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Field observations on spatial variability of surface hoar at the basin scale

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[1] Surface hoar deposited on the snow surface represents, once buried by subsequent snowfall, one of the principal weak layers on which dry snow slab avalanches release. To predict instabilities caused by a buried surface hoar layer, its spatial extent needs to be known. Avalanche forecasting relies, among other things, on meteorological data from automatic stations. In principle, surface hoar formation can be predicted from these data. In order to study the spatial variation in surface hoar formation and destruction, daily observations were made during one winter at 23 locations of different aspect, slope inclination, and wind exposure within an area of about 3 km^2. Four automatic weather stations were located within the study area: one on level terrain and three across a ridge. Despite the good instrumentation the correlation between surface hoar growth and calculated sublimation rate was poor. Distinct spatial patterns of surface hoar growth were found. Surface hoar crystals were frequently larger at the ridge site than in the surroundings of the automatic weather station on level terrain. The variation in surface hoar formation was mainly due to different prevailing wind regimes during the formation periods. The surroundings of the automatic weather station on level terrain were under the influence of local katabatic winds that dried up the air so that growth conditions were locally less favorable. Our observations suggest that predicting surface hoar formation for complex alpine terrain on the basis of data from an automatic weather station, the standard procedure in avalanche forecasting, seems nearly impossible unless at least the local wind regime is known at high resolution ($\leq$10 m). For both surface hoar formation and surface hoar destruction observations suggest wind conditions to be most crucial for spatial variation.

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1. Introduction

[2] Dry snow slab avalanches initiate from a shear failure in a weak snowpack layer or at a weak interface overlain by a cohesive slab. Typically, these weaknesses are formed at the snow surface and are subsequently buried by a snowfall [*Schweizer et al.*, 2003]. They often consist of crystals with plane faces such as surface hoar, facets and depth hoar. These so-called persistent grain types were found in 82% of a large data set of skier-triggered avalanches from Switzerland and Canada [*Schweizer and Jamieson*, 2001]. Surface hoar, once buried, is considered to be a particularly dangerous weak layer [*Föhn*, 2001]. It has a columnar or truss-like texture that changes little over periods of up to several months and remains prone to collapsing which may release gravitational potential energy for fracture propagation [*Jamieson and Schweizer*, 2000].

[3] Surface hoar crystals grow due to deposition of water vapour from the air onto the snow surface. Hence their shape and growth rate depend on temperature and on the excess vapour density over ice. During growth conditions a water vapour flux toward the snow surface is required. This is the case when the snow surface temperature is lower than the saturation (or dew point) temperature in the air above, usually due to cooling of the snow surface by outgoing long-wave radiation.

[4] Growth conditions have been studied by *Lang et al.* [1985], *Breyfogle* [1987], and *Hachikubo et al.* [1995]. *Hachikubo and Akitaya* [1997a, 1997b, 1998] focused on the effect of wind on the sublimation rate, obtained the transfer coefficient of water vapour and found that the sublimation rate of surface hoar can be estimated from meteorological conditions. The importance of wind for surface hoar formation has long been recognized, and *Colbeck* [1988] proposed that light wind favors surface hoar growth by promoting the turbulent transfer of water vapor. He stated that the wind could be a very gentle drainage wind. Such local down flowing winds are also

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known as katabatic winds. These downslope gravity flows are caused by nocturnal radiative cooling near the surface under calm clear-sky conditions [*Barry*, 1992]. On the basis of various field measurements, *Hachikubo* [2001] concluded that in the wind speed range of 0–6 m s^{-1} (wind speed measured 1 m above the snow surface), a specific wind speed maximized crystal growth for relative humidity <80%. For relative humidity >90% the sublimation rate increased with increasing wind speed, at least in the range 0.5–3.5 m s^{-1}. Strong winds (>5–10 m s^{-1}) prevent surface hoar formation by destroying the temperature and vapour inversion near the snow surface as the radiative cooling is offset by turbulent warming [*Gubler*, 1998; *Oke*, 1987]. However, *Seligman* [1936] reported an observation of surface hoar growth during conditions with strong, warm winds. On the basis of the results by *Hachikubo* [2001], surface hoar formation with strong winds seems only possible if the air is nearly saturated. While conditions for surface hoar formation have been studied intensively, the processes responsible for destruction of surface hoar once deposited are limited. Before burial by a subsequent snowfall surface hoar can be destroyed by melting, sublimation, rain or wind [*Gubler*, 1998].

[5] For a dry snow slab avalanche to be released, a weak layer in the snowpack has to have a certain spatial extent so that a substantial area below the slab can fail. This critical size for rapidly propagating fractures has been estimated to be of the order of 10^{-1} to 10 m [*Schweizer*, 1999]. Recent measurements indicate that this large range can be narrowed to about 0.5 to 5 m [*Kronholm et al.*, 2004; *Schweizer et al.*, 2004], i.e., to roughly the scale of the snow cover depth [*Bažant et al.*, 2003]. The upper value of this critical size range has to be considered as the lower boundary for the extent of a potential failure layer. To assess snowpack stability, it is therefore crucial to know the spatial variability of weak layer and slab properties. However, spatial variability at the slope scale cannot be measured easily, but only be determined with extensive sampling [*Kronholm*, 2004; *Kronholm et al.*, 2004].

[6] As long as weak layers that formed at the snow surface are not yet buried, their spatial variability can easily be observed. Assuming that the variability found at the surface is largely preserved after burial, close observation of the snow surface should allow assessment of the spatial variability of subsequently buried weak layers. Of course, this assumption is not valid if, for example, between the last observation and the burial, the weak surface layer is destroyed by strong winds.

[7] Avalanche forecasting strongly relies on data of snow cover and weather conditions measured at so-called representative sites, and in part on snow cover simulation models driven by these data [*Brun et al.*, 1989; *Lehning et al.*, 1999]. With the increasing demand to provide detailed forecasts, extrapolation to the surrounding terrain is sought. However, hardly any verification data are available at present to check the assumptions of distributed models.

[8] Accordingly, our aim was to observe the snow surface at the basin scale with high spatial and temporal resolution, to describe the spatial variability of typical weak snowpack layers that form at the snow surface and to relate the resulting patterns to the snow and weather conditions. As three surface hoar formation periods occurred during the observation period in winter 2002–2003, this paper will exclusively focus on the spatial variability of surface hoar formation and destruction and their relation to standard meteorological measurements.

2. Methods

2.1. Study Site and Instrumentation

[9] Field observations were carried out during the winter 2002–2003 in the Weissfluhjoch-Kreuzweg-Gaudergrat area in the eastern Swiss Alps near Davos (Switzerland; 46°51′N, 9°48′E) (Figure 1). The study area was selected due to its proximity to a ski area providing easy and safe access, and since it was well instrumented and includes a variety of terrain features. The terrain is above tree line, rather complex and part of the northerly slope of the Weissfluh peak (2834 m asl). Four automatic weather stations are located within the study area that covers about 3 km^2. The first one at Kreuzweg (2288 m asl; Figure 1) is a standard, so-called IMIS station as used in the network of the Swiss avalanche forecasting service [*Lehning et al.*, 1999]. It is located on a flat field believed to be representative for the snow conditions in the surroundings. The meteorological sensors are mounted 4.5 m above the ground. About 1 km to the northwest, three stations (GG-North, GG-Top, GG-South) are located across the Gaudergrat ridge (2282 m asl; Figure 1) and were built less than 100 m apart for a snow drift study [*Gauer*, 2001]. The station GG-North is located on a northwest facing 32° steep slope, GG-South is located on a southeast facing 43° steep slope, and GG-Top is on the top of the ridge. Measurements at the automatic stations include air temperature (not ventilated), snow surface temperature (infrared sensor), horizontal wind speed and direction (propeller-type Young anemometer at Kreuzweg, Gill UVW anemometers at Gaudergrat), and relative humidity (capacitive measurement). The meteorological sensors are mounted about 6.5 m above ground. The relative humidity is the measurement with the poorest accuracy, about ±5%. More details on the instrumentation are given by *Gauer* [1999, 2001] and *Lehning et al.* [1999]. Approximately 2 km to the south of the study area another automatic weather station is located on level ground at the Weissfluhjoch study plot (2540 m asl).

2.2. Field Observations

[10] Within the study area 23 observation points were selected and visited on a daily basis, when weather conditions allowed access. They covered all principal aspects and included wind exposed and wind sheltered locations. Slope angles ranged from 0° to 39°, and elevation from about 2100 to 2500 m asl (Table 1). Most of the points were clustered around the automatic stations Kreuzweg (points 2–9) and Gaudergrat (points 12–20). It would have been desirable to have more observation points to cover similar topographical features several times, but the number of points selected (23) was close to the maximum number that could be visited on a single day.

[11] Daily observations of the surface characteristics at each point included: grain type and size, thickness and hardness of the surface layer, type of surface form, and surface roughness. They were classified according to the

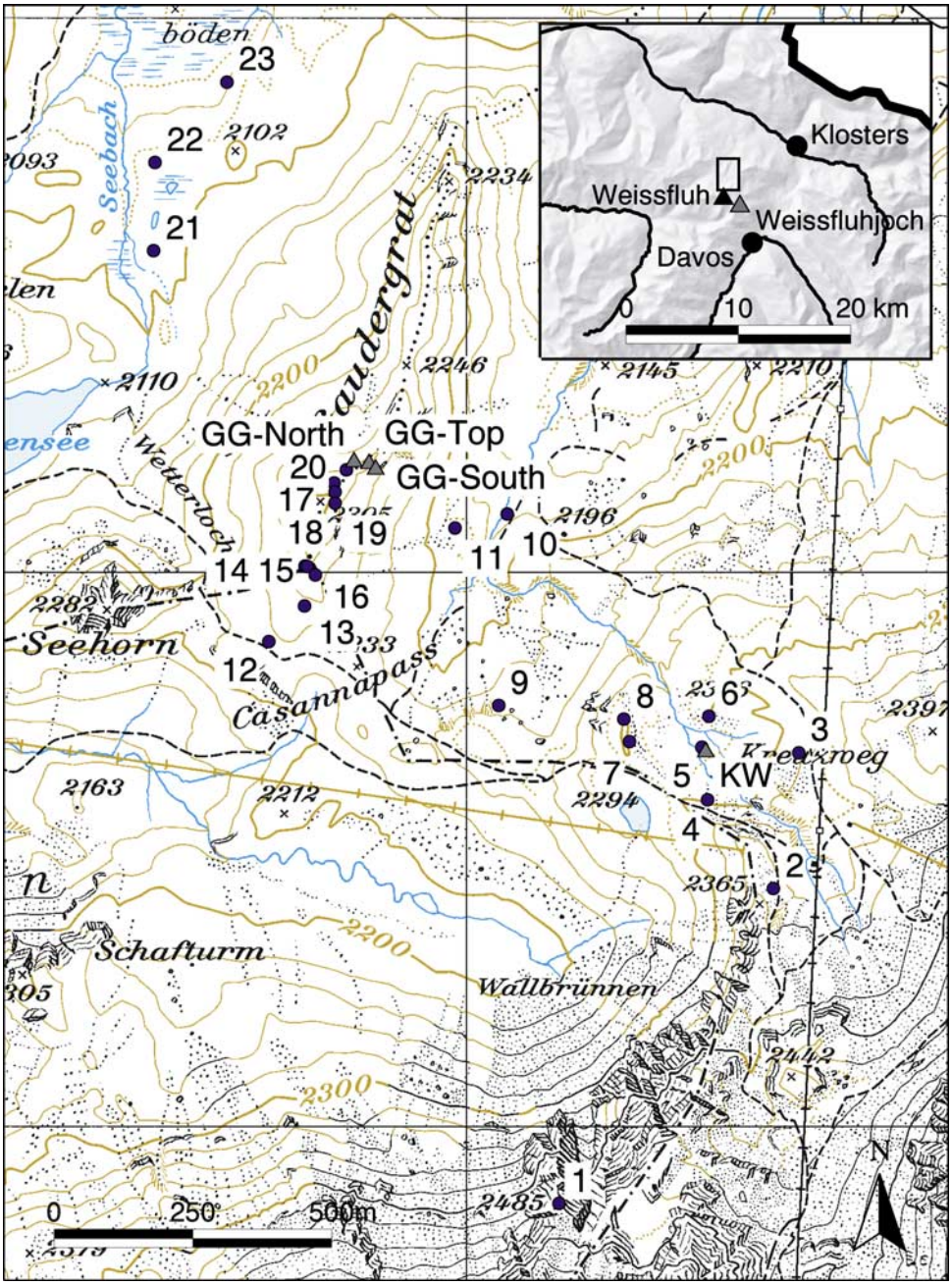

Figure 1. Map of study area (46°51′ N, 9°48′E) in the eastern Swiss Alps (see inset). Locations of the automatic weather stations (triangles) and the observation points are given (KW, Kreuzweg; GG, Gaudergrat). (Map source is PK25©2006 swisstopo (DV033492).)

International Classification of Seasonal Snow on the Ground (ICSSG) [*Colbeck et al.*, 1990]. The size of the crystals was described as a range with the lower number characterizing the overall mean (according to ICSSG) and the larger number characterizing the mean maximum size [*Baunach et al.*, 2001]. The mean maximum size will be used for analysis since it seems more relevant for avalanche formation [*Jamieson and Johnston*, 1999]. Usually one or more layers below the surface layer were characterized as well so that the evolution of the surface layer could be tracked precisely from one day to the next. If the snow surface in the near surroundings (1 m) of the observation point looked irregular, several observations were made to characterize the point. Furthermore, on the way from one observation point to the next (median distance: 124 m) it was observed and recorded if the point observations coincided with the surface properties of the terrain in between observations points.

2.3. Surface Hoar Growth

[12] As the formation of surface hoar is the deposition of vapor on ice, the exchange of latent heat determines, in principle, the amount of surface hoar. However, observations show [e.g., *Föhn*, 2001] that surface hoar crystals do

Table 1. Characteristics of the 23 Observation Points and Maximum Surface Hoar Size Observed During the Three Surface Hoar Formation Periods[a]

Observation Point	Subarea	Slope Angle, deg	Aspect	10 Jan	13 Jan	17 Jan	19 Jan	20 Jan	21 Jan	11 Feb	12 Feb	13 Feb	14 Feb	16 Feb
1	KW	21	N	0	0	0	1.5	1.5	0	1	1	1	1	3
2	KW	26	E	1	1	0	1.25	0.5	0	1.5	1	1	2	6
3	KW	24	WNW	0	0.75	0	0	2	0	1	1	1	1.5	6
4	KW	27	N	1	1	0	1.5	1	0	1.5	1.5	1.5	2	9
5	KW	0	-	0.75	1	0	1	1.5	0	1	1	1.5	2	6
6	KW	20	SW	1	0.75	0	1.5	2	0	0	0	0	0	4
7	KW	19	E	0.75	1	0	1.5	1.5	0	1.5	1	1.5	2	6
8	KW	9	NNW	0.75	1	0	1.5	2.5	0	1	1	1	2	5
9	KW	25	NW	1	1	0	1.5	2	0	1.5	2	2	2.5	10
10	KW	26	NW	1	1	0	1.5	1	0	1.25	1	1.5	2	8
11	KW	0	-	1.25	1.5	1.5	1.5	1.5	0	1.5	1	2	2	4
12	GG	23	SW	1.5	1.5	0	1.25	1	0	0	1	0	0	13
13	GG	24	SSW	1.25	1.25	0	2	1.5	0	0	0	0	0	14
14	GG	25	W	1.5	2	2	n/a	2	1	2	2	1	1	8
15	GG	7	S	1	1	2	n/a	1.5	0	n/a	2	1.5	1.75	18
16	GG	31	SE	1.25	1	0	n/a	1.5	0	0	0	0	0	10
17	GG	23	N	1.5	1.25	2	n/a	3	1	2	5	4	2.5	24
18	GG	5	S	1	1	2	n/a	2	0	4	3	1.5	1.25	15
19	GG	32	E	1.25	1.25	2	n/a	1.5	0	0	0	0	0	12
20	GG	32	NNW	n/a	1	2	n/a	3	0	4	4	4	4	22
21	GG	0	-	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.5	2.5	15
22	GG	8	SE	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.5	2	7
23	GG	27	W	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.5	1.75	10

[a]Values are in mm. The subareas are Kreuzweg (KW) and Gaudergrat (GG).

not always grow when a latent heat flux toward the snow surface exists as theory predicts. With the meteorological data from the automatic stations the latent heat flux Q_E (W m^{-2}) was calculated as [*Lehning et al.*, 2002]:

$$Q_E = -C\frac{0.622L_d}{R_a T(z)}\left[p_s^w(T(z))rH - p_s^i(T(0))\right]. \quad (1)$$

C is the kinematic transfer coefficient, R_a(= 287 J kg^{-1} K^{-1}) is the gas constant for dry air, L_d(= 2.83 MJ kg^{-1}) is the latent heat of sublimation, $p_s^{w/i}$ is the saturation vapour pressure over water or ice, rH (%) is relative humidity and $T(z)$ is air temperature at height z above the snow surface and $T(0)$ is snow surface temperature. An upward flux is positive. If the heat flux is negative, surface hoar might grow. The kinematic transfer coefficient is approximated by [*Lehning et al.*, 2002]

$$C = \frac{ku_*}{0.74\ln\frac{z}{z_0}} \quad (2)$$

k is the von Karman constant with a value of 0.4, u_* is the friction velocity and z_0 is the roughness length. Assuming a logarithmic wind profile with a displacement height $d = 0$, the friction velocity u_* can be given as

$$u_* = \frac{0.4u(z)}{\ln\frac{z}{z_0}} \quad (3)$$

with the wind speed $u(z)$ measured at height z above the snow surface. Substituting equation (3) in equation (2) simplifies the kinematic transfer coefficient to

$$C = 0.216\frac{u(z)}{\left(\ln\frac{z}{z_0}\right)^2}. \quad (4)$$

For the roughness length z_0 a constant value of 1.5 mm is assumed [*Föhn*, 2001]. The saturation vapour pressure with respect to ice or water is approximated by [*Stull*, 2000]

$$p_s^{ice,air}(T_s) = p_0\exp\left[\frac{L_{d,v}}{R_v}\left(\frac{1}{T_0} - \frac{1}{T_s}\right)\right] \quad (5)$$

with p_0 = 611 Pa the triple point pressure, L_v = 2.5 MJ kg^{-1} the latent heat of vaporization, R_v = 461 J K^{-1} kg^{-1} the gas constant for water vapor, and T_0 = 273.16 K the triple point temperature. For direct comparison with observed surface hoar size the sublimation rate E (in kg m^{-2} s^{-1}) will be given

$$E = \frac{Q_E}{L_d}. \quad (6)$$

[13] To calculate the latent heat flux (equation (1)) and the rate of sublimation (equation (6)) at the stations GG-North and GG-South, the wind speed u measured at the station GG-Top was used since it was assumed to be more accurate than the measurements on the slopes.

[14] To compare growth conditions, the study area was divided into two subareas: Kreuzweg and Gaudergrat. We will later show that this division is useful for studying the growth conditions. Observation points 1–11 were grouped into the subarea Kreuzweg, and points 12–23 were grouped into the subarea Gaudergrat. To decide whether or not there was a difference in surface hoar size in the two subareas, the nonparametric Mann-Whitney U test was applied [*Spiegel and Stephens*, 1999]. If the level of significance P was less than 0.05, the two groups were considered as significantly different.

2.4. Surface Hoar Destruction

[15] To analyze surface hoar destruction due to radiative heating, the incoming short-wave radiation was calculated

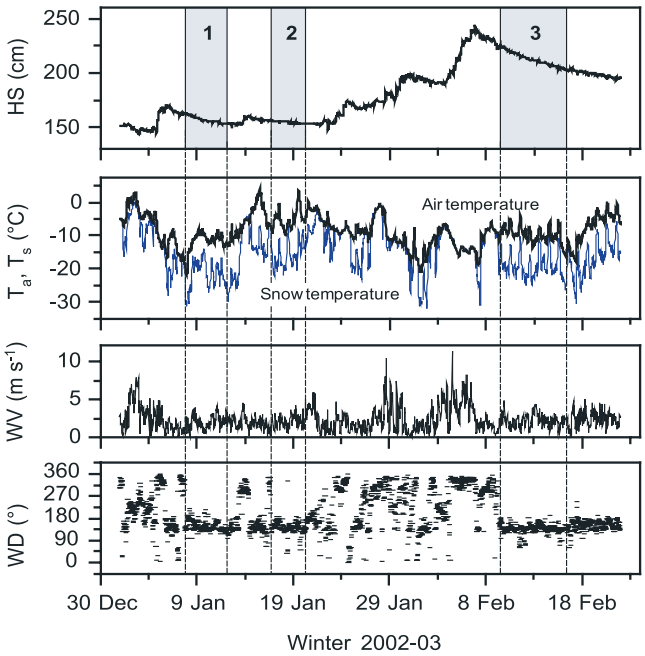

Figure 2. Snow depth (HS), air temperature (T_a) and snow surface temperature (T_s), wind speed (WV) (30 min average), and wind direction (WD) measured at the automatic station Kreuzweg (2288 m asl) during January and February 2003. Surface hoar growth periods (1–3) are indicated.

[*Oke*, 1987, pp. 339–346]. The aim was to find a relation between calculated daily sums of incoming short-wave radiation and the existence of the surface hoar layer at the observation points. We here investigate whether the relative differences in the amount of incoming short-wave radiation between the 22 observation points (point 1 was not taken into account) could explain the observed destruction of surface hoar.

[16] Using the Geographic Information System (GIS) ArcView 8.2 a digital terrain model (DTM) of the study area with a cell size of 5 m × 5 m was built. Slope inclination and aspect were generated from the DTM. On the basis of the measurements at the station GG-Top (which has no shading from the immediately surrounding terrain) maximum short-wave radiation under current atmospheric conditions for each one hour time step was calculated and extrapolated for each grid cell within the study area. Shading due to adjacent terrain was taken into account by the "hillshade" function and the option "model shadows" of the GIS ArcView 8.2 [*McCoy and Johnston*, 2001]. The option "model shadows" allows to model shadows by assigning a value of zero for incoming SW radiation to areas in the shadow of surrounding terrain. Reflections were not considered. Daily and cumulated daily totals (in MJ m^{-2}) of the calculated incoming short-wave radiation for each observation point were compared with the snow surface observations in the field. Since the sensitivity of the radiation sensor depended on the solar elevation angle, only the incoming radiation from 1000 to 1500 hours was cumulated and used as an index of the daily total.

[17] To determine an approximate threshold for surface hoar destruction depending on incoming short-wave radiation and surface hoar size a simple regression tree analysis was performed [*Breiman et al.*, 1998].

3. Results

3.1. Meteorological Conditions and Surface Hoar Observations

[18] During January and February 2003 three periods of surface hoar formation were recorded (Figure 2 and Table 1): 10–13 January, 17–21 January and 10–16 February 2003.

3.1.1. Period 10–13 January 2003

[19] Observations started on 10 January 2003. On that day small surface hoar crystals (0.5–1.5 mm) were recorded at almost all observation points. The crystals were slightly larger in the Gaudergrat (median of maximum size: 1.25 mm) than in the Kreuzweg subarea (median of maximum size: 1 mm) (Table 1). The difference in crystal size between the two subareas was statistically significant (nonparametric Mann-Whitney U test, $N = 19$, level of significance: $P = 0.002$).

[20] Analyzing the meteorological data suggested that the surface hoar had certainly formed after the end of the previous snowfall (6 January 2003) (Figure 2), but probably not before the night of 7–8 January 2003 when the latent heat flux (Figure 3c) became significantly negative. Comparing the data from the different meteorological stations showed that the relative humidity at the stations GG-North and GG-South developed differently from the one at the station Kreuzweg (Figure 3b). Early on 8 January 2003 the relative humidity decreased significantly at the station Kreuzweg to about 50% at 0500 hours, but remained high at the Gaudergrat stations GG-North (85%) and GG-South (95%). A decrease in relative humidity similar to the one at Kreuzweg was recorded at the station Weissfluhjoch (2540 m asl), 2.5 km to the south on the southeasterly slope of the Weissfluh peak. The decrease in relative humidity followed an increase in air temperature (Figure 3a) and a decrease in absolute humidity. Wind speeds were generally low, but mean and maximum (30 min) wind speed were higher at the Kreuzweg (nighttime mean about 1.6 m s^{-1}) than at the Gaudergrat (GG-Top: 0.8 m s^{-1}) (Figure 3d). At the station Kreuzweg, toward the morning of 8 Jan 2003 there were frequent gusts exceeding 5 m s^{-1} (Figure 3e) and the wind was constantly blowing from southeast to south (Figure 3f), i.e., downslope indicating that the wind was katabatic. At Gaudergrat wind gusts were lower and hardly ever exceeded 3 m s^{-1} (Figure 3e), and wind direction varied with mainly northerly components (Figure 3f).

[21] During the night of 7–8 January 2003 the latent heat flux was larger at the Kreuzweg than at the Gaudergrat. This follows from the fact that wind speed and relative humidity affect the latent heat flux counteractively. Considering the whole period during which the latent heat flux was negative (suggesting surface hoar growth) at all three stations (i.e., from 7 January 2003, 1500 hours, to 8 January 2003, 1500 hours) sublimation was largest for the station GG-North (Figure 4a and Table 2).

[22] The surface hoar survived until 13 January 2003, when it was present at all observation points. However, it did not grow significantly after 10 January 2003: Only at 7 out of 19 observation points (37%) the maximum size of the

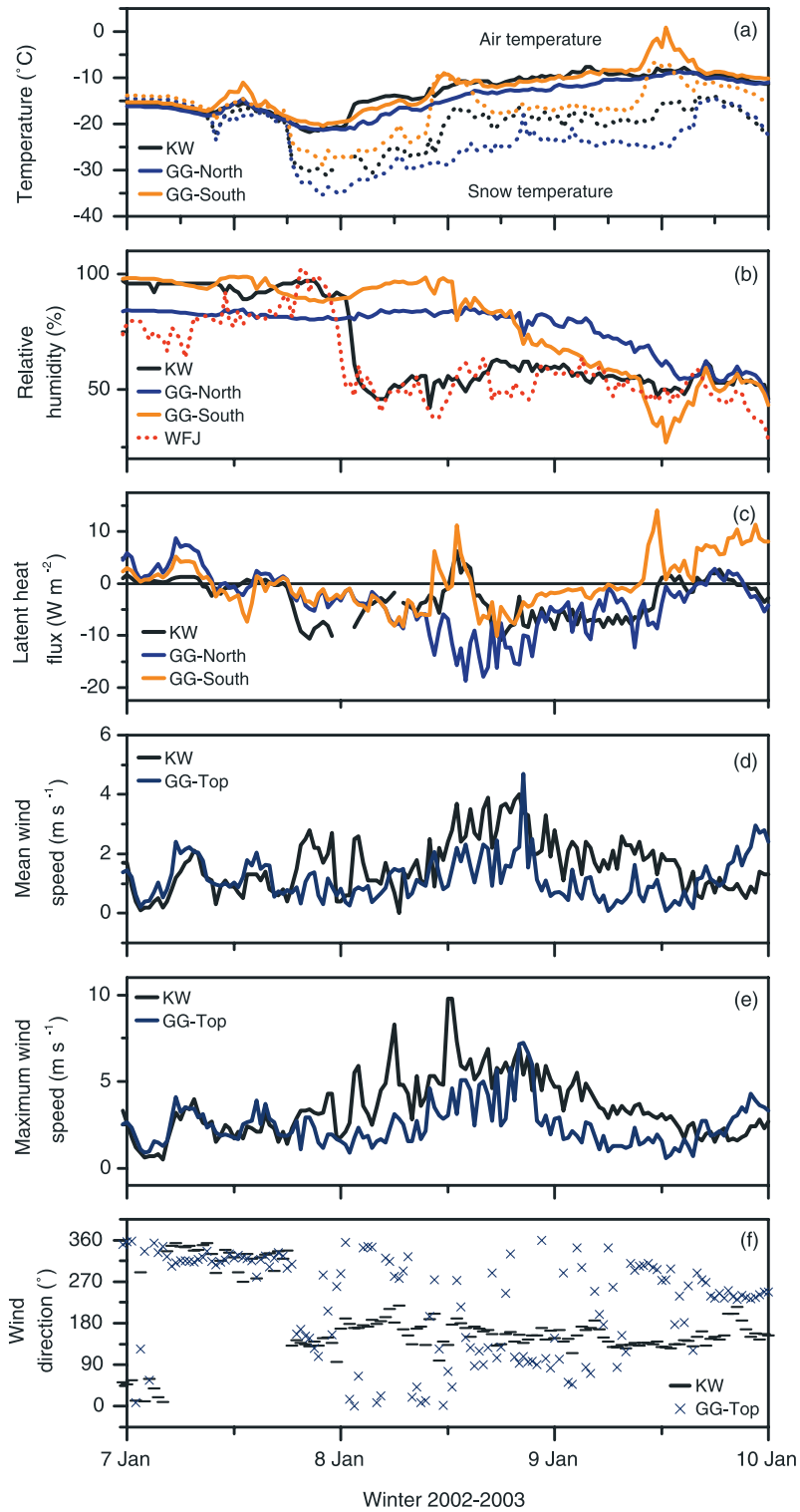

Figure 3. Meteorological conditions for 7–10 January 2003 (observation/growth period 1). Selected data as measured by the four automatic weather stations are given (KW, Kreuzweg; GG, Gaudergrat): (a) air temperature (solid lines) and snow surface temperature (dotted lines), (b) relative humidity, including data from the station Weissfluhjoch (WFJ; dotted line), (c) latent heat flux as calculated by equation (1), (d) mean and (e) maximum wind speed, and (f) wind direction.

surface hoar crystals increased slightly (typically by 0.25 mm), whereas at the majority of the observation points the size remained unchanged or even decreased slightly. This amount of increase and decrease roughly corresponds with the measurement accuracy. Figure 5 shows the maximum size of surface hoar as recorded on 13 January 2003 in the study area. Still, there was a slight trend toward larger crystals in the Gaudergrat subarea (median of maximum

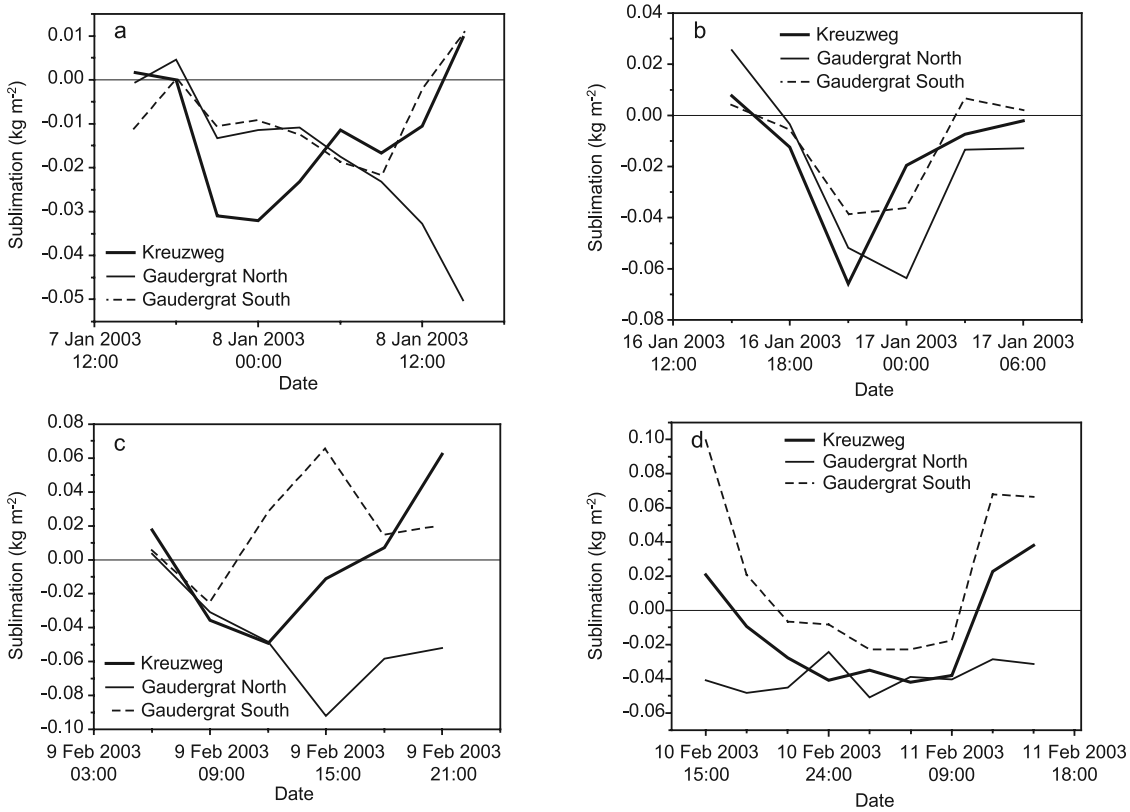

Figure 4. Cumulative mass of sublimation (accumulated over 3 hours) during surface hoar formation periods calculated for the three meteorological stations Kreuzweg, Gaudergrat North, and Gaudergrat South. Periods shown are (a) 7–8 January 2003, (b) 16–17 January 2003, (c) 9 February 2003, and (d) 10–11 February 2003.

size: 1.25 mm) than in the Kreuzweg subarea (median of maximum size: 1.0 mm). The difference was statistically significant ($N = 19$, $P = 0.02$) (Figure 6).

3.1.2. Period 17–21 January 2003

[23] After the snowfall of 13–14 January 2003, warm and sunny weather prevailed with low relative humidity until 16 January 2003 when it was overcast with some very light snowfall. In the evening of 16 January 2003 the sky cleared and subsequently the weather was relatively warm and sunny until 21 January 2003 when it started snowing (Figure 2). During this period of good weather the snow surface became very variable: sun crusts on southerly slopes, occasionally wind crusts, and soft and powdery on shady slopes.

[24] On 17 January 2003 surface hoar (median of maximum size: 2 mm) was recorded in the Gaudergrat subarea, but not at all observation points, in particularly not on 20°–30° slopes of southerly aspect. No surface hoar was observed in the surroundings of the Kreuzweg station.

[25] The meteorological data showed that on the evening of 16 January 2003 the snow surface temperature decreased significantly (Figure 7a) and the latent heat flux became negative (Figure 7c). Toward the middle of the night of 16–17 January 2003 the relative humidity decreased at all three stations, but at the station Kreuzweg the decrease started about 3 hours earlier (Figure 7b). In the second half of the night the air temperature increased with decreasing absolute humidity, causing the relative humidity to drop further to about 20% at all stations by the morning of 17 January 2003. At the station GG-North sublimation was largest (Figure 4b and Table 2) and stayed negative throughout 17 January 2003 (Figure 7c). Wind speeds were higher with stronger gusts at Kreuzweg than at Gaudergrat (Figures 7d and 7e).

[26] During this initial surface hoar formation period (16–17 January 2003) the peak sublimation was slightly higher at Kreuzweg than at the station GG-North (Figure 4b). However, the peak at the station Kreuzweg was narrower than at the Gaudergrat stations. At the station GG-North the maximum sublimation occurred about 3 hours later than at Kreuzweg. Considering the whole period during which the latent heat flux was negative

Table 2. Cumulative Mass of Sublimation During Surface Hoar Formation Periods

Period	Kreuzweg, kg m^{-2}	Gaudergrat North, kg m^{-2}	Gaudergrat South, kg m^{-2}
7 Jan 2003 1500 to 8 Jan 2003 1500	−0.115	−0.155	−0.062
16 Jan 2003 1500 to 17 Jan 2003 0600	−0.108	−0.145	−0.074
9 Feb 2003 0300 to 9 Feb 2003 1800	−0.071	−0.226	0.084
10 Feb 2003 1500 to 11 Feb 2003 0900	−0.193	−0.248	−0.057

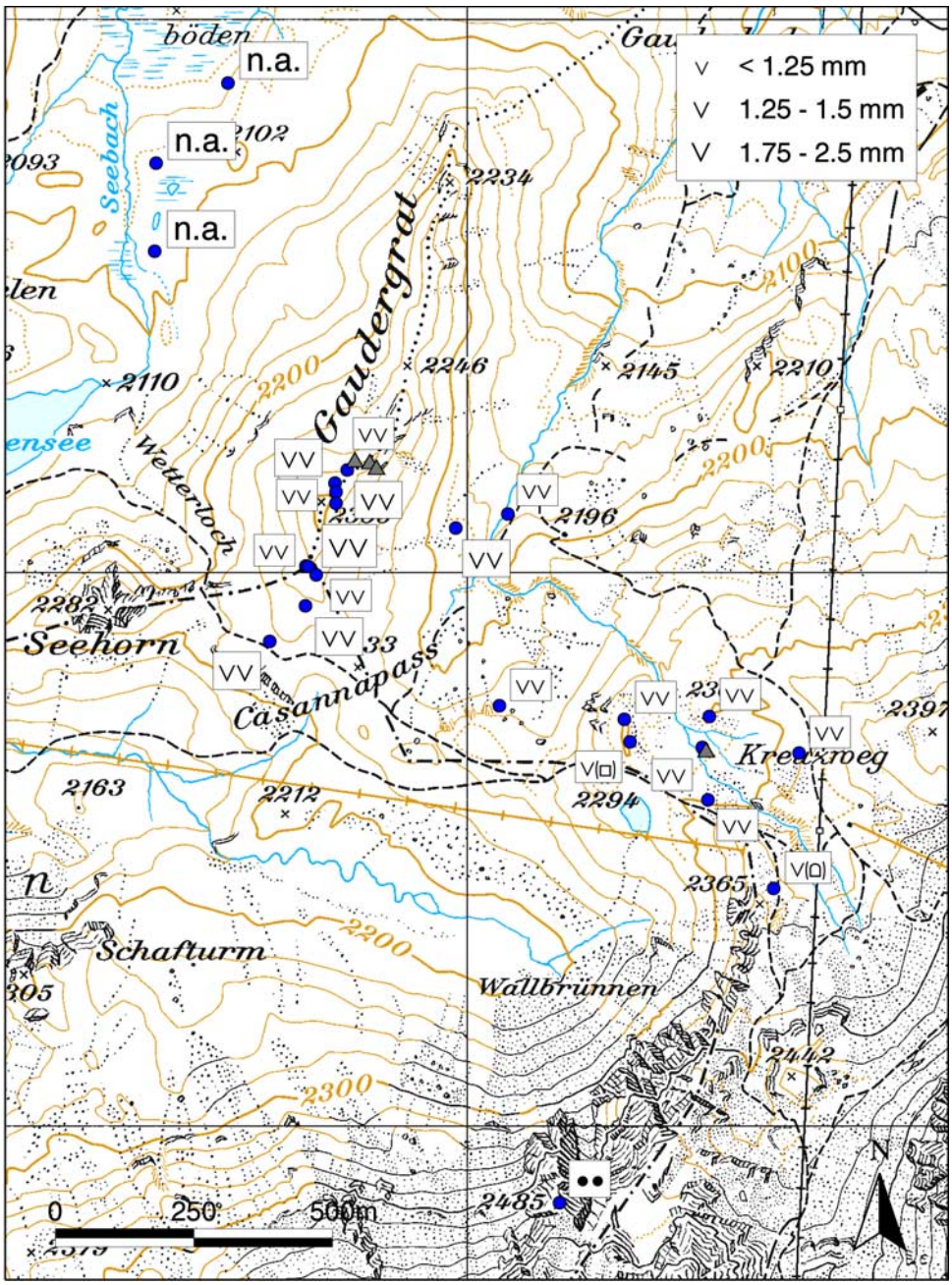

Figure 5. Surface hoar size and distribution in the study area on 13 January 2003. Maximum size of surface hoar is given. At observation points where no surface hoar was present the grain type at the snow surface is given according to the ICSSG [*Colbeck et al.*, 1990]. (Map source is PK25©2006 swisstopo (DV033492).)

(i.e., from 16 January 2003 1500 hours to 17 January 0600 hours) sublimation was largest for the station GG-North (Figure 4b and Table 2).

[27] During the following night of 17–18 January 2003 the latent heat flux was negative at all stations, though only slightly at the station GG-South (Figure 7c). On the morning of 18 January 2003 the sky was slightly overcast exemplified by the evolution of the snow surface temperature (Figure 7a). The latent heat flux became positive for a few hours at all stations. After the sky cleared and mainly during the first half of the following night (18–19 January 2003) a negative flux prevailed, in particular at the station GG-North (i.e., on shady slopes) (Figure 7c). On the morning of 19 January 2003 the relative humidity was low (20%) at all stations (Figure 7b), and from about 0900 hours the latent heat flux was positive even at the station GG-North (Figure 7c).

[28] Given the above described periods of negative latent heat flux, on 19 January 2003 surface hoar was recorded on all but 1 of the 13 observation points (1–13) visited that day, mainly located in the surroundings of the Kreuzweg station (Table 1). At the observation point where no surface

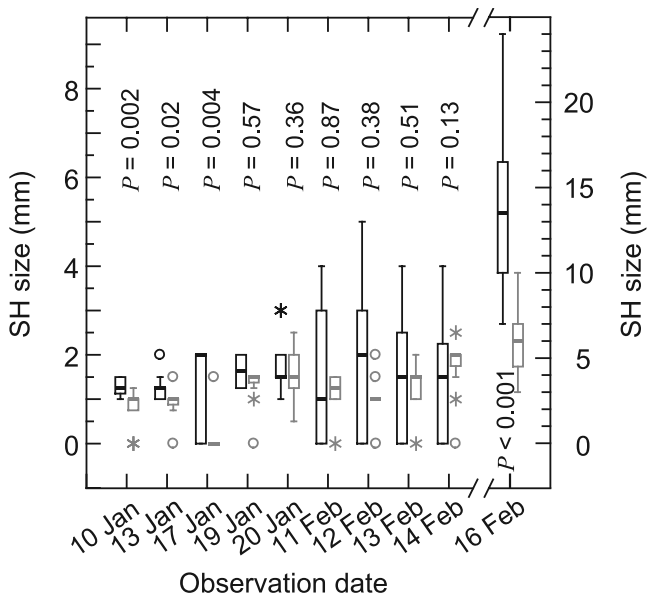

Figure 6. Comparison of surface hoar crystal size between the subareas Kreuzweg (observation points 1–11) and Gaudergrat (observation points 12–23) for different observation dates during the three periods. For each date, Gaudergrat data are given on the left, and Kreuzweg data are on the right. Boxes span the interquartile range from first to third quartile with a horizontal line showing the median. Whiskers show the range of observed values that fall within 1.5 times the interquartile range above and below the interquartile range. Asterisks show outliers, and open circles show far outside values. For each pair the samples from the two subareas were compared with the nonparametric Mann-Whitney U test, and the level of significance P is given.

hoar was observed (point 3) the snow surface was wind affected, suggesting wind erosion. The surface hoar crystal size was fairly uniform everywhere with a median maximum size of 1.5 mm and was independent of aspect.

[29] On 19 January 2003 the air temperature was positive, relative humidity was very low (10%) and snow surface temperature varied strongly with aspect (Figures 7a and 7b). At noon, snow surface temperature was −20°C at GG-North, 0°C at GG-South and −8°C in the flat snow surface at Kreuzweg. During the second half of the night of 19–20 January 2003 the relative humidity increased toward the morning to 80%, and the latent heat flux was particularly negative (Figure 7c). Wind speeds during the first half night were 2–3 m s^{-1} at the Kreuzweg and <1.5 m s^{-1} at the Gaudergrat. In the early morning (about 0600 hours) the wind direction changed to south and wind speed roughly doubled at all stations due to the onset of a föhn wind (Figures 7e and 7f).

[30] On 20 January 2003 at all observation points surface hoar was present, including point 3 where no surface hoar had been observed the day before, confirming that growth conditions prevailed as suggested by the negative latent heat flux. However, in particular in the Kreuzweg area the surface hoar distribution in the immediate surroundings of the observation point was highly variable. Crystals were often wind affected, i.e., stunted (0.5 mm) and wind packed, or even eroded on the windward side of the small surface roughness that had been previously caused by either wind or sun. On the other hand in the lee of small sastrugi or in ski tracks the surface hoar was still upright and up to 2.5 mm large. On 20 January 2003 there was statistically no significant difference (N = 20, P = 0.36) in surface hoar size between the Kreuzweg and Gaudergrat area, though there was a very distinct difference on 17 January 2003 at the beginning of the formation period (Figure 6).

[31] The föhn caused wind speeds which were frequently above 10 m s^{-1} with gusts up to 20 m s^{-1} in the second half of the night of 20–21 January 2003 at GG-Top. Wind speeds were generally higher at Gaudergrat than at Kreuzweg. Consequently, on 21 January 2003 the surface hoar was still intact at only one observation point, and at one other point broken crystals were found in furrows.

3.1.3. Period 10–16 February 2003

[32] A major 2-week snowfall period ended on 8 February 2003. Cumulated new snow depth was about 150 cm (Figure 2). From 9 February 2003 onward a high-pressure system dominated the weather. In the morning of 9 February 2003 the sky cleared, and relative humidity decreased in particular at the station Kreuzweg due to southerly winds reaching 3–4 m s^{-1} (Figure 8). During this period of initially high and then decreasing humidity on 9 February 2003 the latent heat flux became initially negative at all three stations (Figures 4c and 8c). However, during the day it developed quite differently. At the station GG-South and a few hours later at Kreuzweg the heat flux become positive again with decreasing humidity, whereas it stayed negative at GG-North. Consequently, sublimation was largest for GG-North (Table 2).

[33] During the night of 9–10 February 2003 the latent heat flux was negative at the station GG-North, but positive at Kreuzweg and GG-South (Figure 8c). This pronounced difference was primarily due to the lower relative humidity and the different snow surface temperature which caused the saturation vapour pressure to be larger than the effective vapour pressure at the stations GG-South and Kreuzweg.

[34] On 10 February 2003 a few small (1 mm) surface hoar crystals were observed at only two observation points in the Kreuzweg area. They did not form a continuous layer. The snow surface was wind affected at all sites, even on the usually sheltered northerly slopes of the Gaudergrat.

[35] During the day and the following night the absolute humidity increased until the early morning (about 0300 hours) when it first started to decrease at Kreuzweg, where simultaneously the wind speed started to increase to about 3 m s^{-1}. A few hours later the humidity also dropped at the Gaudergrat stations. During this night of 10–11 February 2003 the latent heat flux was negative at all three stations with largest values of sublimation at GG-North (Figure 4d and Table 2).

[36] On 11 February 2003 surface hoar was recorded at most observation points. Surface hoar size was again larger at the Gaudergrat (2–4 mm) than near Kreuzweg at the observation points 1–11 (1–1.5 mm) (Table 1). At all but one of the points where no surface hoar was observed, the snow surface consisted of a melt freeze crust with some facets on top. All these points were on slopes (≥20° steep) of easterly to southwesterly aspect. Because of the more prominent effect of aspect in the Gaudergrat subarea with no

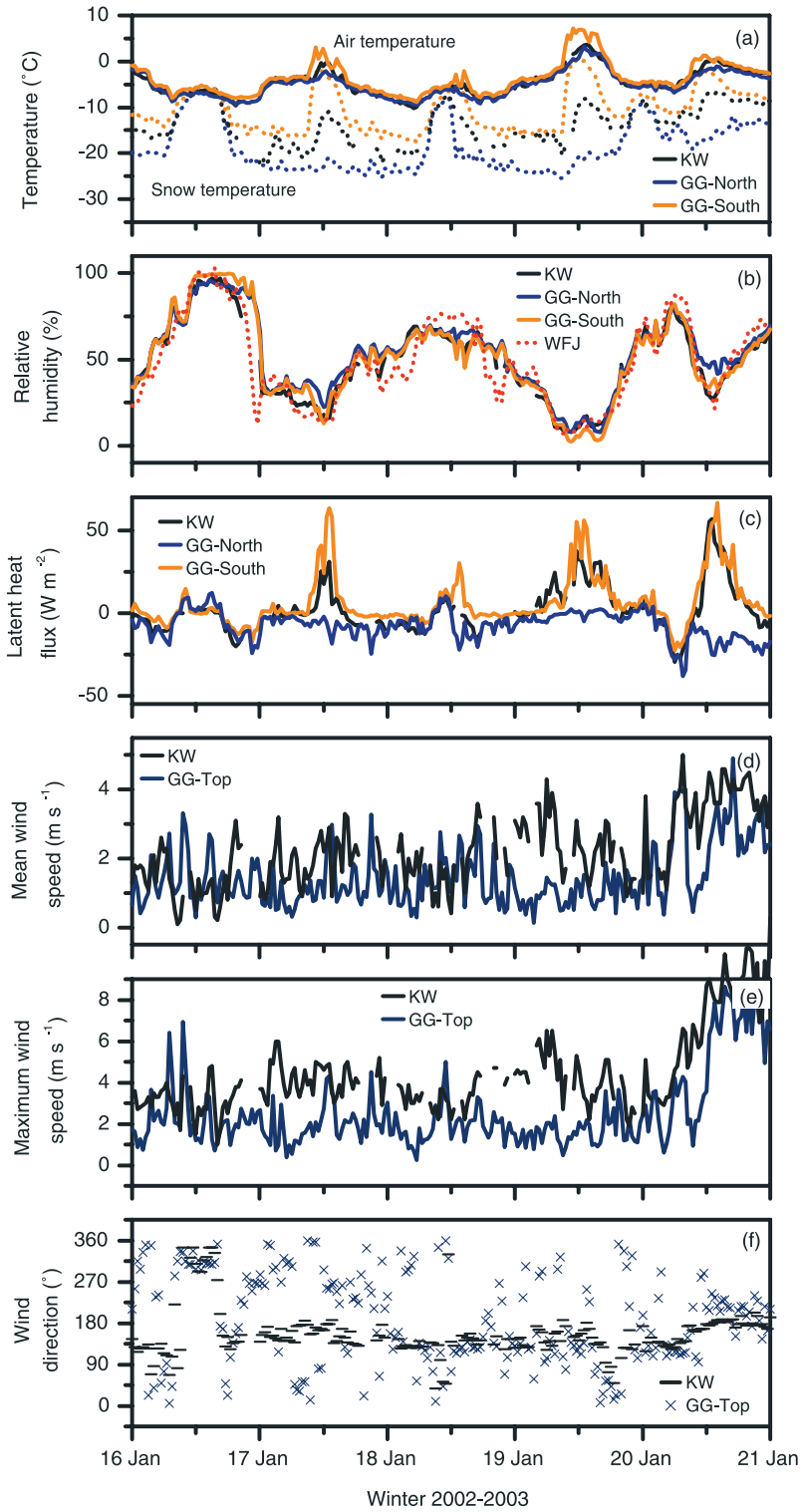

Figure 7. Meteorological conditions for 16–21 January 2003 (observation/growth period 2). Selected data as measured by the four automatic weather stations are given (KW, Kreuzweg; GG, Gaudergrat): (a) air temperature (solid lines) and snow surface temperature (dotted lines), (b) relative humidity, including data from the station Weissfluhjoch (WFJ; dotted line), (c) latent heat flux as calculated by equation (1), (d) mean and (e) maximum wind speed, and (f) wind direction.

observation of surface hoar at half of the observation points, the difference in surface hoar size between the subareas was statistically not significant (N = 19, P = 0.87) (Figure 6).

[37] During the following night of 11–12 February 2003 the latent heat flux was significantly negative only at the station GG-North, but relative humidity was decreasing and fairly low (<40%). Wind speeds were generally low

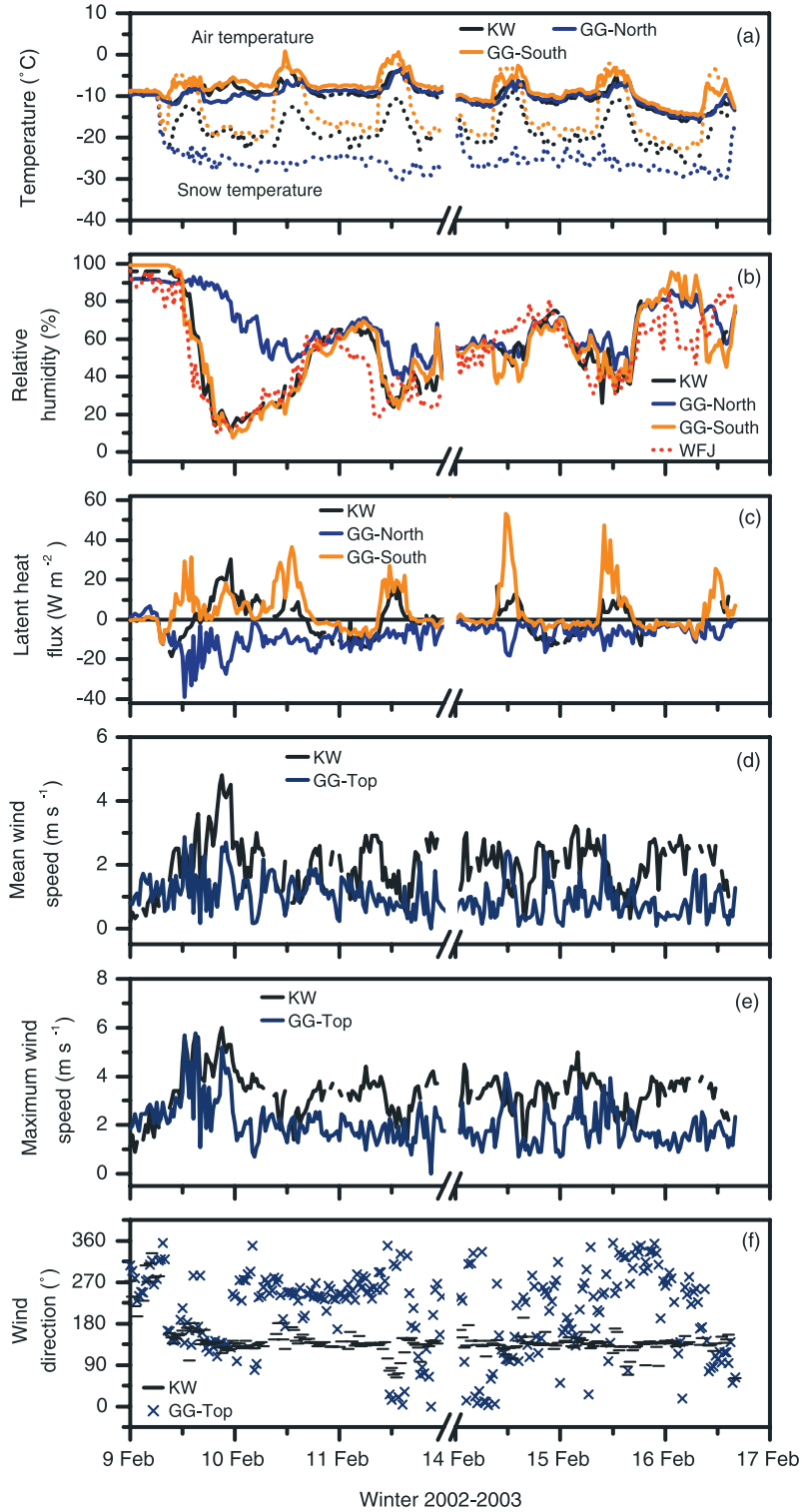

Figure 8. Meteorological conditions for 9–12 and 14–17 February 2003 (observation/growth period 3). Data as measured by the four automatic weather stations are given (KW, Kreuzweg; GG, Gaudergrat): (a) air temperature (solid lines) and snow surface temperature (dotted lines), (b) relative humidity, including data from the station Weissfluhjoch (WFJ; dotted line), (c) latent heat flux as calculated by equation (1), (d) mean and (e) maximum wind speed, and (f) wind direction.

(1–2 m s^{-1}), but again slightly higher at Kreuzweg than at Gaudergrat.

[38] Compared to the previous day there was no significant growth of surface hoar (Table 1). No statistically significant difference in surface hoar crystal size was observed between Kreuzweg and Gaudergrat if all observations points were considered (Figure 6). However, the surface hoar crystals were still larger at Gaudergrat (median of

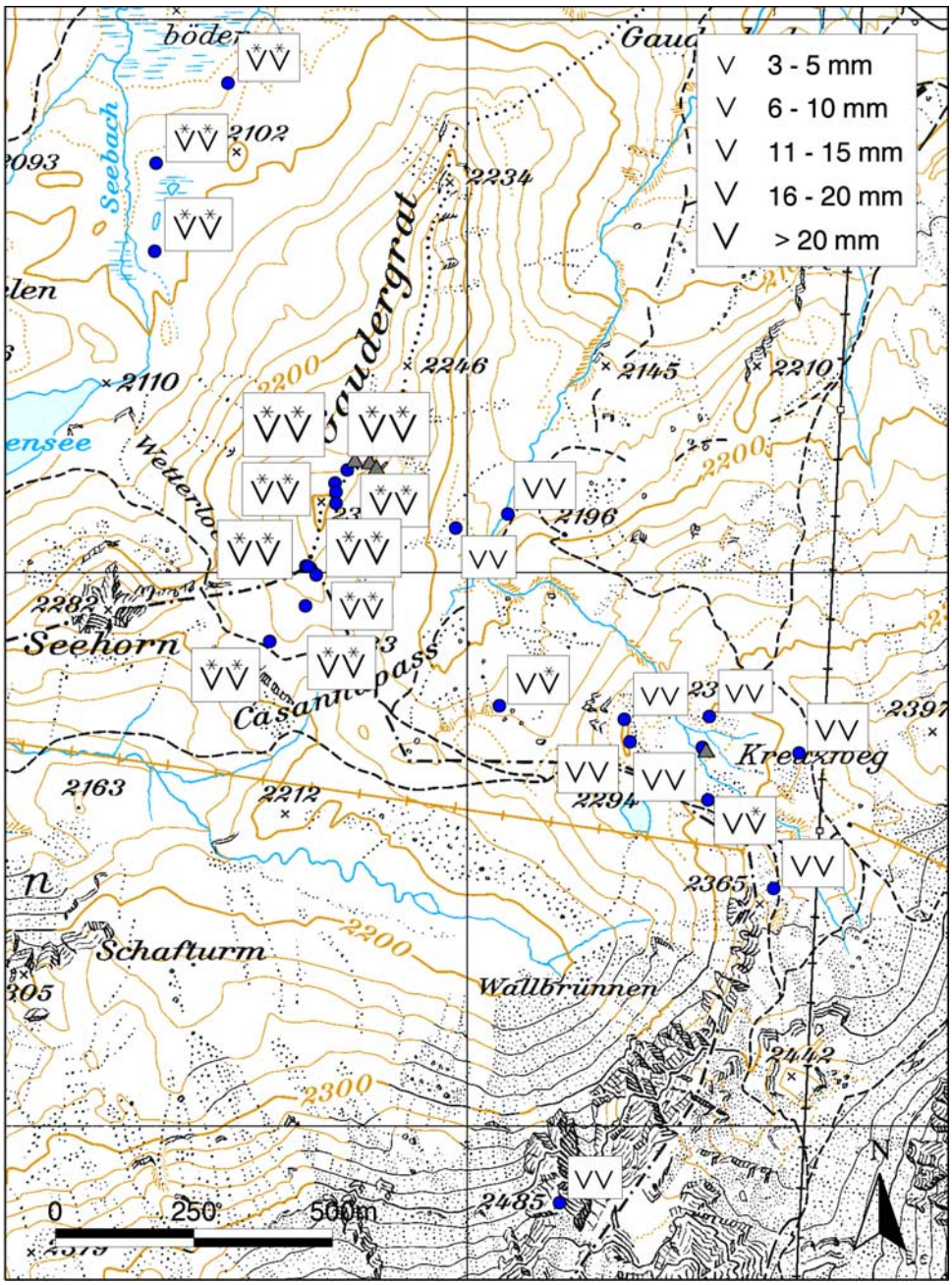

Figure 9. Surface hoar size and distribution in the study area on 16 February 2003. Maximum size of surface hoar is given. A star on top of the surface hoar crystal symbol ("v") indicates that the surface hoar was of feathery type. (Map source is PK25©2006 swisstopo (DV033492).)

maximum size: 2 mm) than at Kreuzweg (median of maximum size: 1 mm). There was a prominent effect of aspect probably due to the difference in incoming short-wave radiation which can be seen from the very different snow surface temperatures (Figure 8a) which even caused melting on sunny slopes.

[39] During the following two days the latent heat flux was constantly negative at the station GG-North and mainly positive at the other two stations. Observations on 13 and 14 February 2003 showed that crystal size did not change significantly, but there was a slight trend to increasing crystal size in the Kreuzweg subarea, and a decreasing trend at Gaudergrat (Table 1). On both observation dates, there was no statistically significant difference in surface hoar crystal size between the two subareas (Figure 6). Observations of the snow surface showed that, in particular in the Kreuzweg area, the wind ripples had transformed into concave furrows due to radiation.

[40] During the night of 14–15 February and particularly of 15–16 February 2003 the relative humidity was high (60–80%) and the latent heat flux was negative, in particular on the shady slopes of Gaudergrat. Wind speed was low, about 2–3 m s^{-1} at Kreuzweg and $\leq$1 m s^{-1} at Gaudergrat.

[41] On 16 February 2003 large surface hoar crystals were observed (Table 1 and Figure 9). In particular at the

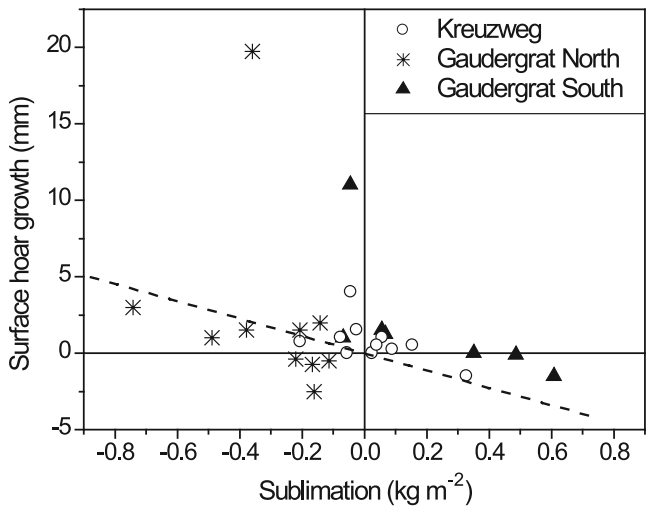

Figure 10. Observed surface hoar growth versus cumulative mass of sublimation between observation dates for the three automatic stations Kreuzweg, Gaudergrat North, and Gaudergrat South. The dashed line shows the linear regression. The correlation was found to be poor (N = 28, R^2 = 0.124; P = 0.061).

Gaudergrat, the surface hoar crystals were of feathery type rather than plate like. The feathery type was much larger and mainly grown on the small, previously existing plate like crystals. Although the absolute humidity was similar during the two nights and there was no significant difference in the latent heat flux (Figure 8c), the air and snow surface temperatures were significantly lower during the night of 15–16 February than of 14–15 February 2003. This suggests that the feathery crystals grew during the night of 15–16 February 2003 when growth conditions must have been more favorable. There was a very distinct difference in crystal size between Kreuzweg (points 1–11) with a median of the maximum crystal size of 6 mm and Gaudergrat (points 12–23) with a median of the maximum crystal size of 13.5 mm (Table 1 and Figure 6). Since the relative humidity sensor at Kreuzweg did not work during the night of 15–16 February 2003, it is not clear whether the smaller crystals at Kreuzweg were again due to decreasing relative humidity as previously observed. However, this is probable, since the wind speed was again distinctly higher at Kreuzweg than at Gaudergrat. Furthermore, at the station Weissfluhjoch which is located topographically similar and subject to a similar wind regime as the station Kreuzweg, the relative humidity decreased from 85 to 65% during the second half of the night. At the Gaudergrat stations the relative humidity stayed above 80% during the whole night (Figure 8b). The difference in growth type between Gaudergrat and Kreuzweg also supports the assumption that the humidity at Kreuzweg developed similarly to Weissfluhjoch. There were generally distinct differences in crystal size depending on aspect (Table 1 and Figure 9).

3.2. Surface Hoar Growth

[42] Figure 10 relates the observed surface hoar growth to the cumulated mass of sublimation between observation dates calculated for the three automatic weather stations Kreuzweg, GG-North and GG-South. For the station Kreuzweg, the surface hoar observation at observation point 5 (Table 1) was used, for the station GG-North the mean of the observation points 17 and 20, for the station GG-South the mean of the observation points 16 and 19. Surface hoar growth was assumed to be the difference in size between two observation dates. Calculated sublimation was cumulated between observation dates. For simplicity the observation time was assumed to be at 0600 hours for all observations. In four cases the period of accumulation was manually adjusted to take into account large positive latent heat fluxes which most likely had destroyed the surface hoar that had formed during the previous period. In those cases, the accumulation started when the latent heat flux became negative again, and the surface hoar size as observed at the end of the period was taken as growth value instead of the difference to the previous period. For the station GG-South, three cases for which the latent heat flux was largely positive and neither surface hoar growth nor destruction were observed (12, 13, and 14 February 2003) are not shown in Figure 10. Even with these adjustments the correlation between surface hoar growth and the cumulative mass of sublimation between observation dates was poor ($N = 28$; $R^2 = 0.124$; $P = 0.061$). For the cases shown in Figure 10 the mean sublimation at Kreuzweg was 0.027 kg m^{-2} and at Gaudergrat −0.089 kg m^{-2}. A sublimation of, for example, −0.2 kg m^{-2} corresponds to 2 mm of surface hoar growth if a density of 100 kg m^{-3} is assumed.

3.3. Surface Hoar Destruction

[43] During the night of 16–17 February 2003 the surface hoar layer was buried by a very light snow fall ($\leq$1 cm of new snow). Subsequently, the wind speed increased with gusts up to 8–10 m s^{-1}. On 18 February 2003 the surface hoar layer was partly eroded or incorporated into a wind crust, i.e., was no longer present as a fragile layer (observation points 1, 2, 4, 5, 7, 8, 14, 17, and 23). At most of the other points the surface hoar layer was still intact. The wind had caused a variability of the surface hoar layer at the scale of 1 m.

[44] In the following days, surface hoar destruction continued, mainly by melting due to radiation. After 3 days on 19 February 2003, the surface hoar had disappeared at 11 observation points, after 5 days at 15 locations. Surface hoar destruction was compared to initial size and incoming short-wave radiation (Figure 11). Surface hoar existence after 3 days was strongly dependent on incoming radiation and partly dependent on initial size. A simple classification tree analysis suggested that surface hoar was preserved after 3 days at locations where the 3-d sum of incoming radiation (between 1000 and 1500 hours) was less than 33 MJ m^{-2} and initial crystal size was larger than 7 mm. Analysis of the spatial pattern of surface hoar destruction after 5 days no longer showed any dependence on initial crystal size. By 24 February 2003 the surface hoar layer had either been destroyed or was strongly metamorphosed at all observation points.

4. Discussion

[45] Observations during three periods of surface hoar formation showed that distinct differences in surface hoar growth at the basin scale existed. Analysis of the meteoro-

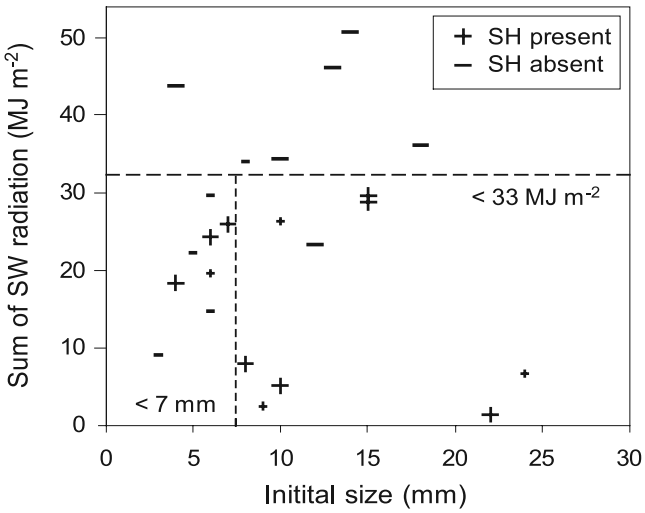

Figure 11. Surface hoar existence on 19 February 2003 in relation to initial size (on 16 February 2003, before onset of destruction) and sum of short-wave radiation (3-d sum). Plus sign indicates that surface hoar was still present on 19 February 2003; minus sign indicates destruction. Small symbols indicate locations where surface hoar destruction was dominated by wind erosion.

logical parameters showed that at Kreuzweg southeasterly (downslope), partly turbulent (shown by frequent gusts), but low winds existed frequently at night and that at the same time the relative humidity decreased. This was not observed at the Gaudergrat where wind conditions were calmer with lower, less variable wind speeds from varying directions and relative humidity was more constant, or remained high for a longer time. These observations suggest that the Kreuzweg subarea was affected by drainage winds from the Weissfluh peak flowing down the Obersäsställi toward the Gauderloch (Figure 1) [*Feick*, 2004]. This wind regime under calm conditions has recently been verified in the course of a numerical snow drift study at Gaudergrat (M. Lehning, personal communication, 2005). The katabatic downslope drainage breeze caused the relative humidity to drop in the Kreuzweg subarea (due to adiabatic heating). The Gaudergrat subarea emerges above the stream of the drainage breeze due to its topography. Accordingly, wind speeds were lower and relative humidity developed differently. Consequently, surface hoar growth conditions were less favorable at Kreuzweg than at Gaudergrat (Table 2 and Figures 4 and 6).

[46] These locally different wind conditions occurred when a high-pressure center dominated and pressure gradient winds were absent. In this case, the measurements at the automatic stations were only representative for a limited area where the specific wind conditions prevailed. In order to predict the formation of surface hoar in complex terrain, the local wind regime (including thermally and topographically induced winds) needs to be known at high resolution. Predicting surface hoar formation for larger areas for the purpose of avalanche forecasting might therefore not be feasible based on measurements from automatic weather stations.

[47] If the whole study area was considered, no correlation was found between aspect and crystal size. However, within the subareas there were effects due to the aspect, increasing with increasing radiation in the course of the winter. On shady slopes the latent heat flux was clearly more negative than on southerly slopes (Table 2 and Figure 4). Crystals were destroyed by melting including evaporation or by sublimation on sunny slopes and did not grow well on melt-freeze crusts, whereas on shady slopes, they grew to larger sizes and were often preserved.

[48] Spatial variability of surface hoar was present at other scales too. Wind destroyed surface hoar locally by turbulent gusts (scale: 1 m) but also systematically on windward slopes (scale: 10–100 m). It caused surface roughness to increase due to wind ripples which again affected the local energy balance and caused variability in surface hoar formation at the scale of 10 cm. Table 3 compiles effects causing spatial variability of surface hoar at different scales. It appears that the wind is the dominating parameter for the spatial variability of surface hoar layers, both for its formation and destruction.

[49] The differences in crystal size in the different areas seem to be due to the different wind regimes during rather calm conditions which directly affected humidity. In other words, in our alpine study area relative humidity and wind speed were strongly coupled as the katabatic winds influencing the Kreuzweg subarea were drying up the air. Therefore it was not observed that a light wind was favorable for surface hoar formation as shown by *Hachikubo* [2001], who made his studies in a maritime climate and had more continuous humidity conditions. Our observations do not question the results of *Hachikubo* [2001], but point out that in complex alpine terrain, the concept of a simple wind speed threshold for surface hoar formation might not hold in general.

[50] During our observations, surface hoar was destroyed by either wind or melting by radiative heating. The first effect caused irregular patterns at the scale of 1 m, whereas the second rather caused regular patterns at the scale of 10–100 m. For the purpose of avalanche warning, a model to predict the evolution of surface hoar while on the surface

Table 3. Summary of Parameters Affecting Spatial Variability of Surface Hoar and the Scale of Variability[a]

Cause of Variability	Influencing Parameter	Scale of Variability	Effect on Surface Hoar Formation	Effect on Surface Hoar Destruction
Thermally induced winds	wind	$1 - 10^3$ m	high	low to moderate
Pressure gradient winds	wind	$1 - 10^5$ m	low	high
Topography	wind	$10 - 10^2$ m	high	high
Topography	SW radiation	$10 - 10^2$ m	high	high
Snow surface characteristics	wind	$10^{-2} - 1$ m	moderate	low to moderate
Snow surface characteristics	SW radiation	$10^{-2} - 1$ m	moderate	low to moderate

[a]All parameters cause spatially varying growth conditions. In most cases the effects are negative on surface hoar formation but positive on surface hoar destruction. However, for example, in the case of short-wave (SW) radiation, the sign of the effect depends on the aspect.

would be useful. Such a model would have to include both its formation and destruction. On the basis of the results from this study, the destruction by radiative heating might be possible to model deterministically, while the destruction by wind might not. Further, one problem that emerged from our simple model was that daily sums were not fully suited since the maximum intensity seems to be relevant. For example, on a steep southeasterly slope the daily sum of radiation might be relatively low, but for 1–2 hours in the morning the intensity might be sufficiently high to melt the surface hoar. Any model used to predict the evolution of surface hoar would therefore have to have a high temporal as well as spatial resolution to capture all relevant processes.

5. Conclusions

[51] The spatial variability of surface hoar formation and destruction was observed at the basin scale. Daily observations were made at 23 locations of different slope and aspect within a small area (3 km^2) at about 2300 m asl in the eastern Swiss Alps.

[52] Distinct spatial variability of surface hoar formation at the basin scale was found. Surface hoar formation was more efficient at the Gaudergrat, a ridge site, than at the Kreuzweg, a study plot site, where an automatic weather station is located. This variability at the basin scale is suggested to be due to different growth conditions caused by local drainage winds (or katabatic winds). The katabatic winds affected the Kreuzweg subarea where they caused the humidity to decrease, whereas the Gaudergrat emerges above the stream of the drainage breeze, so that the humidity remained high for longer. Within the subareas the occurrence of surface hoar was observed to be continuous (not patchy) at the subslope to slope scale which is relevant for avalanche formation. Occasional discontinuous formation was observed in cases with very distinct small-scale (cm) snow surface topography. Overall, topographic parameters such as aspect had a minor influence, but were occasionally relevant in subareas.

[53] Surface hoar growth should be closely related to the latent heat flux which integrates wind, humidity and temperature conditions. However, for our limited set of observations the correlation was poor though the trend and the range of values were approximately right. This poor correlation was found despite the fact that we had a well instrumented study area (4 conventional automatic weather stations within 3 km^2). To better establish the relation between surface hoar growth and microclimatology a more detailed instrumentation would be needed to determine, for example, the exact wind profile under the specific conditions of surface hoar growth.

[54] Therefore, on the basis of the present observations, we suppose that reliably predicting surface hoar formation for an area of complex mountain terrain based on extrapolated sublimation rates from a nearby automatic weather station seems nearly impossible unless at least the local wind regime is known with high spatial resolution ($\leq$10 m).

[55] Surface hoar destruction was mainly due to wind erosion and melting caused by short-wave radiation. The effect of short-wave radiation causes relatively simple patterns in terms of aspect that should be easy to model whereas the destruction by wind is apparently random and probably difficult (if not even impossible) to predict due to the often turbulent nature of wind.

[56] The study shows that predicting the existence of a buried surface hoar layer on a specific steep slope, which is most crucial for avalanche forecasting, is particularly difficult since one of the key parameters affecting surface hoar formation and destruction is wind which is difficult to model and verify at the relevant scale. On the other hand, frequent observations of surface conditions will probably reveal the dominant spatial pattern, e.g., whether the surface hoar distribution is rather wide-spread and depending on elevation or aspect, or whether it is patchy (scale: 10 m). The latter pattern seems to be less frequent which is favorable in view of snow slope stability evaluation by point observation.

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