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Micrometeorological and morphological observations of surface hoar dynamics on a mountain snow cover

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[1] The formation, growth, and destruction of surface hoar crystals is an important feature of mountain snow covers as buried surface hoar layers are a frequent weak layer leading to unstable snowpacks. The energy and mass exchange associated with surface hoar dynamics is further an important part of land-atmosphere interaction over snow. A quantitative prediction of surface hoar evolution based on local environmental conditions is, however, difficult. We carried out measurements of crystal hoar size and total surface mass changes in the period between January and March 2007 on the Weissfluhjoch study plot of the WSL Institute for Snow and Avalanche Research SLF, located above Davos, Switzerland, at 2540 m above sea level. For the first time, a direct comparison between eddy correlation measurements of latent heat flux and lysimeter-like measurements of surface mass change has been made. Results show that the growth of surface hoar crystals is very well correlated with deposition of water vapor during clear-sky nights as measured by two eddy correlation systems placed close to the ground. By analyzing local meteorological data, we confirm that low to moderate wind speed, humid air, and clear-sky nights are the necessary ingredients for the occurrence of significant vapor fluxes toward the surface and thus for the growth of surface hoar. We also confirm that surface hoar crystals tend to preserve during daytime, when strong sublimation occurs, although their size significantly reduces. Despite the complexities associated with mountain terrain and snow surfaces, such as nonequilibrium boundary layers and stratification effects, the hoar formation could be predicted by the snow cover model SNOWPACK, which uses a bulk Monin-Obukhov (MO) parameterization for the turbulent heat fluxes. On the basis of the comparison between direct observations and model predictions, we suggest that neutral stability conditions in the MO formulation provide the most stable and least flawed prediction for surface hoar formation.

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1. Introduction

[2] Mass exchange processes between the snow surface and the atmospheric boundary layer give rise to several characteristic features of the snow cover, each characterized by its own geometrical, mechanical, and thermodynamical properties. Examples include cornices, zastrugi, penitentes [*Corripio and Purves*, 2005] and other features of snow transport [*Doorschot et al.*, 2004; *Lehning et al.*, 2008]. This study is focused on upright standing polyhedral plate-type crystals which are known as surface hoar crystals. The importance of these layers for avalanche warning was discovered at the beginning of the last century (see the review by *Föhn* [2001]). Surface hoar crystals lack intercrystalline bonding and are only weakly attached to the surface, implying that, when buried by snowfall, they form a weak layer in the snowpack which provides a failure plane for slab avalanches [*Breyfogle*, 1987; *Jamieson and Schweizer*, 2000]. It is also known that the shear strength and the cohesion of the buried layers depend on age and overburden pressure [*Föhn*, 1993; *Habermann et al.*, 2008]. This implies that accurate simulations of (1) the formation and sublimation of surface hoar in snowpack models [see *Lehning et al.*, 2002b] and (2) the evolution of density and shear strength of these weak layers, are seen as crucial steps for a solid evaluation of stability condition [*Föhn*, 1993].

[3] Surface hoar crystals are known to be formed by deposition of water vapor onto the snow surface [*Colbeck*, 1988]. However, predicting their formation, particularly in complex terrain where the sign and the magnitude of the vapor fluxes are not trivial, is still a very challenging task.

[4] Initially, surface hoar was reported to be formed in the absence of wind [*Lang et al.*, 1985]. However, *Colbeck* [1988] presented an analysis showing that molecular diffusion alone cannot explain observed growth rates and that some wind

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and therefore turbulent transport is necessary. Qualitatively it has been observed that surface hoar normally develops during cold, clear nights when snow surface temperatures are considerably lower than air temperature [*Colbeck*, 1988]. As soon as the boundary layer air masses become supersaturated, the excess water vapor deposits on the surface. With clear-sky conditions the snow surface cools down due to outgoing longwave radiation, but both the air above and the snow below cool down at lower rates, which is one reason for the establishment of strong temperature gradients. The relative humidity of the air is another important factor for surface hoar growth. Indeed, while clear sky is favorable at the growing time in order to create locally supersaturated conditions at the snow surface because of radiative cooling, the advection of moist air close to the surface and the effects of downward turbulent fluxes are both key for surface hoar production.

[5] The local micrometeorological conditions are known to contribute to second-order effects. For instance different shapes were observed at different temperatures [*Lang et al.*, 1985; *Jamieson and Schweizer*, 2000], as expected from the known habit diagram for snow crystal growth in the atmosphere [see, e.g., *Kobayashi*, 1961]. Wind speed is also believed to play a subtle role. A low wind is necessary to stimulate the growth because it ensures the supply of water vapor, through turbulent fluxes. High wind speed, however, and therefore heating through sensible turbulent heat flux, are inferred to offset the radiative cooling of the snow surface and the inversion may be destroyed, resulting in a change from deposition to sublimation [*Hachikubo and Akitaya*, 1997; *Hachikubo*, 2001].

[6] The formation of surface hoar as a function of the local environmental conditions is not, however, the only question that must be answered. Once surface hoar is formed, its further evolution is even more complicated to follow. Depending on size and density, surface hoar can indeed be reduced or destroyed by high air temperatures, rain and strong winds; that is, these weakly connected crystals are blown away during drifting snow events. *Hachikubo and Akitaya* [1998], on the basis of measurements of the meteorological parameters, calculated the deposition rate during the night and the sublimation rate during the following daytime. According to the calculated sublimated mass, *Hachikubo and Akitaya* [1998] estimated that the crystals should have almost disappeared. By contrast, the surface hoar crystals persisted and were observed to be only rounded and eventually consisted of several parts grown night after night. *Hachikubo and Akitaya* [1998] suggest that, although the surface hoar crystals may sublimate during the daytime, snow crystals beneath the surface are heated by solar radiation and can also sublimate. Part of the water vapor that they provide may partially condensate onto the surface hoar crystals and therefore compensate for their reduction in size.

[7] Non local effects related to the complexity of the mountain terrain are also important. *Feick et al.* [2007] found that surface hoar crystals were frequently larger at the ridge site than in the surroundings of an automatic weather stations on level terrain, probably due to different prevailing wind regimes. The authors concluded that katabatic winds dried up the air around the weather station and that this may lead to less favorable growth conditions. They further inferred that predicting spatial surface hoar formation in a complex terrain seems to be almost impossible, unless the wind regime of the slopes is known, which may become possible in a near future [*Raderschall et al.*, 2008] but is not in the scope of this contribution. Hoar growth was also observed to change with aspect and elevation [*Breyfogle*, 1987; *Cooperstein et al.*, 2005; *Feick et al.*, 2007].

[8] A predictive tool for surface hoar formation must therefore include most of the above physical mechanisms and provide an accurate modeling of the turbulent vapor fluxes responsible for the deposition process leading to the formation of the crystals. The general applicability of Prandtl layer relationships and Monin-Obukhov (MO) scaling to predict surface hoar development was demonstrated by *Föhn* [2001]. He used measured mass change (positive and negative) of surface hoar and the associated profiles of both air temperature and wind speed and found that the data can be explained by the general bulk transfer formalism with an arbitrary (best fit) exchange coefficient. *Lehning et al.* [2002a] used the same data set to show that the MO prediction for the neutral case exchange coefficient (as implemented in SNOWPACK) was practically as good as the best-fit exchange coefficient in explaining the same data set. A linear relationship was also found between deposition rate and the product of water vapor–pressure gradient and the wind speed [*Hachikubo and Akitaya*, 1997] as also predicted by application of the aerodynamic bulk transfer method.

[9] This contribution adds to the knowledge on surface hoar dynamics discussed above by presenting, for the first time, direct (eddy correlation) measurements of latent heat flux together with direct mass change measurements on the surface and bulk transfer simulations with SNOWPACK. So far no study has concentrated on surface hoar formation by accessing latent heat fluxes with high temporal resolution (20 Hz) in the Alpine environment and comparing the results to measured and simulated surface hoar mass. In this context, the simulations serve to validate bulk transfer models to predict latent heat flux and surface hoar formation in complex terrain.

[10] After this introduction, the paper is organized in the following way. The experimental field campaign is described in section 2 together with a brief description of the numerical model used for simulating the exchange of heat and vapor fluxes between snow and atmosphere. Section 3 is devoted to the presentation of results.

2. Experimental Setup

[11] The field campaign took place at the Weissfluhjoch study plot of the WSL Institute for Snow and Avalanche Research SLF, located above Davos, Switzerland, at 2540 m above sea level (see Figure 1). The experimental site has been equipped for meteorological data acquisition since 1936. Field measurements to study surface hoar development were carried out between 16 January and 18 March 2007. Thenceforward the site was visited every morning and every afternoon, except when it was snowing. Direct measurements of snow mass gain and loss as well as of crystal size were performed in situ, while further analysis of snow and crystal samples was carried out in the cold laboratories of SLF in Davos. Redundant estimates of both surface hoar size and snow mass differences during day and night periods were obtained using different techniques and instrumentation. Cumulated sublimation and deposition were measured

Figure 1. Picture of the measurement site taken at the Weissfluhjoch mountain.

twice a day by weighing independently two boxes containing undisturbed sections of the snowpack. Furthermore, two sonic anemometers complemented by two fast gas analyzers were employed to measure turbulent fluxes of water vapor. Details on the experimental equipment and procedure are described below.

2.1. Surface Hoar Crystal Characterization

[12] Classical snow parameters were evaluated in situ while macrophotographs were taken to survey the processes occurring during surface hoar growth (Figure 2). Shape and size of snow crystals taken at the surface were classified according to *Fierz et al.* [2009]. On nine instances during the field campaign, samples of surface hoar crystals were preserved in subfreezing liquid iso-octane to be later photographed in the cold laboratory [*Brun and Pahaut*, 1991]. Figure 2b shows a surface hoar crystal (SHsu) of the sector plate type that was almost exclusively observed during our field campaign. The striations and sharp corners and edges are all signs of strong kinetic growth by deposition during the preceding night.The largest extent of each crystal, i.e., the crystal size, was then measured by image processing using a MATLAB code developed at SLF [*Bartlett et al.*, 2008].

[13] Crystal size varies widely within samples both in the field and in the lab. In Figure 3 the average and maximum size of snow crystals are represented to compare the field measurements (referred to as "field") with the image processing method (referred to as "cold lab"). The agreement between field and laboratory results is good, particularly regarding the maximum grain size. Finally, a video camera recording pictures of the snow surface every minute, day and night, was used to monitor the area of interest, ensuring that no drifting and blowing snow events occurred during the selected periods.

2.2. Mass Gain and Loss

[14] The major goal of the field campaign was to monitor mass gain or loss by deposition and sublimation of water vapor at the snow surface. This was achieved by weighing the mass difference of a sample of snow before and after exposure in the field. For this purpose two open boxes of 40 × 40 × 10 cm with 3 sidewalls were built ad hoc to hold 10 cm thick undisturbed sections of snow. The material chosen for the boxes was 8 mm thick white Forex Classic, which is a closed shell rigid PVC foam (Alcan Airex AG). Having a density of 500 kg m^{-3}, thermal conductivity of 0.06 W K^{-1} m^{-2} and specific heat capacity of about 1 kJ kg^{-1} K^{-1}, Forex Classic should minimize disturbances to both the sample and the surrounding snowpack. Therefore, once placed in the field, the box and the snow contained within it should quickly equilibrate to the temperature of the surrounding snowpack.

[15] The mass difference was estimated using the following procedure: A metal saw was used to cut a piece of snow along the lines defining the lateral faces of a column of side equal to that of the sampling box (40 cm). The snow around the snow cube was removed along three sides and the snow marked at a depth of 10 cm. At this level, the box was pushed into the snow, its beveled open side acting like a blade. Care was taken to obtain a snow section of uniform height. The box was then cleaned from any snow sticking on its outside and brought to the scale for the first weighing. Next a hole of the size of the box must be prepared close to the eddy correlation systems in the undisturbed snowpack. The filled and weighed box was carefully and slowly positioned into the hole, its surface being flush with the surrounding snow (see Figure 4), and left there during the night (16:00–08:00) and the day period (08:00–16:00). After each period the box was weighed again, taking care again of removing any snow or hoar crystals sticking on the outside of any part of the box. Despite the difficulties inherent in the weighing procedure, the consistency of the weight measurements can be judged from Figure 4, where the results from the two boxes used in parallel are compared. Assuming perfect correlation between the measurements, the absolute error e is estimated as the median of the semi differences between the two weights, the relative error (on average below 5%) is obtained as the median of the absolute errors divided by the corresponding measurement.

2.3. Turbulent Fluxes

[16] Two 3-D ultrasonic anemometers CSAT3 (Campbell Scientific, Inc.) and two LI-COR LI-7500 open path fast CO_2/H_2O analyzers (LI-COR Biosciences) were coupled and mounted at 3 and 5 m above ground. Measurements were acquired at a frequency of 20 Hz with a Campbell Scientific CR5000 logger. Hereafter, the lower and the upper couple of instruments (i.e., the lower and upper eddy correlation systems) are referred to as sonic 1 and sonic 2, respectively. During the experimental campaign, the effective level above snow varied depending on snow depth. The levels between the beginning and the end of the periods varied between 1.3 and 1.8 m for sonic 1 and between 3.3 and 3.8 m for sonic 2.

[17] Turbulent fluxes of water vapor were calculated as the covariance between the fluctuations of vertical wind speed and water vapor concentration. The averaging time used to estimate the turbulent fluxes was set to 15 min. For each time window and prior to any calculation, the sonic

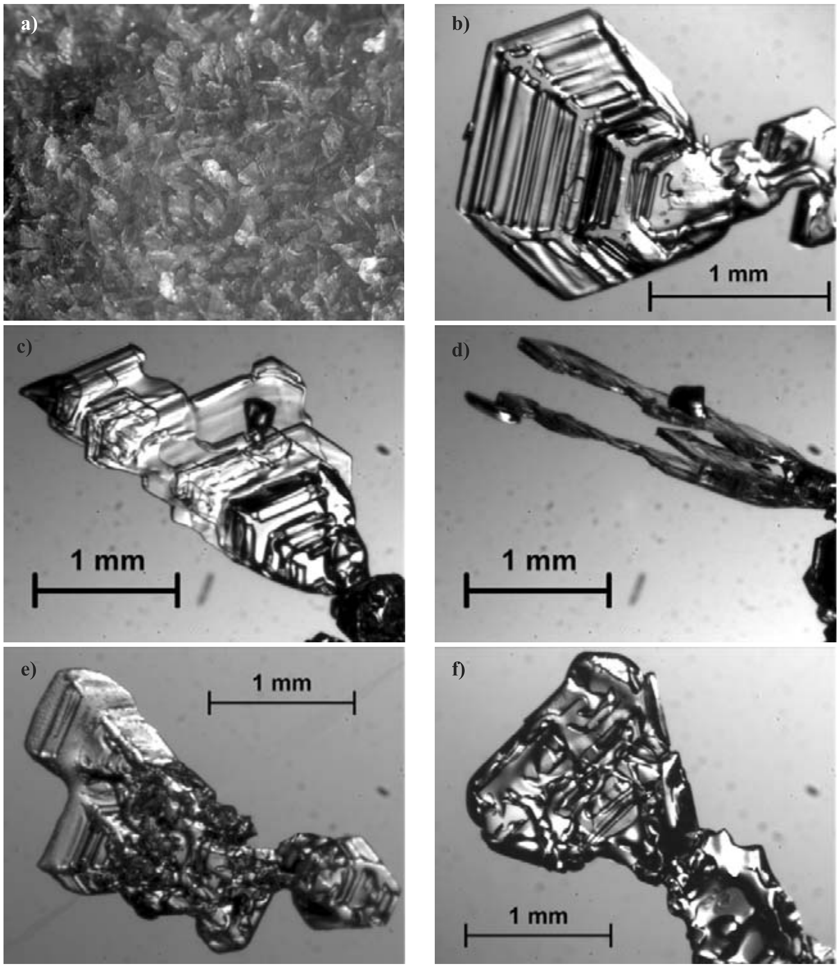

Figure 2. Pictures of preserved surface hoar crystals from the field campaign: (a) 16 March 2007, morning top view of a weighing box; (b) 23 February 2007, typical sector plate surface hoar crystal; (c) 24 February 2007, surface hoar crystals showing the interplay of growth and sublimation phases; (d) 24 February 2007, the same crystals seen from the side, evidencing the plate-like nature of the observed crystals (thickness is about 0.05–0.1 mm); (e) 17 March 2007, surface hoar crystal showing signs of sublimation from the end of the night (see Figure 7b) on its upper edges; and (f) 18 March 2007, crystal collected at 15:45 that day and showing evidence of melting process. In Figure 2e, a near surface faceted crystal points to the bottom right corner.

anemometer coordinate system was aligned to the mean flow direction using the double rotation methodology [*Wilczak et al.*, 2001]. A linear detrending was then applied to the rotated velocity time series.

2.4. Meteorological Data

[18] An automatic weather stations (AWS) is located on the study plot, next to the place where mass gain and loss as well as turbulent fluxes were measured. The half hourly AWS data define the so-called "local" meteorological conditions that are used for the interpretation of the results. Measured data include air temperature and relative humidity (ventilated and heated device), mean wind speed and wind direction, incoming and reflected shortwave radiation (pyranometer) as well as incoming and outgoing longwave radiation (pyrgeometer), snow surface temperature (infrared thermometer) and snow depth (ultrasonic gauge).

2.5. Numerical Model

[19] The snowpack on the study plot was simulated using the model SNOWPACK. The input file was composed from meteorological data (air temperature, wind speed, relative humidity, reflected shortwave radiation, incoming longwave radiation, snow surface temperature and a temperature at the soil surface) measured by the local automatic weather station. Note that the set of input parameters has been chosen to correspond to the operational use of SNOWPACK [*Lehning et al.*, 1999], for which, e.g., only reflected shortwave is available. The total shortwave energy absorbed is then estimated from the albedo model [*Lehning et al.*, 2002a] in SNOWPACK. The turbulent fluxes in SNOWPACK follow a common form of Monin-Obukhov bulk formulation, in which the turbulent exchange coefficient is iteratively calculated from the local roughness length, the wind speed and an estimation of atmospheric stability based on the temperature difference between air and surface. The

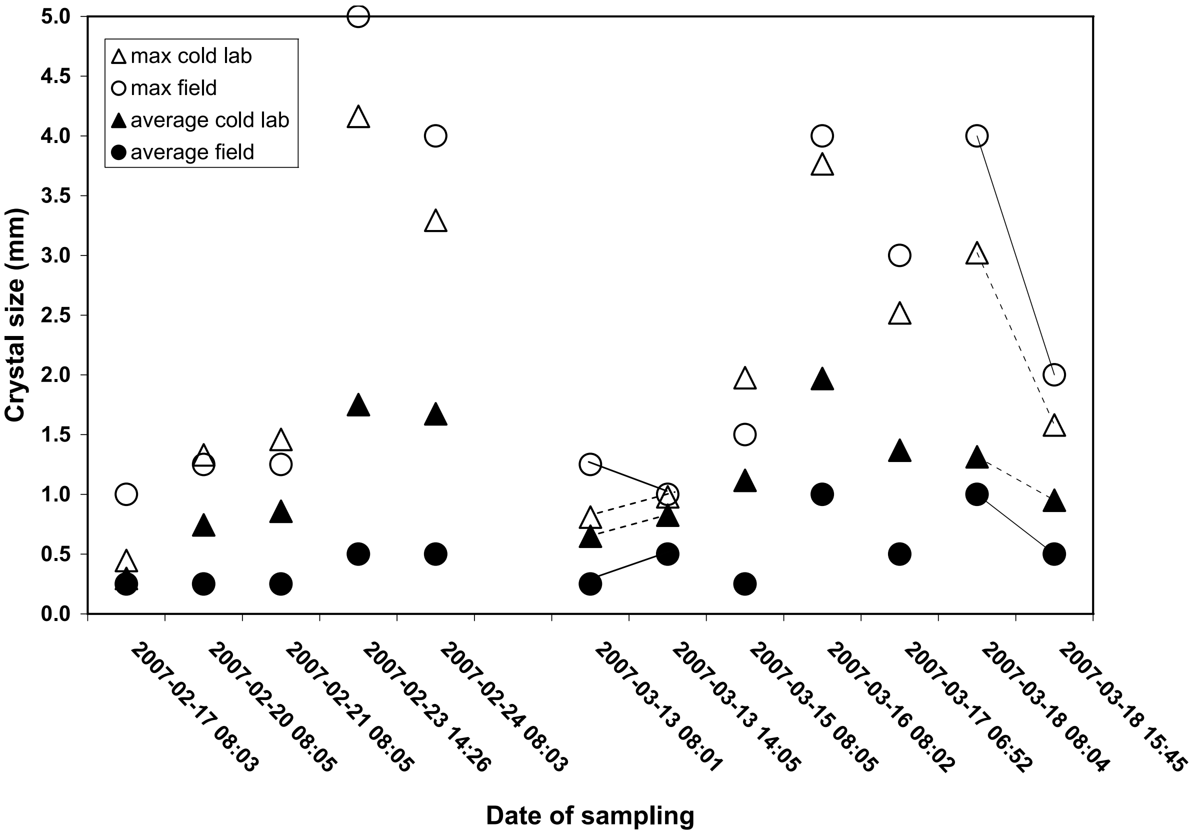

Figure 3. Measurements of the snow crystal size through visual inspection in the field and image analysis of preserved snow samples in the cold laboratories of SLF in Davos.

correction for atmospheric stability is known to create problems over snow, where very often a strong temperature difference between the cold surface and the warmer air causes modeled turbulent fluxes to almost completely shut down, if published stability corrections are used. Observations show that a significant average turbulent exchange is maintained in such conditions. We therefore also present simulations, in which we assume the local atmosphere to be neutrally stratified. This typically leads to higher flux estimations over snow and is discussed in detail below.

[20] The simulation for this study was started on 1 November 2006, prescribing measured snow surface temperature, i.e., using Dirichlet boundary conditions. This means that the (snow) surface temperature is used to solve for the temperature distribution in the snow cover and that therefore the model is forced to reproduce the surface temperature as measured. A uniform value for scalar and momentum roughness of 2 mm was assumed, which lies in between measured values for the site [*Doorschot et al.*, 2004] and typical values for snow [*Clifton et al.*, 2006, 2008; *Manes*

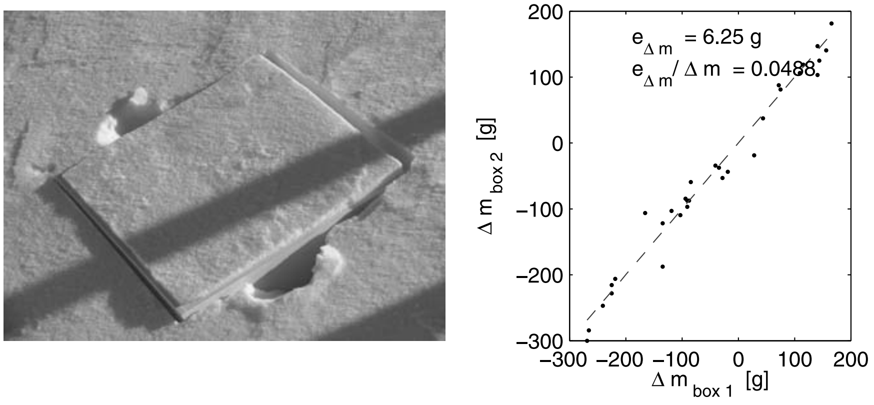

Figure 4. (left) Picture of the box used to estimate gain and loss of mass as placed in the snowpack after the first weighing (21 February 2007, 08:31). (right) Scatterplot of two independent measurements of mass gains and loss.

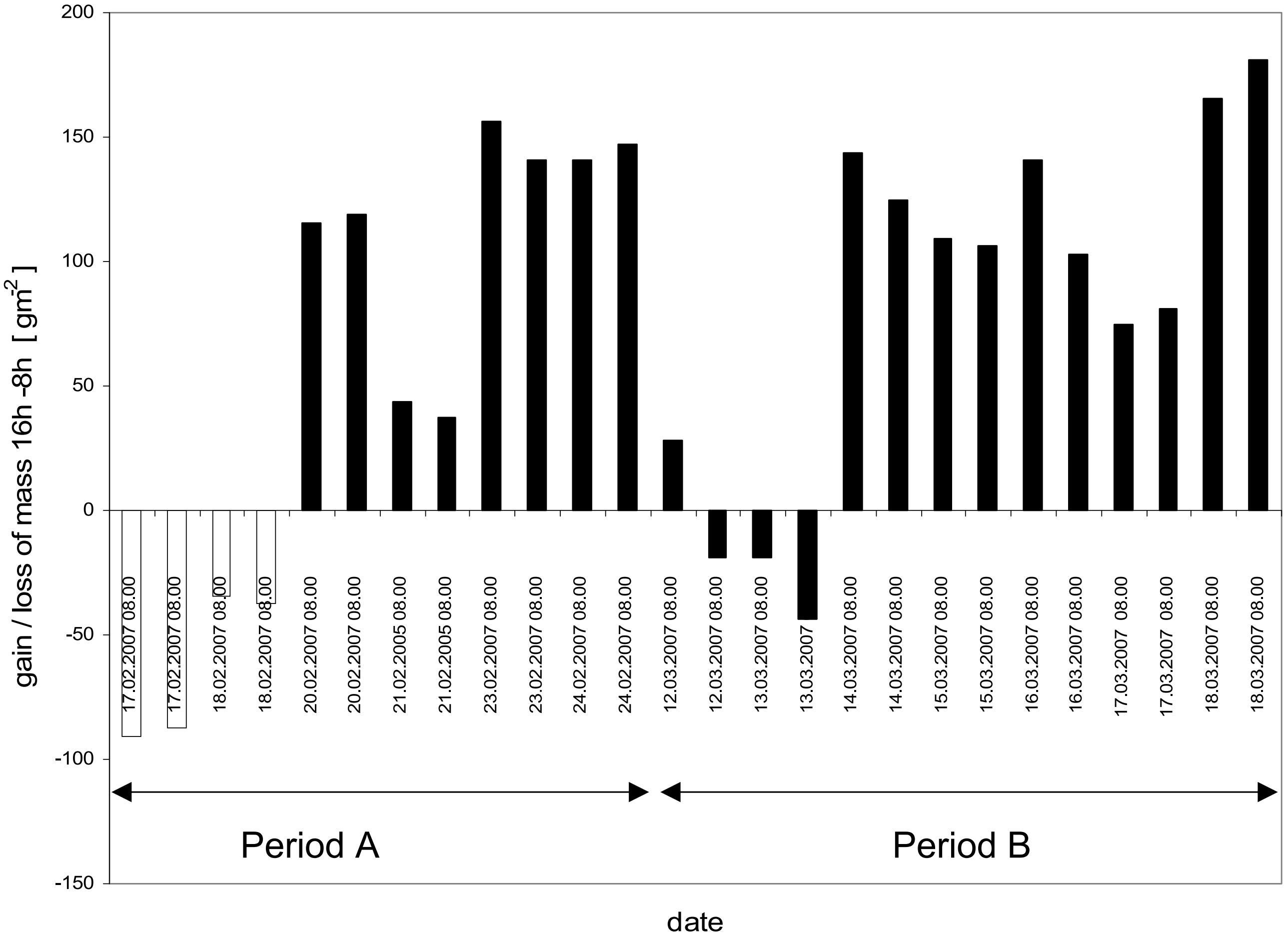

Figure 5. Measurements of the mass differences during the night periods (16:00–8:00). Black (white) bars denote days when surface hoars were (were not) observed.

et al., 2008]. A sensitivity analysis (not shown) suggested that the results are not very sensitive to the choice of roughness parameter.

3. Results and Discussion

3.1. Formation of Surface Hoar

[21] During the field campaign the mass changes of the snowpack were measured by direct weighing of the snow boxes on days and nights with or without surface hoar development. Two periods of the field campaign are distinguished: period A from 16 to 24 February and period B from 11 to 18 March.

[22] The first results are presented in Figures 5 and 6 where the estimated mass changes are shown with an indication on when surface hoar crystals were visually observed to exist on the snow surface. A negative mass difference of the boxes corresponds to a mass loss and therefore to an overall sublimating snowpack. Instead, a positive mass difference is associated with a mass gain and therefore with a snowpack subjected to deposition. We are very confident that mass gain is only due to deposition of water vapor from the atmosphere onto the surface snow of the box. Indeed, the water vapor pressure gradient is perpendicular to the snow surface within both the snowpack and the boxes and thereby lateral mass exchange by vapor diffusion through the open side of the boxes is minimized. We cannot exclude enhanced sublimation during daytime due to absorption of solar radiation by the sidewalls and the bottom of the boxes though.

[23] Figure 5 shows that surface hoar formation was observed mostly during nights of mass gain (deposition). As shown in Figure 6, significant mass loss was systematically recorded during the daytime. Such a solid trend is probably related to the generally high air temperatures which characterized the winter 2007.

[24] We confirm that the key ingredients for surface hoar formation are clear nights associated with humid air, moderate winds and very cold snow surfaces with temperature between −15 and −20°C. In particular, the differences of temperature $\Delta T = T_{air} - T_{surface}$, were mostly in the range $\simeq$ 15 to $\simeq$ 20°C. The relative humidity varied between 30 to 90% but mostly between 60 and 90%. The local wind velocity measured at roughly 4 m above the snow surface never exceeded 4 m s^{-1}. Under these conditions, one would expect primarily sector plate shaped ice crystals to grow while dendritic crystals cannot be excluded at snow surface temperatures around −15°C [*Kobayashi*, 1961]. In this study, however, we only observed surface hoar crystals of the first type (see Figure 2).The dominant wind directions were NW and SE which correspond to the downwind and upwind directions forced by the local terrain, respectively. However, the wind direction did not seem to have any obvious effect on the growth of surface hoar crystals.

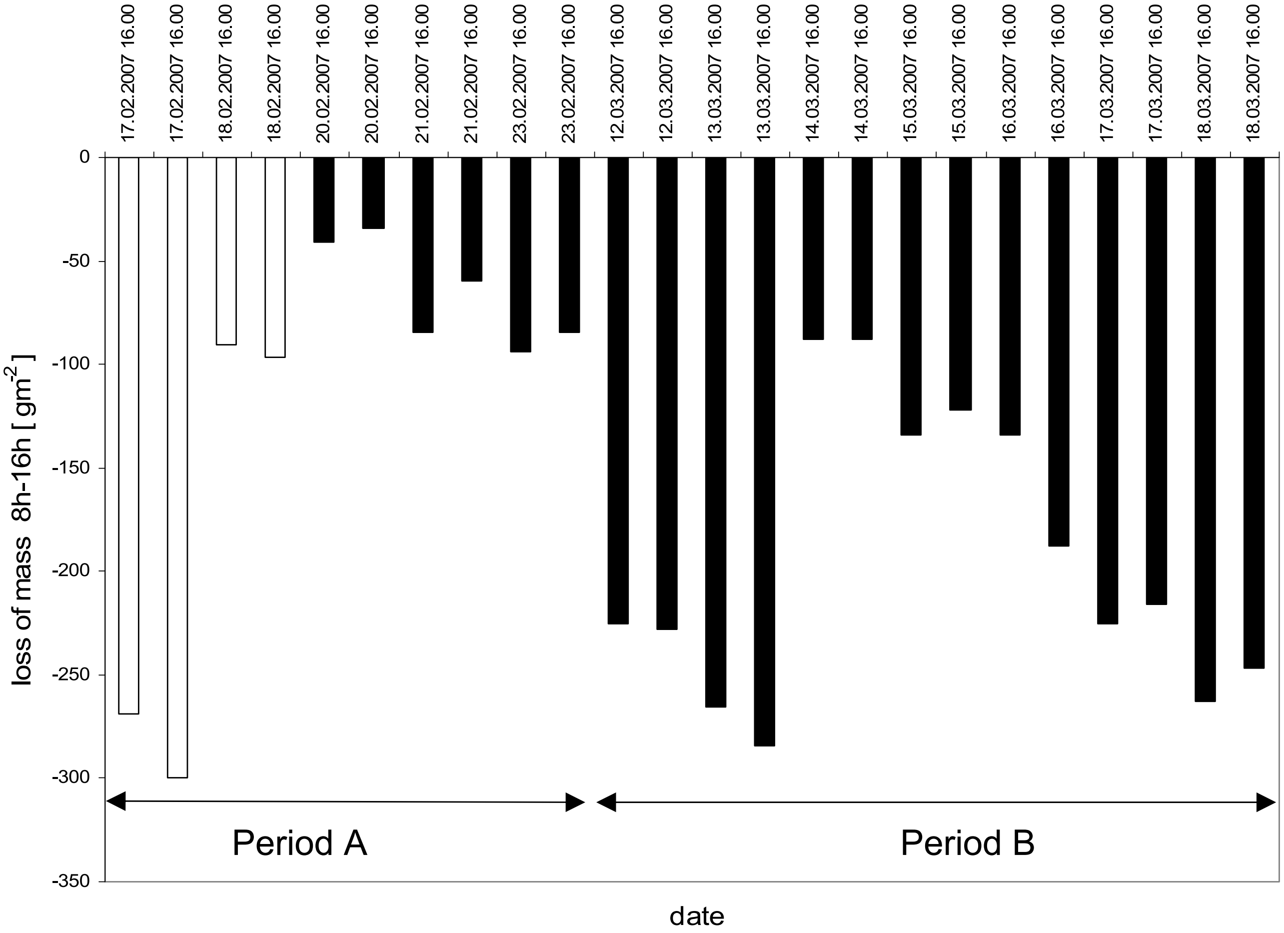

Figure 6. Measurements of the mass differences during the day periods (8:00–16:00). Black (white) bars denote days when surface hoars were (were not) observed.

[25] Although night periods were often associated with mass gain and surface hoar formation, for a few nights this did not happen: we indeed note that on 17 and 18 February, snow mass loss occurred and no surface hoar was observed. Mass loss during the nights is always associated with very dry air conditions, i.e., when the relative humidity of the air was lower than 25%. Such dry air conditions triggered snow sublimation and therefore mass loss of the snowpack.

[26] When sublimation occurs, one would expect to see no surface hoar crystals growing on the snow surface (as it happened for the nights of 17–18 February). However, in the morning of 13 March, surface hoar crystals were observed but a net mass loss of the snowpack was measured by the weighing of the boxes. This is explained by analyzing the two nights before the morning of 13 March: according to our measurements, surface hoar formed during the night of 12 March and survived until 13 March at 8:00. This was checked by carefully examining the video of the evolving snow surface recorded during the nights of 12 and 13 March. Despite the little total mass gain recorded during the night of 12 March, the video clearly shows formation of surface hoar. Instead during the night of 13 March, there is no sign of new crystals forming on the snow surface. The small overall mass gain recorded for the night of 12 March is justified by the occurrence of alternating periods of sublimation and deposition, which resulted in a small net mass gain of the snowpack (we were able to identify this behavior from the analysis of the turbulent fluxes measured by the eddy correlation system; such fluxes are presented and discussed in more detail in section 3.2). We argue that the deposition periods must be responsible for the growth of surface hoar crystals, which then survive the following sublimation periods. The surface hoar crystals of Figure 2c clearly show the interplay of alternating deposition (growth) and sublimation (rounding and smoothing) periods. Our data suggests that surface hoar tends to grow at night, when the snowpack gains mass, and tends to be preserved during daytime. Furthermore, it is interesting to note that the crystals persist even if the sublimated mass equals or is larger than the previously deposited mass. This is highlighted by the measured mass changes reported in Figures 5 and 6. These results are in good agreement with the observations of *Hachikubo and Akitaya* [1998]

3.2. Deposition and Turbulent Fluxes of Water Vapor Toward the Surface

[27] As described in section 2, the snow mass balance has been addressed with three different techniques. The first is the (single value) mass obtained by subtracting the 16:00 and the 8:00 snow weight measurements. The second estimate is given by the integrated water vapor fluxes as obtained

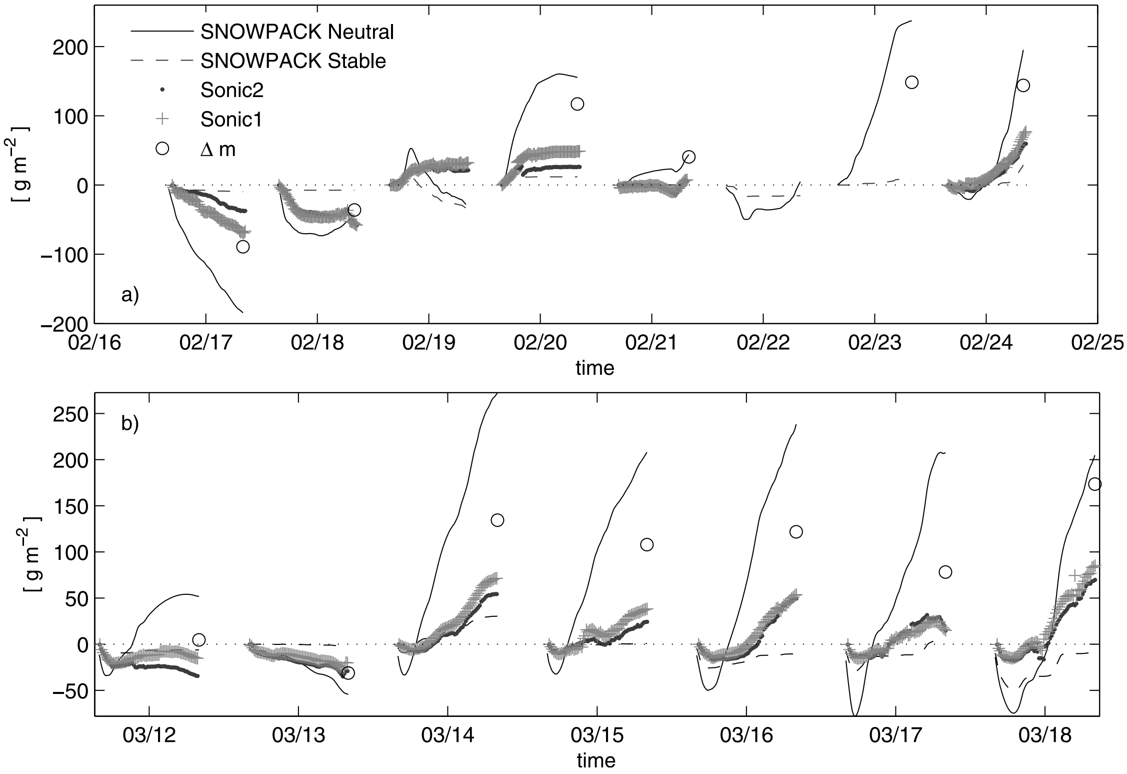

Figure 7. Comparison between the cumulated water vapor flux from sonic 1 and 2, the SNOWPACK simulation, and the mass gain loss during nights of surface hoar formation (16:00–8:00) for (a) period A and (b) period B.

by the eddy correlation system during the same time period (the so-called nighttime from 16:00 to 8:00). The third method is the simulation of both the sublimation and deposition rates by means of the model SNOWPACK.

[28] With respect to the snow weight measurements, which provide information only on the net mass exchange during the whole measurement period, the turbulent fluxes measured by the eddy correlation system allow the water vapor exchange between snow and atmosphere to be monitored every 15 min. The model predictions are used to quantify the applicability of the standard bulk approach as compared to a full set of measured quantities in a real complex topography. The analysis of the data gathered with these three different techniques was carried out for the 12 nights of periods A and B. Only for the night of 23 February, it was not possible to estimate the evolution of the mean water vapor fluxes due to some high noise level in the measurements of the Fast Gas analyzers.

[29] Results are shown in Figure 7, where the mass difference calculated by integrating the water vapor fluxes measured by the eddy correlation system and simulated by SNOWPACK is plotted as a function of time (16:00–8:00) and compared with the direct measurements obtained from the snow weighing procedure (8:00). These plots show that, as discussed in section 3.1, the sign of the vapor fluxes can easily change, so that sublimation and deposition can both occur during the course of one single night.

[30] The comparison of the data shows that the integrated mass fluxes can only approximately reproduce the snow mass change. The cumulated turbulent fluxes measured by the two eddy correlation systems consistently underestimate the weight. However, the general trends of mass exchange rates are captured quite well. This can be appreciated from Figure 8 where the vapor fluxes integrated over the whole

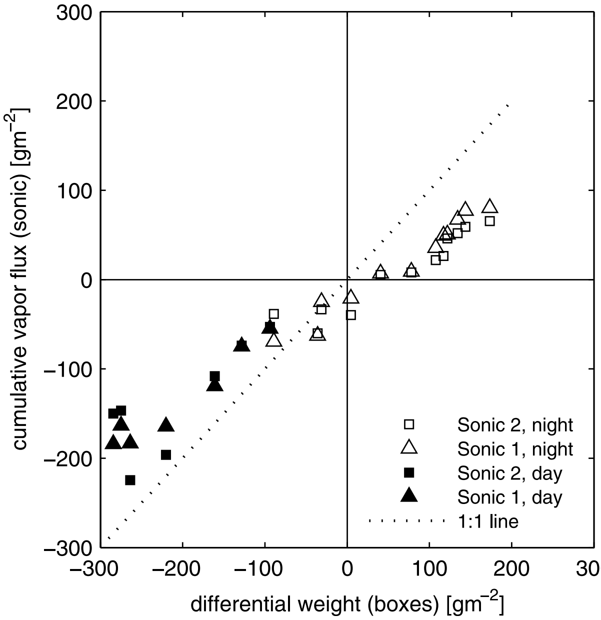

Figure 8. Comparison between the total mass variation (gain and loss) during the nighttime and daytime in the selected periods obtained (1) by the cumulated water vapor flux from sonic 1 and sonic 2 and (2) by the direct measurements (weighing the snow boxes).

night and day periods (from the eddy correlation system) are plotted against the mass gain or loss. The good correlation clearly indicates that, at nighttime, turbulent fluxes play a key role in providing the water vapor necessary to grow surface hoar crystals on the snow surface. The result confirms the theoretical findings of *Colbeck* [1988] who showed that molecular diffusion alone cannot be responsible to justify the typical growth rates of surface hoar crystals observed in nature.

[31] There is still some debate regarding whether the water vapor necessary for surface hoar growth could not originate from the snowpack itself. Indeed, during periods favorable for surface hoar growth, large temperature gradients exist right below the snow surface too and those gradients give rise to corresponding water vapor fluxes toward the surface. If this were the case, surface hoar crystals should show an orientation similar to depth hoar and faceted crystals, i.e., their growing edge pointing toward the primary water vapor source. However, to our knowledge, this is contrary to all observations. In this context, Figure 2e shows an interesting crystal collected in the morning of 17 March 2007. A surface hoar crystal points to the upper left corner and shows clear signs of rounding due to sublimation on its upper edges (as one can see from Figure 7b, on 17 March, sublimation occurred toward the end of the night period). Edges and corners of the crystal pointing toward the bottom right corner, however, are still sharp as expected for a near surface faceted crystal that was exposed to an upward water vapor flux within the snowpack. Furthermore, surface hoar should grow substantially during the daytime when large sublimation fluxes are observed, which again is not the case. Finally, on 15 March 2007, a melt-freeze crust was observed 2 cm below the surface. This crust, which must have formed by subsurface melting the days before, acts as a vapor barrier from below, while strong surface hoar formation was present during this period. All these findings strongly support that the main source of water vapor for surface hoar growth originate in the air right above the surface.

[32] Focusing on the night periods, sonic 1 (i.e., the lower eddy correlation system) consistently captures turbulent fluxes which are 10–25% larger than those measured by sonic 2. We point out that this flux divergence is due to the fact that water vapor fluctuations at the height of sonic 1 are a lot larger than at the height of sonic 2, whereas the fluctuations of the vertical velocity components remain fairly similar at both locations. This result is consistent with the presence of a higher water vapor concentration in proximity of the snow surface. The presence of such significant flux divergence makes it difficult to find out at which height turbulent fluxes should be measured, i.e., at which height an eddy correlation system should be placed. This partly explains the mismatch between the integrated turbulent fluxes obtained from the eddy correlation systems and the snow weight measurements at the snow surface. Other reasons which can justify such a mismatch are associated with the general difficulties of measuring scalar fluxes in complex terrain. Indeed, the lack of horizontal homogeneity implies that vertical turbulent fluxes are not the only driving mechanism for scalar exchange, because advection or lateral turbulent fluxes are very likely to occur and influence the local mass balance [*Finnigan*, 2004].

[33] Figure 7 shows that SNOWPACK is able to simulate the sign of the turbulent fluxes for most of the nights and therefore to predict if either sublimation or deposition is taking place. However, a quantitative comparison between the modeled and measured fluxes remains difficult. The reason for disagreement is that SNOWPACK uses a standard MO parametrization of the atmospheric boundary layer which is valid only for uniform flat terrain and not for complex orography as in our case. Despite all its limitations, the MO parametrization is routinely applied by almost all numerical models to predict scalar fluxes occurring between snow and atmosphere even in mountainous areas. In this paper we therefore briefly show the performance of the model for two typical assumptions, namely a forced neutral exchange and using the stability correction after *Stearns and Weidner* [1993]. The results of the simulations shown in Figure 7 shows that the best performance of SNOWPACK is obtained assuming a roughness length of 2 mm and forced neutral conditions. We acknowledge that neutral conditions are the exception rather than the rule in our experimental field site. Indeed it is well known that stable stratification occurs for flows over snow covered surfaces, especially during the nighttime when severe radiative cooling takes place. However, if the stability correction is used, the SNOWPACK simulations significantly underestimate the deposited or sublimated mass measured by the snow weighing technique. In contrast, the assumption of neutral conditions seems to provide better agreement. The underestimation of turbulent fluxes over snow and in mountains when using stability corrections has already been found and discussed by other authors [*Martin and Lejeune*, 1998]. We note that also model predictions of surface temperatures typically are better for the “forced neutral” assumption for simulations in which the surface temperature is not prescribed (not shown).

3.3. On the Crystal Size

[34] Predicting the size of the crystals is extremely difficult since it requires a known functional relationship between crystal size and the deposited mass and a very good statistical surface characterization [*Löwe et al.*, 2007; *Manes et al.*, 2008]. We can, however, provide a very rough estimate in Figure 9, where the maximum size of the crystals, estimated by visual inspection in the morning and by a more objective cold lab characterization is plotted against the mass change measured during the nighttime by means of the snow weighing technique. There is a clear trend, which appears to be too weak to allow an in depth quantitative analysis, however.

[35] This result suggests that during consecutive nights of surface hoar growth, the size of the crystals correlates well with the deposited mass during the night. This suggests also that surface hoar crystals that survive during the day, significantly decrease their size due to sublimation. This hypothesis is confirmed by Figure 3: on 18 March we have an estimate of crystal size in the morning right after vapor deposition at 08:04 and in the afternoon at 15:45 right after a day of strong sublimation (see Figure 7b) and melting. Figure 2f shows a surface hoar crystal collected on the afternoon of 18 March which actually started to undergo wet metamorphism (melt) but was nevertheless preserved. Due to the combined effects of sublimation and initial melting, the surface hoar crystals thus became significantly smaller. Note that the snow grains located immediately below the

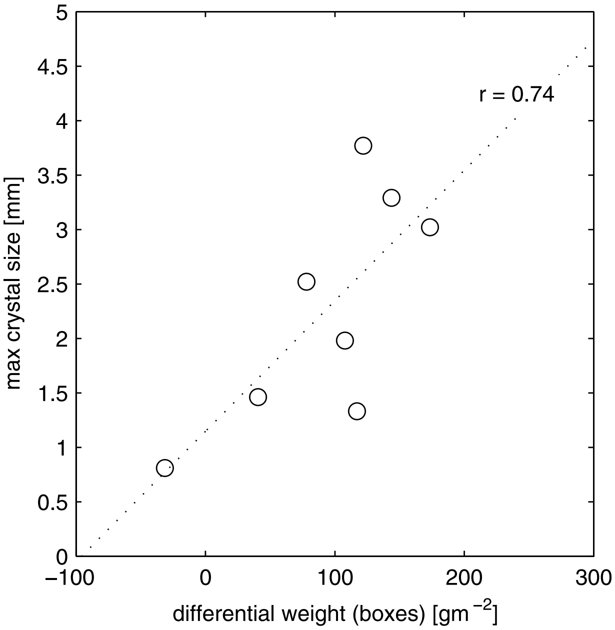

Figure 9. Maximum size of the surface hoar crystals plotted as a function of the mass differences (in the night periods 16:00–8:00) obtained by direct measurements (weighing the snow boxes).

surface hoar crystals were characterized as melt forms, indicating the important role of cooling by emission of longwave radiation on the daytime preservation of surface hoar.

4. Conclusions

[36] Driven by the need to have a fairly accurate prediction of surface hoar formation in complex terrain, data from the Weissfluhjoch study plot have been used in the past to better understand local surface hoar dynamics [*Föhn*, 2001; *Lehning et al.*, 2002b]. In our contribution, we now have had the opportunity to relate the formation of surface hoar, as observed in the field, to local micrometeorological processes, and to compare for the first time eddy flux measurements of moisture transport with direct surface mass change measurements and with SNOWPACK simulations. Our study lead to the following conclusions.

[37] 1. We confirm that surface hoar forms during nights associated with clear sky, low to moderate wind speeds and humid air.

[38] 2. Turbulent latent heat fluxes were found to play a key role in providing the water vapor necessary for the growth of surface hoar crystals on the snow surface.

[39] 3. We observe that surface hoar crystals tend to survive during the day, when strong sublimation takes place and the whole snowpack is losing mass. We argue that the mass of sublimation from the snow surface originates not only from surface hoar crystals (if present) but also from other snow crystals. Thus, surface hoar can survive a sublimation event that could in principle lead to a total loss of the hoar mass.

[40] 4. We confirm that bulk transfer parameterizations based on Monin-Obukhov theory (as used in SNOWPACK) give a reasonable approximation of surface hoar dynamics if certain assumptions are made. The best approximation by the MO bulk formulation has been achieved by assuming neutral stability and a roughness parameter for momentum and scalar transport of 2 mm. Indeed using published stability correction functions for MO flux calculations leads to exaggerated damping of the fluxes.

[41] We acknowledge that the two eddy correlation systems underestimate the local deposition flux (of water vapor) at the surface. This mismatch can be due to the fact that in complex terrain, the mass balance at one point can easily be influenced by advection and/or lateral turbulent fluxes and not just vertical turbulent fluxes. Furthermore since the flux divergence measured by the eddy correlation systems is consistent in sign with a progressively increasing mass flux toward the surface, we could speculate that an eddy correlation system located even closer to the snow surface may capture larger vertical turbulent fluxes.

[42] It is important to note that this study does not attempt to make general recommendations on how turbulent fluxes should be computed in complex terrain using bulk approaches. In this contribution, we also did not aim to optimize such calculations in exploring different combinations of scalar and momentum roughness lengths. However, we point out that, at a number of other sites (not shown here), very often the assumption of neutral stability is the best approximation for calculating the local energy balance over snow in mountainous terrain. This study calls for more systematic investigations of stability effects on the local energy balance in mountains and especially over snow. It is imperative that a multitude of sites with diverse characteristics is studied to formulate general improvements of turbulent flux calculations.

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