Cold Regions Science and Technology 82 (2012) 68–74

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Modeling the spatial distribution of surface hoar in complex topography

N. Helbig *, A. van Herwijnen

Montana State University, Department of Civil Engineering, Bozeman, MT, USA

ARTICLE INFO

Article history:
Received 17 January 2012
Accepted 9 May 2012

Keywords:
Surface hoar
Spatial variability
Complex topography
Modeling
Avalanche forecasting

ABSTRACT

Buried surface hoar is a well-known weak snowpack layer, often associated with snow avalanches. Knowledge about the spatial distribution of surface hoar is therefore of great importance for avalanche forecasting. We investigate if spatial variations of surface hoar in mountainous terrain can be modeled based on terrain characteristics. Using a detailed radiation balance model, distributed radiation over an ensemble of 1800 simulated topographies, covering a wide range of terrain characteristics, was computed. Light winds and increased relative humidity were assumed to be favorable for surface hoar formation. To describe surface hoar formation, we derived a sky view factor threshold associated with the minimum snow surface cooling necessary for surface hoar formation based on laboratory measurements. To describe surface hoar destruction, as a first approach, we assumed that surface hoar only survives on shaded slopes. Applying two simple thresholds to our spatial radiation modelings, 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 spacing between mountains. 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.

1. Introduction

Avalanches start with a failure in a buried weak snowpack layer. There are various types of weak snowpack layers, generally classified as either non-persistent (e.g. new snow) or persistent (e.g. surface hoar or depth hoar) weak layers. One of the main objectives for avalanche forecasting is to characterize the spatial distribution of weak snowpack layers within the forecasting region with a particular view on snow stability. This characterization is most often based on a few point observations, which are extrapolated over the forecasting region based on meteorological observations and forecasts in combination with the personal experience of the forecaster.

It has long been known that once buried, surface hoar forms a weak snowpack layer which can remain hazardous for extended periods of time (Paulcke, 1938). Indeed, many fatal avalanches start in a weak layer of buried surface hoar (e.g. Föhn, 1992; Jamieson and Johnston, 1992). Surface hoar crystals, both beautiful and very fragile, form on the snow surface during cold clear nights. Cloudless sky, humid air and low to moderate wind speeds are necessary meteorological preconditions for the formation of surface hoar (Colbeck, 1988; Hachikubo and Akitaya, 1997, 1998; Stössel et al., 2010). Due to longwave (LW) radiative cooling, the snow surface becomes much colder than the air resulting in a water vapor flux toward the snow surface (deposition) and the development of surface hoar crystals. While the preconditions for surface hoar formation are relatively well understood, the evolution and survival of surface hoar crystals on the snow surface, e.g. due to the influence of wind or incident solar radiation, are less clear (Stössel et al., 2010). Even though two more recent studies have clearly observed the differing impact of shortwave (SW) radiation on surface hoar survival by field observations on an inclined forest opening (Lutz and Birkeland, 2011) and on three nearly flat areas, two at treeline and one in the alpine (Shea and Jamieson, 2011), the exact thresholds for the maximum or total input of incident SW radiation remain unspecified.

Due to the complex interactions between meteorological parameters and topography, the spatial distribution of surface hoar in mountainous terrain is complicated. Several studies have addressed this issue with field measurements on single slopes with varying azimuths (e.g. Cooperstein et al., 2004), on flat fields with varying elevations (Föhn, 2001) and in sparse forests or forest openings (e.g. Gubler and Rychetnik, 1991; Höller, 1998; Lutz and Birkeland, 2011; Shea and Jamieson, 2010, 2011). Additionally, several studies addressed the scale ranges of surface hoar layers by conducting many field measurements over larger regions (e.g. Borish et al., 2010; Feick et al., 2007; Hägeli and McClung, 2002; Schweizer and Kronholm, 2007). Results from these studies confirm the micrometeorological preconditions for surface hoar formation and emphasize the spatial variability of surface hoar due to the variation of

* Corresponding author.
E-mail addresses: norahelbig@gmail.com (N. Helbig), alec.van.herwijnen@gmail.com (A. van Herwijnen).

0165-232X/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2012.05.008

Table 1
The table presents the combinations of σ and ξ, the L/ξ ratios and mean sky view factors F_{sky} for the mean slope angle $\zeta = 31°$.

ξ [m]	σ [m]	L/ξ	F_{sky}
1000	364	3	0.924
900	328	3.3	0.924
800	291	3.8	0.916
700	255	4.3	0.909
600	218	5	0.902
500	182	6	0.897
400	146	7.5	0.889
300	109	10	0.885
200	73	15	0.882

meteorological conditions as well as terrain characteristics. While in most cases, observed variations in surface hoar could qualitatively be explained (e.g. katabatic winds, daytime shading), until now, no thorough attempt has been made to systematically relate surface hoar formation and survival to terrain parameters in order to tackle the spatial variation solely due to terrain features for alpine areas.

In this study, we investigate if the spatial distribution of surface hoar in complex topography can be simulated by using simple terrain characteristics for the two major meteorological preconditions for surface hoar formation and survival. These are LW radiative cooling for the formation of surface hoar and incident SW radiation for the destruction. Rather than using a limited set of real topographies, we used a large ensemble of simulated topographies covering a wide range of typical terrain characteristics. Assuming meteorological conditions favorable for surface hoar formation, we investigate the spatial distribution of surface hoar based on simple thresholds for the sky view factor (expressing the ratio of the flux falling on an inclined surface from the visible part of the sky to that received from an unobstructed hemisphere) and incident direct beam SW radiation (i.e. sun or shadow indicator). Even though we chose simple criteria for the formation and survival of surface hoar crystals on the snow surface, this study demonstrates a new avenue for spatially modeling surface hoar existence, which is of great importance for avalanche forecasting. Since our statistics of spatially modeled surface hoar layers are in line with those from previous spatial field studies over larger regions, this study provides new insight in the spatial variability of surface hoar in mountainous terrain.

2. Methods

2.1. Random topographies and terrain parameter

Isotropic Gaussian random fields (GRF) were used to generate a comprehensive set of simulated discrete topographies with a fixed domain size $L = 3$ km and fixed grid size (grid cell size) $\Delta x = 30$ m (i.e. 10,000 grid cells per topography) (for Gaussian random fields see e.g. Adler, 1981). Note that from a detailed analysis of slope and slope components of several real topographies, Helbig and Löwe (2012) found that, for a domain size of 3 km, slope characteristics of real topographies are well approximated by Gaussian statistics. The advantage of using GRFs is that these are fully characterized by two characteristic length scales, namely a valley-to-peak elevation difference σ (i.e. height of mountains), the square root of the variance, and a lateral extension ξ (i.e. width of mountains), the correlation or scale length of topographic features. As outlined in Helbig and Löwe (2012), the mean slope $\tan\zeta$ per domain size L equals $2\,\sigma/\xi$ with mean slope angles ζ computed from subgrid first partial derivatives (slope components) $\partial_x z$ and $\partial_y z$ in orthogonal directions (here, east–west, north–south) via $tan\zeta = [(\partial_x z)^2 + (\partial_y z)^2]^{1/2}$. Thus, by varying these two length scales, but keeping the ratio constant, a variety of topographies with the same mean slope angle can be created (for more details cf. Helbig and Löwe, 2012).

In total, we used 1800 simulated topographies with a mean slope angle of 31°, covering a broad range of characteristic scales (Table 1). For each of the nine different σ and ξ combinations, 200 topographies were generated, a number that was found to result in reliable σ, ξ values estimated from computed covariance vectors (cf. Helbig and Löwe, 2012). For each grid cell, three terrain parameters were determined: slope angle ζ, azimuth angle ϕ and sky view factor F_{sky}. Note that a mean (domain-averaged) slope of 31° was chosen in order to focus on those slopes where dry snow slab avalanches typically release (e.g. van Herwijnen and Heierli, 2009). Topographic azimuth angles were computed from first partial derivatives via $tan\phi = \partial_y z/\partial_x z$ counting counterclockwise, with $\phi = 0°$ representing a south facing slope. Finally, the sky view factor was computed from anisotropic terrain view factor sums (for computational details cf. Helbig et al., 2009). For our isotropic GRFs, the probability density functions of slope angle, azimuth angle and sky view factor are shown in Fig. 1.

2.2. Distributed radiation modeling

Distributed radiation over our ensemble of topographies was computed using a detailed, validated SW radiation balance model (Helbig et al., 2009, 2010). Several model simplifications are applied to study the spatial distribution of surface hoar solely due to the influence of terrain characteristics. We chose nine constant sun elevation angles $\theta_e = 10, 20, 30 \ldots 90°$ to capture the influence of varying sun elevation angles. Since for isotropic GRFs topographic azimuth angles are uniformly distributed (Fig. 1b), we used a constant sun azimuth angle. Note that roughly uniform topographic azimuth angle distributions were also found for seven real topographies from Switzerland and the US, covering a wide range of geomorphologies, mean slope angles and domain sizes (Helbig and Löwe, 2012). Even though our results

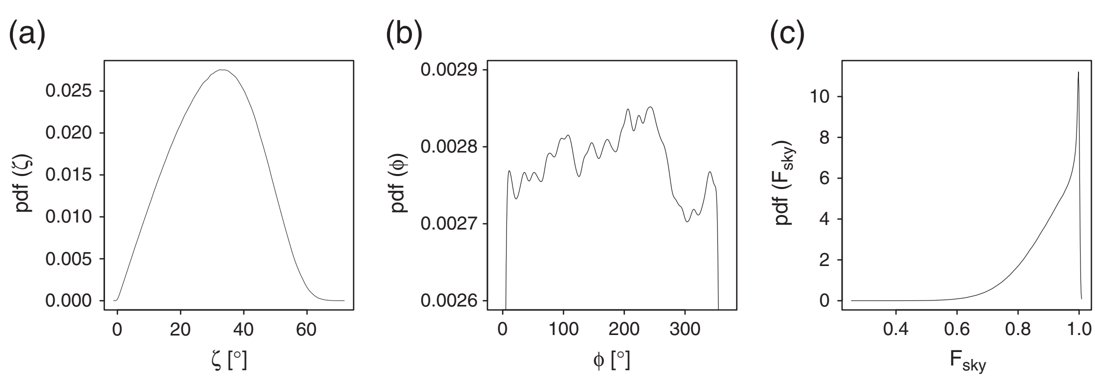

Fig. 1. Overview of the probability density functions (*pdf*) of the main topographic descriptors for all simulated topographies (Table 1), (a) *pdf* of slope angles ζ, (b) *pdf* of topographic azimuth angles ϕ and (c) *pdf* of sky view factors F_{sky}.