measurements at different locations to do so. We justify our choice in Sect. 2.3.

7. *1862:24 Why was the number 12 selected and what was different between the 12 runs?*

   The 12 virtual slopes were vaguely described in the discussion paper, so we have revised Sect. 2.3 to make the choice of virtual slopes clearer. Six slope simulations were used to isolate the effects of slope incline, namely north and south facing slopes with inclines of 15, 30, and 45 (Fig. 9). Another eight slope simulations were used to isolate the effects of slope aspect, namely 30 slopes in eight cardinal directions (Fig. 10). This combines to give 14 slopes (6+8), however since the north and south 30 slopes are duplicated, there are only 12 unique slopes (14-2). The number of slopes were sufficient to show the predominant effects of incline and aspect in the model (e.g. Fig. 9–10).

8. *1863:3 The paper mentions that the sensitivity of SNOWPACK was analyzed, although you fail to mention any specific method for the sensitivity analysis. Were the input parameters (i.e., the weather data) perturbed systematically or some sort of formal selectivity analysis performed on the model?*

   It seems that you generally ran the model with direct input from the weather data and then extracted each timestep to build up a dataset to perform an informal sensitivity analysis. Without defining the input parameter distributions it is not possible to determine the true sensitivity of the system. Thus, the word sensitivity should be avoided as it has a specific meaning. Also, the distribution of input parameters at an hourly rate used to formulate the model input should be reported.

   Was any consideration given to the inaccuracies of the supplied weather data and how these inaccuracies impact SNOWPACK? For example, does the wind speed differing between 1 and 2 m/s produce drastically different growth rates?

   You mention the importance of various results in the remaining portions of the paper; how has the importance of a factor determined?

   We have addressed many of these comments above in the "General comments" section, as they reflect the reviewers general concerns about the analysis of meteorological data. In short, we provide more detail in the methods section and changed our interpretation of the analysis throughout the manuscript to avoid sensitivity type statements.

   The distribution of input parameters are now shown in Fig. 2 as the box widths are proportional to the square root of the number of observations in each group.

   Inaccuracies in the NWP inputs were broadly addressed in Sect. 3.2 Evaluation of weather forecasts, but we now discuss the implications of these errors on the surface hoar model at the end of Sect. 3.1. The question of how NWP errors affect growth rates is important, however a formal sensitivity analysis is needed to answer it. Also, a sensitivity or uncertainty analysis of the entire SNOWPACK model would be valuable to the snow cover modelling community.

9. *1864: 3-4 It is stated that longwave radiation was less prominent and go on to discuss that the weather surrounding the study where generally clear during the entire study. This highlights a limitation of the analysis presented, without comparing weather conditions throughout a wide breath of conditions it is difficult to determine what conditions*

are the most influential, thus your results are limited and only apply to narrow set of input conditions.

Our revised manuscript no longer makes statements about the relative importance of weather inputs. We also expanded the analysis to cover six months of weather data to cover a broader range of input weather conditions. The analysis shows general conditions associated with surface hoar growth, and suggests some probable interactions between the inputs.

10. *1870: 6-7 Surface hoar modeled with SNOWPACK was sensitive to the moisture content of the air, where warm and moist air produced the most surface hoar. This sentence is misleading; it implies that a complete sensitivity analysis was performed, which it was not. This conclusion is only for a very specific set of data using a sampling scheme that is biased to certain conditions given the supplied weather parameters.*

    Our new interpretation of the weather data avoids claims about model sensitivity and gives a broader conclusion: Modelled surface hoar growth was associated with warm air temperatures, high humidity, cold surface temperatures, and low wind speeds.

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Meteorological, elevation, and slope effects on surface hoar formation

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Abstract. Failure in layers of buried surface hoar crystals (frost) can cause hazardous snow slab avalanches. Surface hoar crystals form on the snow surface and are sensitive to micro-meteorological conditions. In this study, the role of meteorological and terrain factors were investigated for three ~~surface hoar layers~~ layers of surface hoar in the Columbia Mountains of Canada. The distribution of crystals ~~was observed~~ over different elevations and aspects ~~during~~ was observed on 20 days of field observations during a period of high pressure. The same layers were modelled ~~on a~~ over simplified terrain on a 2.5 km horizontal grid by forcing the snow cover model SNOWPACK with forecast weather data from a numerical weather prediction model. ~~The moisture content of the air (i.e. absolute humidity) had the largest impact on modelled~~ Modelled surface hoar growth ~~, with warm and moist air being favourable~~was associated with warm air temperatures, high humidity, cold surface temperatures, and low wind speeds. Surface hoar was most developed ~~at certain elevation bands , usually corresponding to elevations with warm humid air, light winds , and cold surface temperatures~~in regions and elevation bands where these conditions existed, although strong winds at high elevations caused some model discrepancies. SNOWPACK simulations on virtual slopes systematically predicted smaller surface hoar on south-facing slopes. In the field, a complex combination of surface hoar and sun crusts were observed, suggesting the simplified model did not adequately resolve the surface energy balance on slopes. Overall, a coupled weather–snow cover model could benefit avalanche forecasters by predicting surface hoar layers on a regional scale over different elevation bands.

1 Introduction

Surface hoar (frost) is a type of ice crystal that forms on the snow surface (Fierz et al., 2009). Failure in layers of buried surface hoar crystals can release hazardous snow slab avalanches. The formation of surface hoar crystals is sensitive to micro-meteorological conditions, which makes their distribution in complex terrain difficult to predict.

Surface hoar forms when water vapour ~~sublimates~~ deposits onto the snow surface. The dominant method of vapour transport is believed to be the turbulent flux of latent heat (Foehn, 2001; Hachikubo and Akitaya, 1997; Horton et al., 2014; Stoessel et al., 2010). Snow cover models such as the Swiss snow cover model SNOWPACK (Lehning et al., 2002) and the French model CROCUS (Brun et al., 1992) simulate surface hoar formation by calculating vapour fluxes with meteorological data. Vapour fluxes and the formation of surface hoar depend on meteorological conditions Slaughter et al. (2011). Slaughter (2010, p. 199) performed a sensitivity analysis on modelled vapour fluxes and found incoming longwave radiation was the most important input, as it regulated surface cooling. In the field, surface hoar often forms ~~in clearings~~ on surfaces with open sky view and clear skies (Shea and Jamieson, 2010). Light wind speeds also influence vapour fluxes, as Hachikubo (2001) found the strongest fluxes at speeds between 0.5 and 3.5 $\mathrm{m\,s^{-1}}$. Faster wind speeds tend to transport too much sensible heat to the surface, or even knock over the crystals. Accordingly, the distribution of surface hoar often depends on wind exposure (Feick et al., 2007). Solar radiation can also melt or sublimate surface hoar crystals, making their distribution sensitive to slope incline and aspect (Helbig and van Herwijnen, 2012; Shea and Jamieson, 2010) and shading by terrain and vegetation (Lutz and Birkeland, 2011).

The meteorological factors that affect surface hoar formation apply over various spatial scales (Schweizer and Kronholm, 2007). Layers often form across entire mountain ranges ($> 100\,\mathrm{km}$) during periods of high pressure (Haegeli and McClung, 2003), and vary at regional scales ($10\,\mathrm{km}$) due to local air masses and clouds. At ~~a~~ basin or drainage scales ($1\,\mathrm{km}$), layers vary with slope aspect, incline, and elevation due to variations in wind, radiation, and valley clouds (Feick et al., 2007; Colbeck et al., 2008; Schweizer and Kronholm, 2007). At a slope scale ($100\,\mathrm{m}$), layers can vary due to vegetation, ground roughness, and local winds (Bellaire and Schweizer, 2011). In Canada, public avalanche forecasters communicate the distribution of hazardous surface hoar layers for general elevation and aspect bands on a ~~mountain range~~ regional scale.

Surface hoar layers could potentially be mapped with spatial weather and terrain inputs. The SNOWPACK model has been applied on a grid in complex terrain with downscaled weather inputs in Alpine3D (Lehning et al., 2006); however, gridded surface hoar formation with such a model has not been verified. Helbig and van Herwijnen (2012) developed a gridded surface hoar model using terrain-based rules (i.e. sky view and sun exposure), but did not account for meteorological conditions. Meteorological data from a regional scale numerical weather prediction (NWP) model has been used to model surface hoar (Bellaire et al., 2011, 2013; Bellaire and Jamieson, 2013; Horton et al., 2014). Forecast data from a NWP model with 15 km resolution were input into SNOWPACK, and the resulting surface hoar layers were verified with study plot observations from Mt. Fidelity in Glacier National Park, Canada. While the results were promising, they did not take advantage of the spatially continuous data available from NWP models. Furthermore, Schirmer and Jamieson (2015) suggest high resolution NWP models (e.g. 2.5 km) offer large improvements over regional models in complex terrain.

The goal of this study was to investigate how meteorological and terrain factors influence surface hoar formation. Surface hoar layers were spatially modelled over simplified terrain by forcing SNOWPACK with weather data from a high resolution NWP model (2.5 km horizontal resolution). The model results are compared to field observations to explain when and where surface hoar formed, and ~~whether these effects can be forecast~~ to determine whether hazardous layers could be predicted with a coupled weather–snow cover model.

2 Methods

2.1 Field studies

Field studies were done in the Columbia Mountains of British Columbia at Glacier National Park (GNP) and around the town of Blue River (Fig. 1). The mountains have a transitional snow climate with deep snowpacks and critical layers of surface hoar and melt-freeze crusts (Haegeli and McClung, 2003). Valleys are densely forested up to treeline elevations around 2000 m, with expansive alpine and glaciated regions above treeline, and rocky peaks reaching elevations greater than 3000 m.

The distribution of surface hoar crystals was observed during 20 field campaigns between 15 January and 10 February 2014. Three layers formed over ~~a~~ this period of relatively high pressure. Snowfall buried ~~these~~ the layers on 22, 29 January, and 10 February, which are the dates used to identify each layer. A typical field campaign consisted of travelling by ski from valley bottom to the top of the treeline (between elevations of 1000 and 2300 m). ~~Routes were chosen to cover~~ Between 5 and 15 sites were chosen along the routes to sample surface hoar over a range of elevations and slope aspects~~, and between 5 and 15 sites were chosen for sampling. Sites were deemed to be representative of the sky view, sun exposure, and wind exposure on surrounding slopes.~~.

The sites were either uniform flat fields or large open slopes with inclines between 20 and 30° (median incline of 28°). Site parameters including location, elevation, aspect, and incline were recorded. The sky view factor at each site was estimated and was typically greater than 75 %, except for some sites at low elevations where large openings did not exist. Wind exposure was subjectively estimated with an ordinal scale. Sites below 2000 m were typically sheltered by sparse forests, while sites at higher elevations were exposed to some prevailing winds. Overall, the sites were chosen to be representative of potential avalanche start zones at that elevation. Test profiles were done at each site to identify layers of surface hoar and melt-freeze crusts in the upper 10 cm of the snowpack. Layer boundaries, grain shape~~and size, and hand hardness~~ , and grain size were observed in 255 profiles of the upper snowpack during the 20 field campaigns (CAA, 2014).

2.2 Numerical weather forecasts

Numerical weather data were collected from 225 grid points in GNP and 168 grid points around Blue River (Fig. 1). The data were produced by the high resolution deterministic prediction system (HRDPS) operated by Environment Canada (Erfani et al., 2005). The HRDPS, also known as GEM-LAM, is a numerical weather prediction model with a 2.5 km horizontal grid. The model is initiated four times a day to provide operational forecasts over southwestern Canada. Time series were produced with the data from the 06:00 and 18:00 coordinate universal time initiations, and included air temperature, relative humidity, wind speed, wind direction, incoming shortwave radiation, incoming longwave radiation, and precipitation. The first six hours of forecast values were neglected to minimize errors from model spin-up (Weusthoff et al., 2010). Air temperature and humidity were forecast for 2 m above ground, while wind speed and wind direction were forecast for 10 and 40 m above ground.

Forecasts were compared with air temperature, relative humidity, and wind speed measurements from automatic weather stations in GNP (Fig. 1). The park operates nine automatic weather stations at ~~relevant elevations~~ elevations relevant for avalanche forecasting along the Trans-Canada Highway corridor (Schweizer et al., 1998). The 10 and 40 m wind speeds were compared because operational experience found 10 m HRDPS wind speeds were unreliable in GNP. The forecast wind speeds were fit to two-parameter Weibull distributions (Table 1), where the location parameter describes the centre of the distribution and the shape parameter describes the spread (Stull, 2014, p. 645). Weibull distributions were also fit to wind speed measurements from eight stations with anemometers roughly 10 m above ground. Two of the stations ~~are~~ were located on wind exposed ridgetops, while the other six ~~are~~ were relatively sheltered. The 10 m forecasts winds were lighter and did not have as much spread as the station measurements (i.e ~~small~~ smaller location parameter and ~~large~~ larger shape parameter). The 40 m forecast winds had a similar location parameter to the sheltered stations (2.0 $\mathrm{m\,s^{-1}}$) and a more realistic shape parameter. Accordingly, surface hoar was modelled with 40 m HRDPS winds, as they better represented typical 10 m speeds at sheltered sites.

2.3 Surface hoar model

Surface hoar formation was modelled with the Swiss snow cover model SNOWPACK (version 3.2.1). The model uses weather inputs to reconstruct the structural, thermal, and mechanical properties of the snow cover over the winter season (Lehning et al., 2002). Layers of surface hoar are added by the ~~sublimation~~ deposition of water vapour onto the surface. ~~Sublimation~~ Deposition is driven by the turbulent flux of latent heat, which is modelled with a bulk method. The bulk method assumes down-gradient fluxes proportional to a turbulent transfer coefficient. The transfer coefficient is calculated each time step using wind ~~speeds~~ speed and assuming neutral atmospheric stability (as verified by Stoessel et al., 2010). Surface hoar can be removed from the surface by ~~negative vapour fluxes~~ vapour fluxes away from the surface, surface melting, or when wind speeds surpass a user defined threshold ($3.5\,\mathrm{m\,s^{-1}}$). Hachikubo (2001) found vapour deposition rates decreased at wind speeds greater than $3.5\,\mathrm{m\,s^{-1}}$. Crystal size was calculated from the deposit mass by assuming a layer density of $30\,\mathrm{kg\,m^{-3}}$ (Horton et al., 2014).

SNOWPACK simulations were done with forecast weather data from ~~each HRDPS grid point. A flat field simulation was done~~ HRDPS grid points in GNP and around Blue River. Flat field simulations at each grid point ~~, along with 12 virtual slope simulations~~ were used map the regional distribution of surface hoar layers (Sect. 3.3.1) and examine the effect of grid point elevation (Sect. 3.3.2). Virtual slope simulations were done at each grid point to model the predominant effects of slope incline and aspect (Sect. 3.3.3). Slope simulations in SNOWPACK adjust the incoming short-wave and longwave radiation based on slope geometry (Helbig et al., 2010), while other weather inputs remain constant. ~~Effects~~ Sky view factor, terrain shading, and effects of wind direction such as snow transport ~~were neglected. Simulations were done for slopes with 30inclines at eight cardinal aspects, as well~~ are neglected. To illustrate the effects of slope incline, virtual slope simulations were done on north- and south-facing slopes with inclines of 15, 30, and 45° ~~on north and south facing slopes~~. To illustrate the effects of aspect, simulations were done on 30° slopes in eight cardinal directions.

~~The sensitivity of SNOWPACK to meteorological inputs was analyzed in terms of modelled surface hoar growth rates. Surface hoar sizes and meteorological inputs were taken from flat field simulations between 15 January and 10 February 2014. The change in crystal size was calculated for each~~

2.4 Analysis of meteorological inputs

The meteorological inputs from flat field simulations were analyzed to determine the weather conditions associated with surface hoar formation. The analysis used simulations between October 2013 and March 2014 at all 393 HRDPS grid points in GNP and Blue River. Only time steps with surface hoar on the surface were included in the analysis to focus on conditions that directly influenced formation. Meteorological inputs at each time step were compared to the change in modelled surface hoar crystal size over that time step (i.e. ~~an hourly~~ hourly crystal growth rate). ~~The simulations were pooled to get 239152 growth rates with corresponding~~ Growth rates were positive when crystals increased in size and were negative when crystals shrank or disappeared. The pooled set of meteorological inputs and modelled growth rates consisted of 448,651 time steps with positive growth rates, 189,269 time steps with negative growth rates, and 32,126 time steps with no change in crystal size. Modelled growth rates were compared to input values of air temperature, relative humidity, wind speed, and incoming longwave radiation, ~~and modelled~~ along with modelled values of snow surface temperature. ~~Absolute humidity, the mass concentration of water vapour in the air (), was calculated from the air temperature and relative humidity . This variable describes the moisture content of the air, and was included because it is important in vapour flux calculations.~~

3 Results and discussion

3.1 Meteorological effects

The ~~fastest surface hoar growth rates in SNOWPACK resulted from warm and humid air (Fig. 2a–c). This corresponded to absolute humiditybetween 2 and 4,~~ distribution of surface hoar layers depends on changes in meteorological conditions over space and time. In this section, the meteorological conditions associated with surface hoar formation modelled by SNOWPACK are summarized. The amount of water vapour available to form surface hoar depended on both relative humidity and air temperature, as cold air held less moisture (i.e. lower absolute humidity). The highest modelled growth rates were associated with air temperatures between -10 and $0\,^{\circ}\mathrm{C}$ ~~, and relative humidity greater than 60~~(Fig. 2a), with less growth at colder air temperatures. The highest growth rates were also associated with relative humidity between 70 and 90 % ~~. Each of these variables influenced the moisture content of the air. Modelled~~ (Fig. 2b). While high relative humidity should favour surface hoar growth~~was slow at cold temperatures because cold air holds less moisture. For example, air colder than -10 will always have an absolute humidity less than 2, and thus a relatively low moisture supply~~, values greater than 90 % may have occurred during periods with more cloud cover and therefore less radiative cooling. Surface hoar shrinkage was common when the relative humidity was less than 50 %.

Cold ~~surfaces also promoted~~ surface temperatures also favour surface hoar growth, ~~as the fastest growth occurred when the modelled surface temperature was~~ such as on nights with low incoming longwave radiation when radiative cooling is dominant (Slaughter et al., 2011). The highest surface hoar growth rates were associated with incoming longwave radiation between 175 and 200 $\mathrm{W\,m^{-2}}$ and modelled surface temperatures between -20 and $-10\,^{\circ}\mathrm{C}$ (Fig. ~~2d~~2c–d). Growth ~~slowed when the surface was colder than -20, likely because the air would have been colder and drier. Cloud cover influences surface cooling, where the greatest cooling occurs with clear skies (i.e low incoming longwave radiation). In general, low values of incoming longwave radiation should favour growth, but low values actually reduced growth in this study (Fig. 2e). found modelled vapour fluxes were predominantly affected by~~ may have slowed during periods with less incoming longwave radiation ~~. However, longwave radiation was less prominent in this study because skies were clear throughout most of the study period. In this case, the lowest incoming longwave radiation values corresponded to very cold periods when the air was relatively dry. Incoming radiation and cloud cover certainly affect surface hoar formation over longer time periods, but during a period of high pressure,~~ and colder surface temperatures because the ~~moisture content of the air appears to have a larger impact~~absolute humidity of the air would likely be lower. Surface temperatures above $-5\,^{\circ}\mathrm{C}$ were associated with surface hoar shrinkage, as the vapour fluxes may have been away from the surface or the crystals would melt at $0\,^{\circ}\mathrm{C}$.

~~Modelled~~ Wind speeds below $1.5\,\mathrm{m\,s^{-1}}$ typically resulted in surface hoar growth ~~rates generally decreased with wind speed~~ (Fig. ~~2f). The fastest growth occurred at speeds below~~ 2e), while wind speeds between 1.5 ~~, with moderate growth and shrinkage up to the threshold speed of~~ and $3.5\,\mathrm{m\,s^{-1}}$ resulted in either growth or shrinkage. Since SNOWPACK calculates both sensible and latent heat fluxes, ~~this trend supports the idea that strong winds warm the surface warming through~~ the snow surface is likely to warm from sensible heat transport at higher wind speeds (Hachikubo and Akitaya, 1997), which could shrink surface hoar. Surface hoar ~~was destroyed~~ never grew in the model when the wind speed exceeded the $3.5\,\mathrm{m\,s^{-1}}$ ~~, evident by the negative growth rates in Fig. 2f~~threshold. While the concept of a threshold wind speed agrees with field experience, the interactions between surface hoar and strong winds should be investigated further, ideally under controlled laboratory settings.

~~The main link between meteorological variables and surface hoar modelled in SNOWPACK is the vapour flux~~Modelled surface hoar growth was associated with meteorological conditions that agree with common field experience, such as during clear and calm nights (Slaughter et al., 2011). The largest ~~vapour fluxes resulted from high humidity and~~ growth rates occurred with warm temperatures, ~~but cold surfaces and light winds were also favourable. Moisture supply appeared to have the largest effect on~~ humid air, cold surface temperatures, and low wind speeds. However, these conditions did not always coexist, as interactions between meteorological inputs appeared to limit growth in some cases. For example, cold temperatures and clear skies limited the potential moisture supply. Such interactions are evident in Fig. 2 and likely affect the distribution of surface hoar layers, as meteorological conditions vary over complex terrain.

Whether using measured or forecast weather data, errors in the meteorological inputs would affect modelled surface hoar formation~~during a high pressure period, but surface cooling and wind could be more important in other situations. Furthermore, since winds are difficult to forecast, poor wind forecasts can still have a large effect on modelled surface hoar~~. The impact would depend on the sensitivity of the model, which would likely be similar to sensitivity analysis of Slaughter (2010, p. 176), who found modelled vapour fluxes were sensitive to incoming longwave radiation, air temperature, wind speed, and relative humidity. The following section evaluates the forecast meteorological inputs.

3.2 Weather forecast evaluation

~~Air temperatures measured in GNP~~ Weather conditions measured at stations in GNP during a high pressure period were compared to HRDPS forecasts at corresponding elevation bands in Fig. 3–5. Measured air temperatures were warmer when the 22 and 29 January layers formed than when the

10 February layer formed (Fig. 3). Forecast air temperatures had similar temporal trends. Weather station measurements suggest the atmosphere was stable during the study period, with ~~inversions evident~~ obvious temperature inversions between 17 and 22 January and between 6 and 9 February. Lapse rates forecast by the HRDPS were ~~closer to neutral , with a~~ close to neutral for most of the period (median value of $-6.0\,^{\circ}\mathrm{C\,km^{-1}}$~~. Inversion conditions were not forecast, however, the lapse rates were relatively smaller during these periods (~~), although they were slightly weaker during the inversions (-3 to $5\,^{\circ}\mathrm{C\,km^{-1}}$). It appears the HRDPS underestimated cool air pooling in the valleys~~during this high pressure period.~~, which agrees with Vionnet et al. (2014) ~~found~~ who found HRDPS forecasts had warm biases in valleys and cold biases in the mountains~~with HRDPS forecasts~~. Cold air pooling could slow surface hoar growth in valley bottoms by reducing the moisture content of the air and by causing katabatic winds (Feick et al., 2007).

Relative humidity measured in GNP fluctuated between 20 and 80 % during clear weather periods and were higher during precipitation events on 15, 22, and 29 January, and 10 February (Fig. 4). Forecast humidity was ~~generally~~ typically drier than measured values, but had similar temporal trends. Dry biases have been reported in NWP forecast verifications over western Canada (Bellaire et al., 2011; Mailhot et al., 2012; Vionnet et al., 2014). Valley clouds were observed in GNP between 23 to 25 January and may explain some of the dry biases. Valley clouds likely caused higher humidity at the stations, but forecast humidity remained low, suggesting the HRDPS did not predict valley clouds (Mo et al., 2012). Valley clouds affect surface hoar formation by providing moisture near the top of the cloud (Colbeck et al., 2008), but this process would be difficult to model without precise and accurate cloud forecasts, and thus ~~were~~ was probably not resolved.

Relative humidity measured at the stations ~~generally~~ typically decreased with elevation, while forecast humidity increased slightly ~~with elevation~~ (Fig. 4). ~~Absolute humidity always decreased with elevation in the HRPDS because of colder air. Absolute~~ In both cases, the absolute humidity usually decreased ~~at the stations as well, but because of lower relative humidity. So although forecast temperature and humidity lapse rates were not always correct, less moisture was usually predicted at higher elevations~~because of colder air temperatures.

Winds were ~~generally light~~ typically light over the period, but stronger winds were measured on 16, 18, and 30 January and 3 to 7 February (Fig. 5). Some of the major wind events were forecast by the HRPDS, particularly at alpine grid points, but were usually less pronounced than station measurements. While forecast wind speeds usually increased with elevation, measured winds were ~~more~~ primarily influenced by local topography. For example, the low elevation station at Rogers Pass experiences gap winds and was often windier than sheltered stations at higher elevations. Such local effects were not expected to be resolved with wind forecasts on a 2.5 km horizontal grid (Vionnet et al., 2014). Previous studies required grid resolutions on the order of ~~10~~ 5 to 100 m to resolve phenomenon in complex terrain such as thermal winds (Chow et al., 2006; Mott et al., 2014) and ridgetop recirculations (Raderschall et al., 2008). Furthermore, even when these phenomena are resolved, they cannot be forecast without precise initial conditions. Feick et al. (2007) commented that the inability to forecast wind at relevant scales is one of the biggest limitations in forecasting surface hoar size. In recognition of this limitation, HRDPS wind speeds should be considered regional rather than local forecasts.

While not shown, high elevation HRDPS grid points also had more precipitation, less incoming longwave radiation, and more incoming shortwave radiation. This resulted in large diurnal radiation fluctuations and colder snow surface temperatures at high elevation grid points. Radiation ~~measurements~~ forecasts were not verified with station measurements, but agree with common experience (Liston and Elder, 2006).

3.3 Surface hoar distribution

Surface hoar crystals observed between 15 January and 10 February varied with local site characteristics. The 22 and 29 January layers ~~generally~~ typically had larger crystals than the 10 February layer, but exceptions were common. Surface hoar was modelled with HRDPS data over simplified terrain on a regional scale~~with HRDPS data~~, making it difficult to verify with individual slope-scale field observations. Despite these challenges, the observed distributions were partially explained by regional, elevation, and slope effects.

3.3.1 Regional effects

Surface hoar modelled on the HRPDS grid was clustered in sub-regions in GNP (Fig. 6). For example, surface hoar was only modelled in the west end of park on 22 January and was larger in the west end on 29 January. Regional patterns usually corresponded with patterns in the meteorological inputs. In this case, forecast humidity was ~~generally~~ typically higher in the west due to orographic lift, which caused more surface hoar growth. Similarly, regions with strong winds or above-freezing temperatures had less surface hoar.

While field campaigns were done in different sub-regions, it was difficult to get a single representative crystal size to compare with the model. In general, the field campaigns found larger surface hoar ~~on~~ in the west end of the park. For example, on 21 January, the largest surface hoar observed in the west end of the park (Mt. Fidelity~~in the west end~~) was 15 mm, but the following day the largest surface hoar in the centre of the park ~~than on~~ (Hermit Mountain) was only 8 mm. Similarly, on 28 January the largest surface hoar observed on Mt. Fidelity was 18 mm, compared to 14 mm the previous day in the centre of the park (Ursus Minor Mountain~~in the centre~~). On 6 February, surface hoar up to 12 mm was observed in the east end of the park (Tupper Mountain), compared to 8 mm the following day in the center of the park (Ursus Minor Mountain). While only point observations, the field campaigns support some of the trends in Fig. 6 and suggest layers of surface hoar could be mapped on a regional scale.

Given the clustering of weather inputs and modelled surface hoar, the HRDPS probably did not resolve processes at 2.5 km resolution (i.e. basin-scale). Semi-variogram analysis (not shown) found forecast variables were usually autocorrelated up to 20 km away. This distance may correspond to the effective resolution of the HRDPS, or perhaps the actual scale of weather ~~patterns~~systems. Variations within sub-regions ~~appear to be dominated by local elevation differences~~ primarily resulted from elevation differences between neighbouring grid points. Accordingly, field observations ~~were~~ are compared to surface hoar modelled at HRPDS grid points within a 10 km radius in the upcoming sections (roughly 50 grid points).

3.3.2 Elevation effects

Surface hoar modelled with HRDPS data was often influenced by grid point elevation (Fig. 7). The 22 and 29 January layers were largest at treeline elevation grid points (1800 to 2200 m), while the 10 February layer was largest at below treeline grid points~~(Fig. 7)~~. The weather forecast over different elevations clearly impacted the model. Warmer forecast temperatures at low elevations caused surface hoar to melt, evident by the diurnal pattern of growth and melt between 18 and 22 January. Winds at high elevations destroyed surface hoar when wind speeds exceeded 3.5 $\mathrm{m\,s^{-1}}$, such as on 18 and 27 January. ~~Higher~~ High elevation grid points had colder surface temperatures ~~and~~ but lower absolute humidity, which had offsetting effects on surface hoar growth. Favourable conditions existed at treeline elevations for the 22 and 29 January layers (Fig. 7). However, favourable conditions for the 10 February layer were at low elevations, because ~~higher elevations had very cold temperatures and therefore~~ high elevations were very cold and therefore had low absolute humidity. Accordingly, growth was favoured at low elevations, such as the valleys in the northeast corner of the park (Fig. 6c).

Surface hoar was observed over a range of elevations in flat fields on Mt. St. Anne near Blue River and Ursus Minor Mountain in GNP. ~~Crystal sizes observed~~ Observed crystal sizes on Mt. St. Anne ~~generally~~ typically decreased with elevation on 21 January (Fig. 8a). Strong winds appeared to limit growth at the high elevation sites, as signs of recent wind transport were evident in the field. ~~Crystal sizes modelled at nearby HRPDS grid pointswere generally smaller at high elevations as well. The~~ At nearby HRDPS grid points, large forecast wind speeds limited surface hoar formation at many points, resulting in little to no modelled surface hoar. A subset of the grid points were not affected by strong winds and modelled crystal sizes increased with elevation. The choice of the 3.5 $\mathrm{m\,s^{-1}}$ threshold wind speed clearly impacted which grid points had modelled surface hoar.

The same sites on Mt. St. Anne were visited on 27 January (Fig. 8b), but this time surface hoar increased in size with elevation~~(Fig. 8b)~~. No signs of wind transported snow were evident at the high elevation sites. ~~Surface~~ The same day on Ursus Minor Mountain in GNP, observed surface hoar also increased in size with elevation ~~the same day on Ursus Minor Mountain~~ (Fig. 8c). Mild temperatures and calm winds ~~likely allowed this layer to form~~ over this period likely allowed surface hoar growth at alpine sites. Sizes modelled at HRDPS grid points near each mountain on 27 January were variable, but ~~generally~~ typically increased with elevation. An exception was some of the highest elevation grid points near Mt. St. Anne, where modelled surface hoar was smaller. On 7 February, observed and modelled crystal sizes ~~generally~~ typically decreased with elevation on Ursus Minor Mountain (Fig. 8d), as high elevation sites experienced cold, dry, and windy conditions.

While the HRDPS modelled general elevation patterns, ~~the sizes~~ surface hoar sizes at neighbouring grid points were highly variable and sensitive to the wind speed threshold. Furthermore, the field observations were also variable, making quantitative verification difficult. Avalanche practitioners often observe surface hoar layers over specific elevation bands ~~, likely because of changes in temperature, humidity, wind, and clouds~~where specific meteorological conditions exist. Accurate and precise NWP model forecasts are needed to model these effects. The HRDPS appears to forecasts some general elevation trends, but will probably not pinpoint specific elevation bands.

3.3.3 Slope effects

SNOWPACK simulations on virtual slopes systematically predicted less surface hoar on slopes exposed to solar radiation (Fig. 9). North-facing slopes consistently had large surface hoar regardless of slope incline, but south-facing slopes were very sensitive to slope incline. Steep south slopes had a diurnal cycle of surface hoar growth and melt, particularly during warm periods such as 24 to 26 January. As a result, extended periods of clear weather often resulted in major differences between surface hoar modelled on north and south slopes, such as the 29 January layer.

Surface hoar observed ~~in the field did not have such a consistent pattern~~ on large open slopes had less consistent patterns over different aspects~~(Fig. 10). South slopes~~ . Slopes at treeline elevations often had comparable or even larger surface hoar ~~than~~ on south slopes than on adjacent north slopes ~~.~~ (Fig. 10). Although care was taken to chose slopes with similar sky view (>75 %), slope angle (20 to 30°), and wind exposure, minor variations in these parameters between the slopes made isolating aspect effects difficult.

A more prominent impact of solar radiation ~~on south slopes~~ was the formation of sun crusts beneath the surface hoar crystals due to sub-surface warming (Birkeland, 1998). Sun crusts were regularly observed on south slopes between 15 and 29 January (e.g. Fig. 10a–f), but were rarely observed afterwards (e.g. Fig. 10g). Colder air temperatures in February likely offset radiative warming. Surface hoar ~~was~~ crystals were not necessarily smaller on south slopes ~~when this occurred~~after sun crusts formed. For example, on 21 January~~the south site~~ , the south slope on Mt. Fidelity had an 18 mm thick sun crust underneath 9 mm surface hoar crystals, which were larger than crystals observed at any of the adjacent ~~sites~~ slopes (Fig. 10a). In other cases, surface hoar was smaller when overlying ~~crusts, particularly over thick~~ sun crusts (e.g Fig. ~~10b–e). Sun crustswere less common with the 10 February layer (e.g. Fig. 10f), likely because cold temperatures offset radiative warming~~10b–f), particularly when overlying thick crusts. SNOWPACK simulations on south-facing slopes rarely modelled sun crusts, suggesting sub-surface melting by solar radiation may not have been accurately simulated.

Virtual slope simulations in SNOWPACK ~~tended to~~ may exaggerate radiation effects on surface hoar. Incoming radiation on slopes is adequately modelled in SNOWPACK (Helbig et al., 2010), but the complete surface energy balance may not be. A major simplification ~~in SNOWPACK~~ is that turbulent fluxes on slopes are modelled with the same turbulent transfer coefficient as a flat field. In reality, turbulent fluxes (including vapour fluxes) are influenced by slope factors such as ~~local~~ small-scale terrain features, ~~drainage winds, and prevailing winds. Since sun crusts were rarely simulated, sub-surface melting caused by solar radiation may not have been accurately simulated either.Turbulent~~ vegetation, and local winds. These factors likely influenced the different sizes of surface hoar observed on slopes (Fig. 10). Also, turbulent fluxes on slopes likely offset the effects of ~~direct solar radiation~~ radiation fluxes, as observed in snow melt studies (e.g., Mott et al., 2011). While SNOWPACK has a relatively sophisticated snow surface energy balance model, ~~there are clearly more complex~~ processes that affect surface hoar formation on slopes are clearly more complex. A comprehensive model would need to resolve high resolution wind fields, along with improved modelling of turbulent fluxes, radiation absorption by the surface, snow melt, terrain and vegetation shading, and local sky view effects from ~~terrain shading~~ topography and vegetation.

4 Conclusions

Surface hoar ~~modelled with SNOWPACK was sensitive to the moisture content of the air, where warm and moist air produced the most surface hoar. Snow surface temperaturesand wind speeds had secondary, but important, effects~~formation modelled with the snow cover model SNOWPACK was associated with warm air temperatures, high humidity, cold surface temperatures, and low wind speeds. Meteorological factors ~~played an important role on~~ influenced which surface hoar layers ~~were largest~~had large crystals, as well as the regions and elevation bands where they formed. Low elevations ~~tended to have~~ typically had favourable humidity and wind speeds, while high elevations had favourable surface temperatures. These offsetting effects made surface hoar formation favourable at treeline elevations for two layers, and at below treeline elevations for another layer. Field observations typically agreed with modelled elevation patterns, although there were some discrepancies at high elevations where the effect of strong winds was difficult to model. Factors affecting surface hoar formation on slopes were highly variable and thus difficult to model by only accounting for slope incline and aspect. SNOWPACK systematically predicted less surface hoar on slopes exposed to solar radiation~~,~~; however, this was not necessarily observed in the field, as solar radiation tended to form sun crusts under surface hoar rather than reduce surface hoar growth.

Avalanche forecasters could benefit from such a model chain by spatially tracking layers prone to releasing slab avalanches. The high resolution NWP model appeared to have sufficient quality to forecast surface hoar ~~over different elevation bands~~ on a regional scale ~~. Avalanche forecasters could benefit from such a model by spatially tracking layers prone to releasing slab avalanches~~during a period of high pressure. Some elevation effects were modelled, but improving the modelling of surface hoar formation under windy conditions would help simulations at high elevations. Finer scale meteorological phenomenon, such as valley clouds and local winds, were not adequately resolved by the weather model~~. This~~ , but should improve in the future with better quality ~~and resolution~~ NWP models. ~~Future surface hoar models~~ The surface hoar model could be improved by downscaling meteorological data to account for local terrain features (e.g., Liston and Elder, 2006), ~~accounting for~~ modelling sky view effects such as vegetation and terrain shading (e.g. Helbig et al., 2010; Lutz and Birkeland, 2011), and improving modelled fluxes on slopes.

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Table 1. Weibull distribution parameters fitted to station and forecast wind speeds (ridgetop station values in brackets).

Source	Location parameter ($\mathrm{m\,s^{-1}}$)	Shape parameter
Stations	0.5, 1.1, 1.7, 2.0, 2.3, 2.6, (4.0), (8.1)	0.9, 1.0, 1.2, 1.2, (1.4), 1.5, 1.8, (1.9)
10 m forecast	0.9	2.6
40 m forecast	2.0	1.7

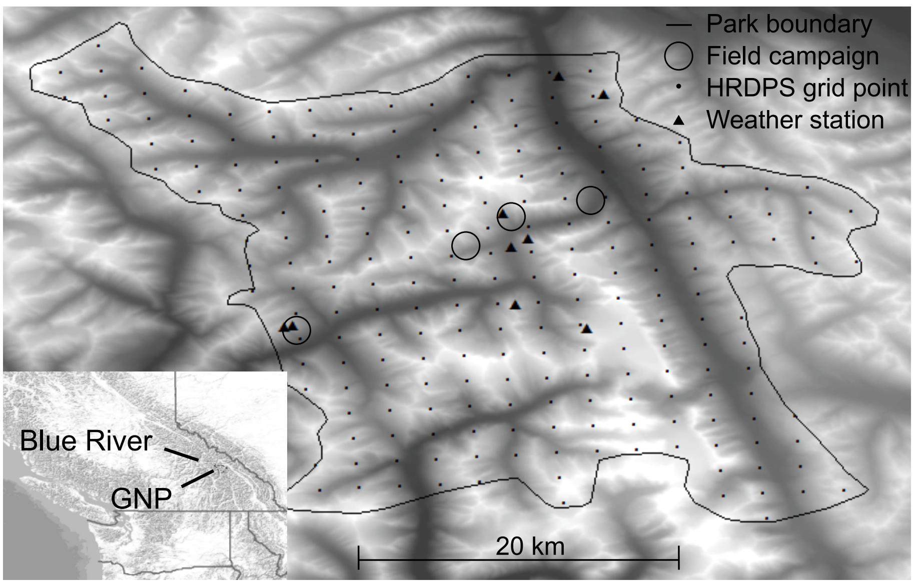

Figure 1. Map of Glacier National Park (GNP) with the locations of field campaigns, High Resolution Deterministic Prediction System (HRDPS) grid points, and weather stations (30 m digital elevation model basemap from DMTI Spatial). Inset map shows southwestern Canada and the location of GNP and Blue River.

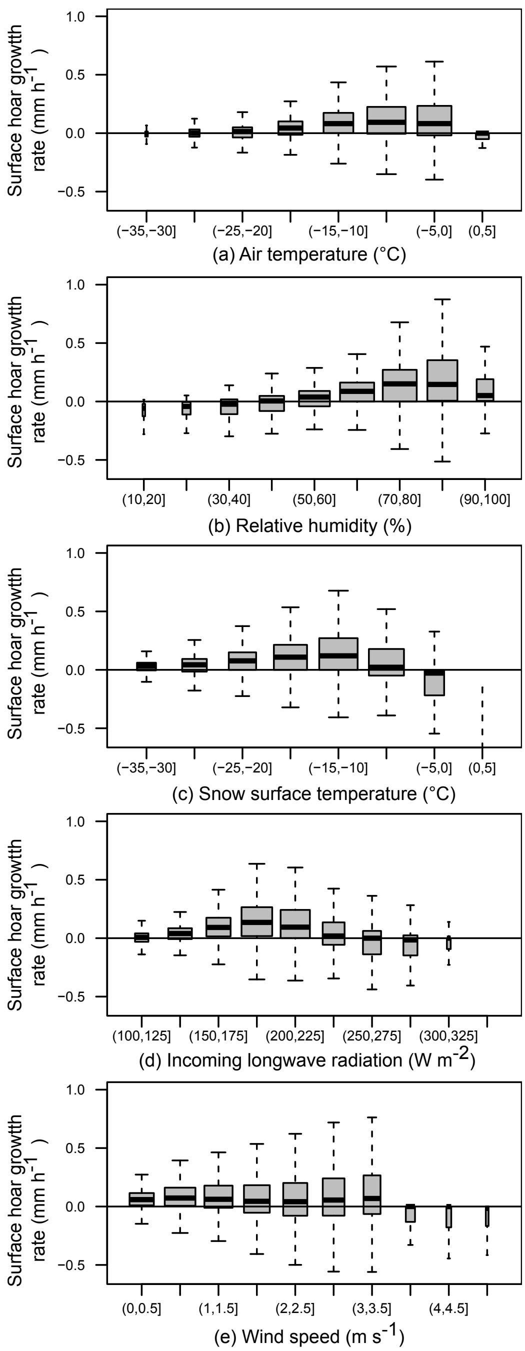

Figure 2. Surface hoar growth rates modelled by SNOWPACK for ~~different~~ input values of **(a)** ~~absolute humidity, (b)~~ air temperature, ~~(c)~~ **(b)** relative humidity, ~~(d)~~ **(c)** modelled snow surface temperature, ~~(e)~~ **(d)** incoming longwave radiation, and ~~(f)~~ **(e)** wind speed. Plots are based on ~~239152 sets of~~ hourly SNOWPACK inputs and outputs over six months at 393 HRDPS grid points (670,046 total growth rates). ~~Black lines indicate~~ For a given range of input values the median growth rate ~~and~~ is shown with a black line, boxes span the ~~height~~ interquartile range of ~~the grey band indicates~~ growth rates, whiskers span growth rates within 1.5 times the interquartile range~~for a given meteorological input~~, and outliers are not shown. Box widths are proportional the square root of the number of inputs in each group.

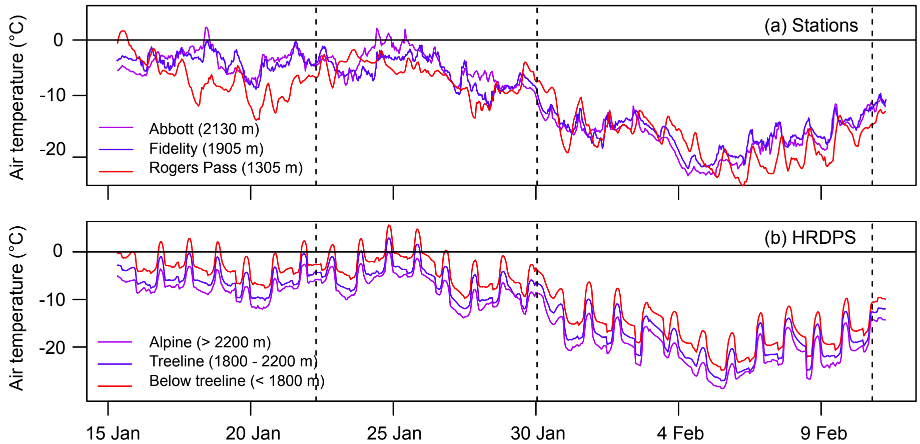

Figure 3. Air temperatures **(a)** measured at stations and **(b)** forecast by the High Resolution Deterministic Prediction System (HRDPS) in Glacier National Park. Forecasts were grouped by grid point elevation, with 35 alpine points ($> 2200\,\mathrm{m}$), 92 treeline points (1800 to $2200\,\mathrm{m}$), and 98 below treeline grid points ($< 1800\,\mathrm{m}$). The median temperature in each band is shown. Surface hoar crystals were buried on 22, 29 January, and 10 February as indicated by the vertical dashed lines.

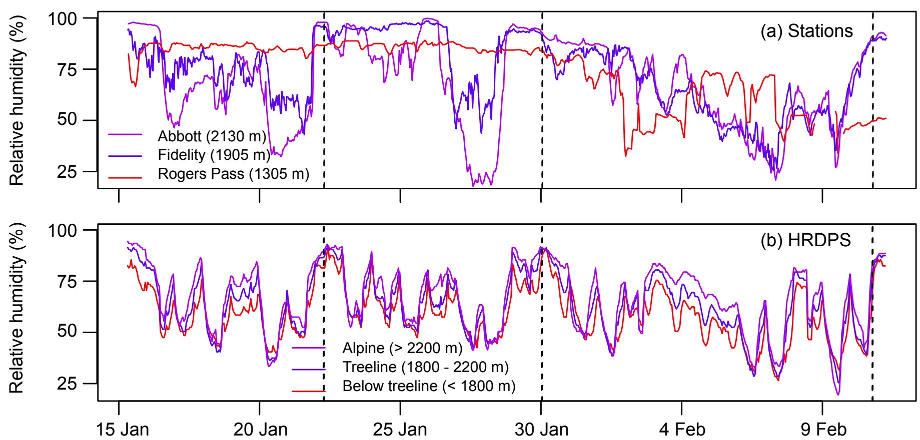

Figure 4. Relative humidity **(a)** measured at stations and **(b)** forecast by the High Resolution Deterministic Prediction System (HRDPS) in Glacier National Park. Same format as Fig. 3.

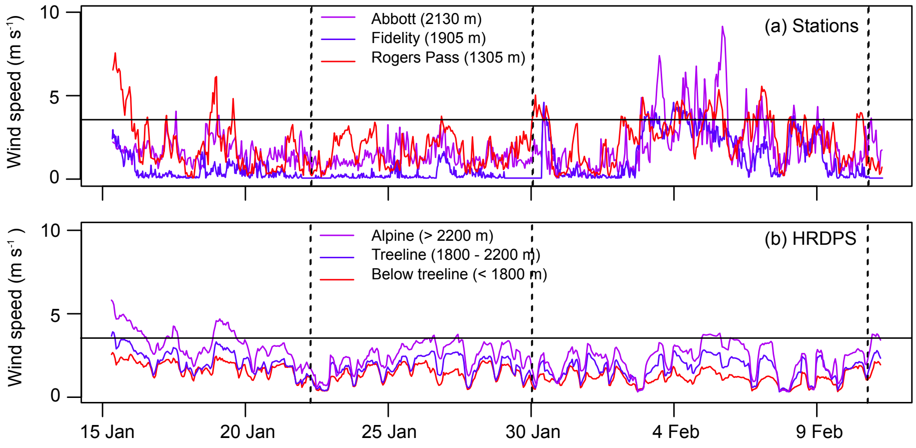

Figure 5. Wind speeds **(a)** measured at stations and **(b)** forecast by the High Resolution Deterministic Prediction System (HRDPS) in Glacier National Park. The $3.5\,\mathrm{m\,s^{-1}}$ threshold is shown with a horizontal line. Same format as Fig. 3.

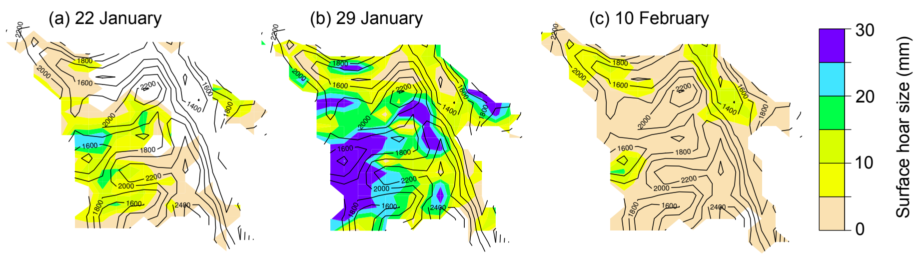

Figure 6. Modelled surface hoar sizes at High Resolution Deterministic Prediction System (HRDPS) grid points in Glacier National Park on **(a)** 22 January, **(b)** 29 January, and **(c)** 10 February. Black contour lines show the topography of Glacier National Park resolved by the model.

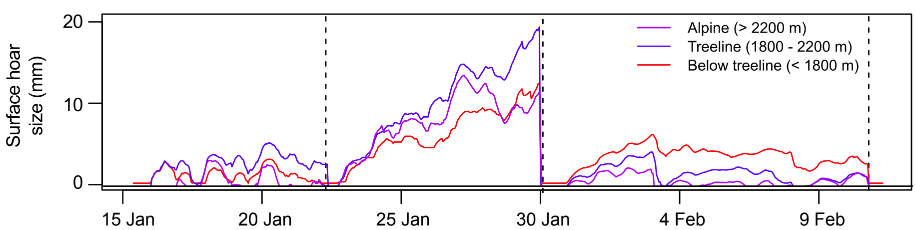

Figure 7. Modelled surface hoar sizes at High Resolution Deterministic Prediction System (HRDPS) grid points grouped by elevation bands in Glacier National Park. Same format as Fig. 3.

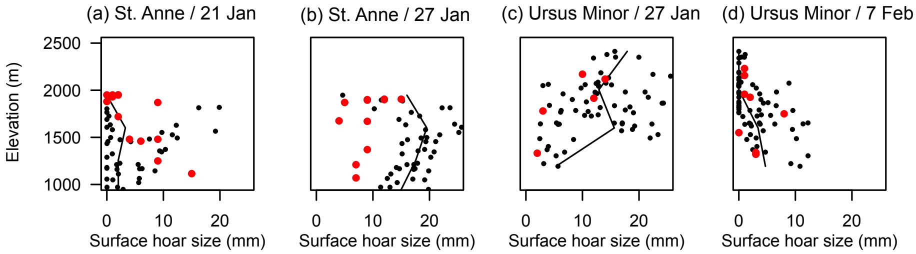

Figure 8. Surface hoar sizes observed over different elevations on Mt. St. Anne and Ursus Minor Mountain (red dots). Black dots show the sizes modelled at grid points within a 10 km radius of the mountains, and the moving average with a black line.

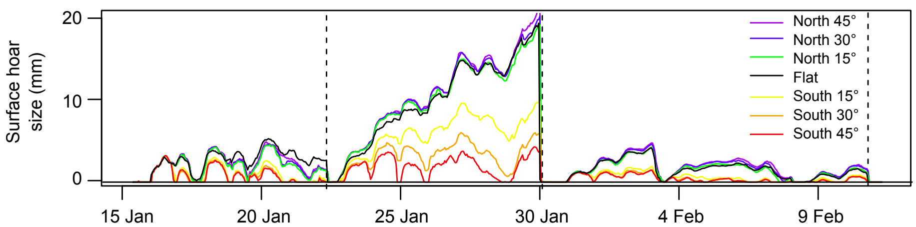

Figure 9. Modelled surface hoar sizes on north- and south-facing slopes with various inclines. ~~SNOWPACK simulations~~ Simulations were done with ~~forecast data~~ SNOWPACK using forecasts from the High Resolution Deterministic Prediction System at 92 ~~treeline elevation~~ grid points at treeline elevations (1800 to 2200 m) in Glacier National Park. The median crystal sizes for each slope are shown.

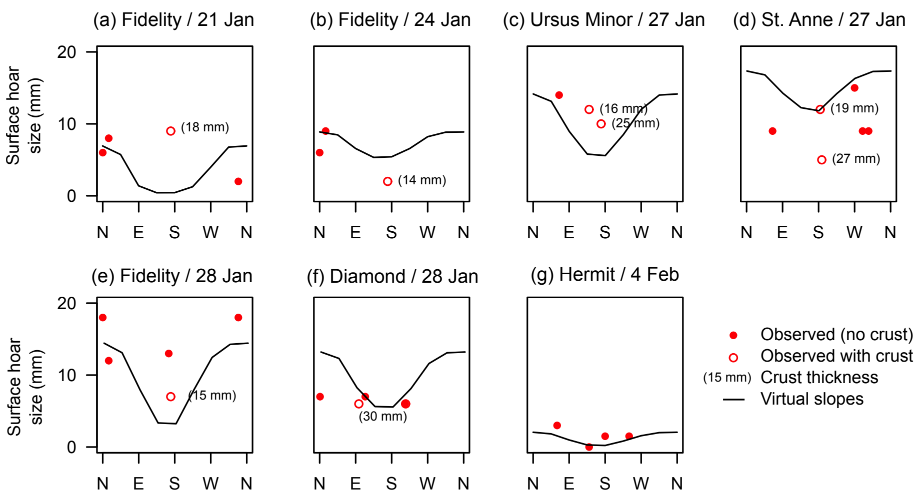

Figure 10. Surface hoar sizes observed at treeline elevations over different slope aspects during 7 field campaigns. Surface hoar ~~was~~ observed without underlying sun crusts are shown with ~~(~~solid red dots~~) and without (hollow red dots)~~, while surface hoar observed with underlying sun crusts are shown with hollow red dots (and the thickness of the crust ~~thicknesses printed~~ to the right). Black lines show the ~~sizes~~ median size modelled on slopes at 8 cardinal aspects with 30° inclines~~at 8 cardinal aspects~~. Slope simulations were done ~~at~~ with forecast data from grid points at treeline elevations within a 10 km radius of the mountain~~, and the median crystal size for that aspect is shown~~.