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The role of soil volumetric liquid water content during snow gliding processes.

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Abstract

In recent years, our understanding of snow gliding and glide-snow avalanches has improved; however, the contributing factors are still poorly understood and difficult to measure. In particular, the role of soil properties has not been considered as much as other environmental parameters (e.g. air temperature). Focusing on soil properties we established a monitoring site in the Italian Alps, in the release zone of a WSW-facing avalanche path. The area is typically characterized by intense snow gliding that results in the formation of large glide cracks, often leading to the release of a glide-snow avalanche. The site was equipped with four glide-snow shoes to measure snow gliding movement. Temperature and water content sensors were located at the snow-soil interface and at different depths within the soil. Meteorological data were recorded by a nearby automatic weather station, and snowpack properties were evaluated using manual snow profiles and SNOWPACK simulations; additionally, soils were characterized with special emphasis on the physical properties of the upper soil horizons. During two monitoring seasons, we registered a cold-temperature event characterized by gradual and continuous snow gliding and three warm-temperature events with glide-crack formation and evolution, in one case resulting in a glide-snow avalanche. Univariate (Mann-Witney U-test) and multivariate (Classification Trees) analyses allowed us to find significant differences between gliding and non-gliding periods, and confirmed the importance of distinguishing between cold and warm-temperature events. In particular, for warm-temperature events we found that the most significant parameters were a large snow depth, strong settlement and high air temperature. For cold-temperature events we found that, together with a large snow depth, the volumetric liquid water content, both at the snow-soil interface and within the soil, played a fundamental role. Moreover, for the cold-temperature events we found a strong correlation between daily glide rates and the soil volumetric liquid water content, with an exponential relationship at the snow-soil interface and at 5 cm depth within the soil. These results highlight the relationship between the snow gliding process and the soil conditions, which have been identified among the main environmental factors related to the development of snow gliding.

Keywords: snow gliding, glide-snow avalanche, snow-soil interaction, soil plastic and liquid limits

1. Introduction

Snow gliding, defined as the slow downhill movement of the entire snow cover on the ground, may lead to the formation of folds and cracks within the snowpack (In der Gand and Zupancic, 1966). Eventually, the movement may speed up and a crack may develop into a glide-snow avalanche (McClung and Schaerer, 2006). However, a glide crack does not necessarily result in glide-snow avalanche release, and in case it does, the time span from crack opening to the avalanche release may vary from a few seconds up to several months (Feick et al., 2012). Due to this high temporal variability, glide-snow avalanches still represent a major point of uncertainty for forecasting programs at all scales (Peitzsch et al., 2012; Reardon and Lundy, 2005; Stimberis and Rubin, 2004). Glide processes in snow and glide-snow avalanche release have been studied since the 1930s and are summarized in three recent reviewing publications (Ancey and Bain, 2015; Höller, 2014; Jones, 2004) which conclude that snow gliding is favoured by a smooth ground surface (in der Gand and Zupancic, 1966; Leitinger et al., 2008; McClung and Schaerer, 2006; Newesely et al., 2000), a lowermost layer of wet snow (in der Gand and Zupancic, 1966; McClung and Clarke, 1987) and a temperature at the snow-soil interface close to 0 °C (McClung and Clarke, 1987). Snow gliding can typically be observed on slopes with incline of at least 15° (McClung and Schaerer, 2006). Based on McClung and Clarke (1987), an enhanced gliding speed is connected to increased liquid water content at the snow-soil interface. Since monitoring the snow-soil interface is very demanding, different methods for tracking gliding speed were developed in the past (van Herwijnen et al., 2013).

As the presence of water is the key-contributing factor to snow gliding conditions, it is important to know how the liquid water content at the snow-soil interface evolves. The main processes associated with producing water are melting at the snow surface and rain-on-snow events. In fact, Clarke and McClung (1999) related most observed glide-snow avalanches to either snowmelt or rain-on-snow events using air temperature as a proxy and consequently called these glide-snow avalanche warm-temperature events. However, glide-snow avalanches have also been observed after prolonged periods of dry weather with sub-freezing temperatures, so-called cold-temperature events, which could not be explained with air temperature (Clarke and McClung, 1999). More recently, different processes that may lead to the presence of water at the snow-soil interface were investigated (Dreier et al., 2016; Mitterer and Schweizer, 2012). The results of both analyses underlined again the importance of differentiating between cold and warm-temperature events (Clarke and McClung, 1999), which seem to be driven by different soil, snow (Mitterer and Schweizer, 2012) and meteorological factors (Dreier et al., 2016).

All reviewing articles further conclude that there is a general lack of understanding of the exact glide-snow avalanche release mechanism, especially concering the interaction of the two porous media (snow and soil). Höller (2014) concludes that "*The increasing number of glide-snow avalanches in certain winter periods might be associated with the soil and ground surface conditions in late autumn and early winter; however, this assumption is primarily based on observations and not yet confirmed by relevant investigations. In this context, the soil conditions and the conditions at the snow–soil interface should be investigated.*". In fact, snow and soil are connected and represent a highly dynamic system, characterized by layered particles of different grain size and shapes with appreciable quantities of air and water. The strata encountered in a snowpack are in some ways analogous to the horizons that make up a soil profile. The interactions between the two domains are so strong that they must be considered a continuous system (Guymon, 1978). The presence of discontinuities in the physical properties of both snow and soil strata represents a potential triggering factor for snow movements and soil erosion, respectively (Chiaia and Frigo, 2009; Stanchi et al., 2014, 2012). First attempts in modelling the water transport behavior at the snow-soil interface (Mitterer and Schweizer, 2012) showed that a strong pressure gradient at the snow-grass interface causes an upward flux of water. Water in the model moved from the soil towards the snowpack. Consequently, if the substrate is a wet porous medium (i.e.

soil), water can be present within the basal snow layer even without basal melting (Mitterer and Schweizer, 2012). Moreover, in a wet soil, the high liquid water content might contribute to soil cohesion loss and the production of a thin mud layer, which could reduce the roughness and friction at the snow-soil interface.

Until now, only few studies have focused on the role of soil during snow gliding processes (Baumgärtner, 2016; Mitterer and Schweizer, 2012) and therefore our aim is to contribute to a better understanding of these processes with an integrated approach.

2. Data and methods

2.1. Study area

The study area, located in the Aosta Valley Region (NW-Italy), very close to the Mont Blanc Massif, includes the so-called *Torrent des Marais - Mont de la Saxe* avalanche path. The avalanche path runs on a WSW-facing slope from 2115 m to 1250 m a.s.l. (Fig. 1). The selected avalanche release area, at an elevation of about 2100 m a.s.l., is typically characterized by intense snow gliding and the formation of large glide cracks, often developing into a glide-snow avalanche, mainly during springtime. However, from time to time also in late autumn glide-snow avalanches were observed. The crack or avalanche crown width typically ranges between 30 and 100 m. A groundwater source is present in the south-eastern part of the crack zone. The slope, characterized by a mean angle of 30°, is covered by abandoned pastures and patches of bare soil providing a smooth surface favourable to snow gliding (Newesely et al., 2000). The bedrock is mainly black argillic schists, calcareous sandstones and, in some places, porphyritic granites. The soils in the study area (Haplic Cambisol (Humic, Dystric) according to IUSS, 2006) appeared frequently disturbed by snow gliding and snow avalanche phenomena, with the removal of the upper horizons (5-20 cm) and the consequent exposure of the subsoil (Ceaglio et al., 2012). In the study area, at about 2000 m, the long-term mean precipitation is 730 mm yr^{-1} (1992-2012), and the mean annual air temperature is +2.8 °C (1992-2012); the average cumulative snowfall is about 630 cm (2002-2012).

Data collection

For this work, the data were collected in the hydrological years 2009-2010 and 2010-2011, which hereafter will be called winter seasons or just seasons 2010 and 2011. All snow and meteorological parameters (Tab. 1) were provided by the automatic weather station (AWS) *Pré-Saint-Didier Plan Praz*, which is operational since 2002 and placed 9 km further south from the study site at 2044 m a.s.l.

To determine the physical properties of the snowpack, snow pit observations were made in a safe zone in the south-eastern part of the study area, where the avalanche rarely releases and only during periods characterized by low avalanche danger. Observations were performed according to Fierz et al. (2009). In addition, weekly snow profiles from the manual snow station *Morgex-Les Ors* located at 2144 m a.s.l. 9 km further south-east from the study site, were used, as this station is considered representative for the snowpack in the study area.

In the avalanche release area, instrumentation was installed for measuring snow gliding and snow and soil properties (Fig. 2). Two couples of glide-snow shoes, connected to potentiometers (Sommer®), were placed within the area where glide-cracks were observed in the past: a first couple (G1-G2) was placed in the north-western part of the glide crack zone, while a second couple (G3-G4) was placed in the south-eastern part, closer to the center of the glide crack zone, and to a groundwater spring. The wires connecting the shoes to the potentiometers were 4.5 m long during the winter season 2010 and 20 m long in the winter season 2011. Longer wires were used in the second season, because length proved not sufficient in the first season. In addition to the glide-snow shoes, temperature sensors (Campbell - 107 Temperature Probe) and volumetric liquid water content probes (Campbell-CS616 - Water Content Reflectometers WCR) were placed at the snow-soil interface and at two different soil depths (5 cm and 15 cm).

These sensors were installed in a place representative of the soil conditions of the study site (A in Fig. 2). Another system with the same set of sensors was placed very close to the groundwater spring (B in Fig. 2) in order to measure soil conditions in a waterlogged area with evidence of soil erosion; Stahr and Langenscheidt (2015) reported that these kind of conditions might potentially cause snow gliding. The data loggers were set to record measurements every minute and to store average (maximum in case of snow gliding) values every 30 minutes.

Soils were sampled (3 replicates) at 5 and 15 cm depth within plots A and B and analyzed in laboratory in order to determine soil physical properties according to standard methods (SISS, 1997): skeleton content (%), Atterberg plastic (LP, %) and liquid (LL, %) limits. The Atterberg Limits, determined through the cone penetrometer method, represent the soil moisture content values determining the transition from the semi-solid to the plastic state, and from the plastic to the liquid state, respectively (Lal and Shukla, 2004; Stanchi et al., 2012). The use of Atterberg Limits has been extended to the field of natural hazard assessment and investigation, mainly either for unstable phenomena involving the first decimeters of soil as shallow landslides or for the evaluation of soil erosion susceptibility to snow avalanches (Confortola et al., 2011; Stanchi et al., 2014, 2012).

2.3. Methods

During the winter season 2010, the snow gliding data registered by the glide-snow shoes G1 and G2 were analysed from 8 November 2009 until 18 March 2010, the day when a glide-snow avalanche released. For the glide-snow shoes G3 and G4 the data were analysed from 8 November 2009 until 14 February 2010, when the maximum cable length was reached. During the winter season 2011, snow gliding data registered by all the glide-snow shoes were analysed from 8 November 2010 until 30 April 2011, when the site was almost snow free, with only few snow patches left.

We performed univariate (Mann-Witney U-test) and multivariate (Classification Trees) statistical analyses to explore differences between periods of gliding (identified as those days with a daily glide rate greater than 0.5 cm/d measured by at least 3 glide-snow shoes) and periods of no gliding; initially we considered the whole dataset at once and then we classified into cold- and warm-temperature events.

During the winter season 2010, we identified periods of continuous, gradual gliding (defined with a daily glide rate greater than 0.5 cm/d measured by the four different glide-snow shoes) in which we performed further statistical analyses. We correlated glide-snow rate and soil parameters either using synchronous data or considering a time lag by means of the programming language R (R Team, 2014) and the software SPSS (IBM, 2013). In addition, we used a model fitting tool within R (AICcmodavg and fit.model package) to establish links between the glide-snow rate and the volumetric liquid water content measured in plot A. We considered daily values, which were obtained by averaging the 30 minutes average values for all parameters, except for the daily glide-snow rate, which was calculated as the difference of the cumulative gliding at 23:30 h between two consecutive days.

The soil parameters measured in B, closer to the water spring, were analyzed qualitatively, in order to evaluate their potential influence on soil cohesion loss and on snow gliding processes.

Availability of snow pit observations was limited due to logistic and safety reasons and therefore sparse in time. Consequently, we performed numerical simulations with the physical-based multi-layer snow cover model SNOWPACK (Lehning et al., 2002a,b; Wever et al., 2015), driven with meteorological input data from the *Pré-Saint-Didier Plan Praz* weather station. We used air temperature, relative humidity, wind direction and speed, solar radiation and snow depth to run the model. In order to mimic the snow cover for the glide-snow avalanche site, we adopted the input parameters for the slope angle, aspect and elevation of the test site. The simulated snow cover temperature was then used, combined with snow profile observations, in order to evaluate the temperature regime during the gliding process, i.e. to classify into cold-temperature and warm-temperature events.

We assumed that the distinction between a cold and a warm-temperature event is related to the origin of liquid water at the snow-soil interface: in a cold-temperature event the necessary wet snow-soil interface originates either from snow melting at basal layers of the snowpack or from suction; in a warm-temperature event the water originates from melting processes at the snow surface, percolates through the snowpack and ponds at the snow-soil interface.

3. Results

3.1. Winter season 2010

The winter season 2010 was characterized by a cumulative snowfall (821 cm) higher than the long-term average and an air temperature lower than the average from December until February, but higher than for the period mid-March until the end of April (dataset for period 2002-2011). The snow-soil interface temperature did not freeze since a sufficient snow depth was able to insulate the soil from the cold air temperature and remained close to 0 °C until the end of February (Fig. 3).

A glide crack was observed during the field work on 1 February 2010; its opening probably started in the last days of January. The glide crack finally evolved into a glide-snow avalanche on 18 March 2010 (Fig. 4). On this day the highest peak of daily glide-snow rate was registered with the glide-snow shoe G1 (100.9 cm/d) (Fig. 3). Unfortunately, the cables of glide-snow shoes G3 and G4 already reached their maximum length on 14 February 2010, after a long period of continuous and gradual gliding; therefore they did not record the avalanche event. The snow gliding started one week earlier for the glide-snow shoes G3-G4 than for the other pair and the daily glide-snow rate was higher for the prior pair than for the latter one (see also boxplots in Fig. 5), with a mean daily rate of 3.5 cm/d for both G1 and G2 and of 4.4 cm/d and 4.3 cm/d for G3 and G4, respectively.

The measured soil volumetric liquid water content (VLWC) in A had an average value (determined until the avalanche release on 18 March) of 24 % at 5 cm depth and of 21 % at 15 cm depth; the maximum values were 31 % at 5 cm and 26 % at 15 cm depth, respectively. In B the average values of VLWC were 47 % and 46 %, and maximum values were 53 % and 49 %, at 5 cm and 15 cm depth, respectively.

We classified the gradual and continuous gliding, which occurred from the beginning of the season until 14 February for G3-G4 (end of cable) and until 26 February and 6 March for G1 and G2, respectively, as a cold-temperature event. The mean air temperature was generally below zero (Fig.

3), even though in January it rised above 0 °C for a short period. However, we believe that during this period, conditions did not allow water percolating from the snow surface down to the snow-soil interface withouth subsurface refreezing, as the snow cover was typicaly in a winter condition with subfreezing snow temperatures.

The glide-snow avalanche recorded on 18 March 2010 was classified as a warm-temperature event. It occurred after a substantial rise of air temperature (daily averages from -13.3 °C to +3 °C from 9 to 18 March), which produced a strong snowpack settlement of 25 cm (Fig. 3). From 10 to 18 March, the snowpack glided downwards 303.5 cm in G1 and 64.8 cm in G2, reaching the total cable length of the snow shoes; the mean glide-snow rate in this period was 34 cm/d in G1 and 7.4 cm/d in G2. The maximum glide-snow rate was recorded from G1 between 15:30 and 15:35 on 18 March 2010, when the glide-snow shoe in G1 moved downwards by 47.4 cm, indicating the time of the glide-snow avalanche release.

3.2. Winter season 2011

The winter season 2011 started with earlier and heavier snowfall events than the season 2010, but the cumulative snowfall (548 cm) was lower. The air temperature was higher than the average (dataset for period 2002-2011), especially during February and from mid March until the end of April, when daily average air temperatures exceeded 0 °C several times. The snow-soil interface temperature was not constantly around 0 °C as in 2010, but showed an oscillating behavior related to thawing/freezing episodes (Fig. 6). A strong temperature decrease at the snow-soil interface was registered in A after a glide crack started to open on 17 January, which very likely exposed the soil where the probes were buried (Fig. 7). Between 16 and 17 January 2011 the glide-snow shoes registered a peak of daily glide-snow rate of 135.8 cm/d in G2 and of 481.6 cm/d and 447 cm/d in G3 and G4, respectively (Fig. 6). The only other significant glide-snow movement was registered on 4 April from glide-snow shoes G3-G4 (as the other couple of glide shoes were already free of snow): the daily glide-snow rate was 113.9 cm/d in G3 and 776.6 cm/d in G4.

Glide-snow shoes G3-G4 registered larger snow glide movements than G1-G2: the cumulative glide was 791 cm and 1493.7 cm for G3 and G4, respectively, and 226.7 cm in G2, while G1 did not move at all. The mean daily glide-snow rate was 3.8 cm/d and 7.2 cm/d in G3 and G4, respectively, and 1.1 cm/d in G2. In this season no glide-snow avalanche released. In comparison to season 2010, in this season, the glide-snow shoes did not move for long periods, but when moving, they moved faster and over larger distances than in 2010 (Fig. 5 and 6).

The measured soil volumetric liquid water content (VLWC) in A had an average value (determined until the snow melting observed on 23 March) of 26 % at 5 cm depth and of 27 % at 15 cm depth; the maximum values were 34 % at 5 cm and 32 % at 15 cm depth, respectively. In B the VLWC average and maximum values were 43 % and 49 %, and 57 % and 51 %, at 5 cm and 15 cm depth in the soil, respectively; large fluctuations were registered in VLWC at 5 cm depth (Fig. 6).

We classified the two important snow gliding events of this season as warm-temperature events. Both events occurred after a consistent rise in air temperature with exceptional values for the period (mean daily temperatures of +3.5 °C at 2000 m a.s.l. with a maximum of 11.4 °C on 16 January 2011; mean daily temperatures of +7.5 °C with a maximum of 12.3 °C on 3 April 2011), producing a strong wetting and settlement of the snowpack.

3.3. Gliding versus non-gliding periods

By contrasting gliding vs. non-gliding periods results showed that periods of gliding and periods of no gliding were characterized by different meteorological and soil paramenters (Tab. 2). When considering the entire dataset, only snow depth was found to be statistically significantly larger for gliding days than for non-gliding days. When considering cold-temperature snow gliding events only, the VLWC at the snow-soil interface was higher than in periods of no gliding, while the VLWC at 15 cm in soil was lower (Fig. 8). For warm-temperature events, the VLWC at 5 cm depth in soil was significatively higher in gliding periods than during periods of non-gliding; the daily average and maximum air temperature and the settlement were higher in gliding periods than in periods of non-gliding (Fig. 9).

When applying a multivariate approach (Classification Trees), results show that when combining warm- and cold-temperature events, the discriminant factor between gliding and non-gliding was the VLWC at the snow-soil interface with a threshold value of 5% related to snowpack movement. For cold-temperature events the discriminant variable for gliding versus non-gliding periods was the VLWC at the snow-soil interface with a threshold value of 5 % (Fig. 10); for warm-temperature events the gliding periods were characterized by a snow depth of at least 133 cm, a maximum air temperature greater than 5.4 °C and a VLWC at the snow-soil interface of 2.4 % (Fig. 10).

3.4. Correlation of snow gliding with meteorological and soil variables for the cold-temperature event

The cold-temperature event, which occurred in 2010, lasted some days, therefore we had enough data to perform correlation analyses (N = 37, 67, 50 and 47 for G1, G2, G3 and G4, respectively). Instead, as the warm-temperature events occurred rapidily in less than nine days, unfortunately sample size was not large enough to perform the same analyses.

During the cold-temperature event the daily glide-snow rate was positively correlated with the volumetric liquid water content at the snow-soil interface and at 5 and 15 cm depth in the soil (Tab. 3). The time-lagged analyses found that the best correlation was with synchronous data.

We fitted models which were able to well describe the relationship between the daily glide-snow rate and VLWC at the snow-soil interface and at 5 and 15 cm depth in the soil (Fig. 11): the daily glide-snow rate showed a linear relationship with VLWC at 15 cm depth in soil, while the relationship was exponential with VLWC both at the snow-soil interface and at 5 cm depth in soil. As it seemed that the curves present a different shape for the two pairs of glide-snow shoes, we also tried to fit the data of G1-G2 and G3-G4 separately: doing so, a better fit was found for the couple G3-G4 than for G1-G2.

3.5. Soil characteristics

Focusing on the soil physical properties, the topsoil (0-10 cm depth) differed significantly from the deeper soil horizons (10-20 cm depth). It was constituted by a organo-mineral horizon with hard, medium granular structure and 10% content of sub-angular fine gravel with abundant fine roots. The underneath horizons had a soft, medium granular structure and were characterized by 35-70% of angular coarse gravel and very few fine roots. These differences in soil properties were reflected in the plastic (LP) and liquid (LL) limits, that in the topsoil resulted higher (L LP: 65-67%; L: 76-82%) than in the underlying soil horizon (LP: 36-54%; LL: 48-67%), which represents the ground surface in many eroded patches in the study site; consequently, considering the soil moisture content recorded in this study, the possibility of a significant reduction of soil cohesion in the subnivean zone was considerable, in particular close to the groundwater source. During a field survey in spring 2010, we observed the presence of a thin mud layer at the snow-soil interface while digging a snow pit in the south-eastern part of the study area, closer to the groundwater source (Fig. 12).

4. Discussion

Our results underline the fact that it is important to classify glide-snow activity into cold- and warm-temperature events, which is in agreement with the most recent research on this topic (e.g. Dreier et al, 2016; Peitzsch et al., 2012). The statistical analyses of gliding versus non-gliding periods revealed that – when ignoring this classification – explaining relationships for both periods are vanishing or become less pronounced (Tab. 2 and Fig. 8 and 9). Considering all gliding periods together revealed that gliding periods had higher VLWC at the snow-soil interface, thicker snowpacks and lower values of VLWC at 15 cm soil depth. Except for the latter parameter, it is a known and widely accepted fact that a wet interface and a considerably thick snowpack are key-contributing factors to snow gliding (Höller, 2014; Jones, 2004; Mitterer and Schweizer, 2012).

When classifying the gliding periods into warm- and cold-temperature events, the statistical analyses provided more insight into the processes governing the formation of the wet interface.

During gliding periods of warm-temperature events, air temperature (daily mean and maximum) was significantly higher, and the decrease of snow depth was significantly stronger, than during non-gliding periods; moreover, in periods of gliding new snow amount was significantly lower than in periods of no gliding (Tab. 2, Fig. 9). Both, high air temperatures and the strong decrease in snow depth indicates a melting snowpack suggesting that water was produced at the snow surface and percolated through the snowpack (e.g. Peitzsch et al., 2012). Having percolated the entire snowpack, VLWC at 5 cm soil depth was significanlty higher for warm-temperature gliding periods than during non-gliding periods, while values of VLWC at the snow-soil interface and at 15 cm soil depth did not show any statistically relevant difference. In other words, warm-temperature events were characterised by high air temperature, strong snow settlement and high values of VLWC at or close to the snow-soil interface.

Cold-temperature gliding periods were characaterised by significantly higher values of VLWC at the snow-soil interface, lower values of air temperature (minimum, mean) and lower values of VLWC at 15 cm soil depth than during non-gliding periods (Tab. 2, Fig. 8). The low values of VLWC at 15 cm depth in soil during gliding periods might be related to suction. The statistical analyses suggests that cold-temperature gliding events in our dataset could be characterised by an upward movement of water. Mitterer and Schweizer (2012) already showed with a simplified modelling approach that the difference of liquid water content between snow and soil is largest at the interface. The resulting hydraulic gradient moves water from the soil into the snow. Together with the measurement results by Baumgärtner (2016) our data represents the first evidence of this process.

Moreover, our analysis of VLWC and glide rate measurements shows that the amount of water at the interface is correlated with an increase in gliding speed. In particular, in the case of the cold-temperature snow gliding event in 2010, the glide-snow rate was strongly correlated with the measured soil volumetric liquid water content (Tab. 3): faster gliding rates corresponded to higher amounts of VLWC. These findings again agree with the recent results of Baumgärtner (2016), who found a strong correlation between glide-snow rates and VLWC in the soil for data gathered in an experimental site during the period October-January. For our data, we found an exponential relation between glide-snow rates and VLWC at the snow-soil interface and at 5 cm soil depth and a linear relation with VLWC values at 15 cm soil depth (Fig. 11). The exponential and linear relationship between the glide-snow rates and the VLWC was better defined for the glide-snow shoes pair G3-G4 than for G1-G2 which might be due to site specific conditions (e.g. position of the glide-snow shoes pairs in the crack and vicinity to the water source).

The results suggest that the amount of water closer to the snow-soil interface has a strong impact on gliding acceleration (Fig. 11). The increase in glide-rates is known to be a reasonable precursor of glide-snow avalanche activity (Stimberis and Rubin, 2011; van Herwijnen and Simenhois, 2012). The exponential correlation of the glide rate with VLWC at the snow-soil interface and at 5 cm depth in soil shows similar behaviour as the exponential increases of gliding velocity shortly before a glide-crack turns into a glide-snow avalanche (van Herwijnen et al., 2013). In our data of VLWC at 5 cm soil depth, approximately at the threshold where the derivative of the exponential function becomes larger than one, the glide rate increases dramatically, while the VLWC increases little. The change occurred in the period before we believe that the glide crack started to open. The observations are in accordance with Clarke and McClung (1999), who pointed out that the rupture and release of the snowpack are more likely to be consequences of increased glide-snow rate than of a threshold in the glide-snow rate. In our case, though, the increase was possibly not strong enough and consequently no avalanche released after the glide-crack opening during the observed period of cold-temperature event. In case of warm-temperature events the movements were faster, but sample size was too small to perform the same statistical analysis we made with the cold-temperature event. Still, we think that the behaviour might be similar, with the only difference that the supplied water is arriving from the snow surface, while for the cold-temperature events it arrives either from the soil or from snowpack basal melting.

In addition, we observed changes in VLWC which we attributed to freezing of water. At the beginning of season 2010, VLWC measured in A at 5 cm soil depth was roughly 25 % and it dropped abruptly to 14 % on 20 December 2009 (Fig. 3). These decrease occurred in a period of prevailing low air temperatures and shallow snow cover, which are reflected in subfreezing temperatures at the snow-soil interface and in the topsoil (Fig. 3). Snowfalls increased the total snow depth and insulated the soil, where the VLWC increased to a value similar to the initial one. Changes in VLWC are either attributed to water flow or to phase changes. Since the sharp decreases in VLWC occurred during a cold period with soil temperatures below 0 °C, we think that freezing processes led to this decrease in VLWC (Brooks et al., 2011). Since the relative permittivity of water is about 20 times larger than that of ice, the significant drop in permittivity measured in A suggests rather a phase change than water movement causing this change. Similarly, after the snow depth increased, insulating the soil, the frozen water in the soil or snow could melt leading to an increase in VLWC. During periods of low VLWC and sub-freezing soil temperatures, no gliding was registered (Fig. 3), while the snowpack started again to glide as soon as the soil temperatures had reached roughly 0 °C.

In addition, the amount of VLWC feedbacks with the phase change of water: freezing will be much slower at high water content than at low water content. Water heat capacity is higher than frozen soil one, and water freezing adds latent heat to the soil water system. These two factors explain the different behavior of plot A and B in terms fo soil temperatures and VLWC (Fig. 3 and 6). At the beginning of winter larger decreases of temperature and VLWC occurred in plot A than in plot B, because of the inertia due to the greater amount of liquid water in plot B.

Abrupt VLWC changes occurred in plot B in 2011. We think that also in this case a water phase change can explain the strong decrease registered in VLWC at 5 cm depth in plot B at mid January 2011 (Fig. 6). In this case, the opening of a glide crack occurred on 17 January (as also registered by the glide-snow shoes) and possibly exposed the soil, where the sensors were buried, to the cold air temperatures registered in the following period. Subsequently the soil temperature dropped below 0 °C and the soil water froze. The same considerations on water phase changes are valid for the other sharp changes registered for VLWC at 5 cm depth in plot B (Fig. 6).

Therefore the amount of water content is not only important itself for snow gliding, but it has also a cascading effect on the soil thermal regime: it plays a major role in keeping the temperature at the snow-soil interface close to 0 °C, which is in turn again a predisposing factor for snow gliding. In other words, the strictly inter-connected water flow and thermal dynamics of both soil and snow porous media influence glide-snow processes.

Due to the high soil volumetric liquid water content recorded especially in B throughout both winter seasons, and in particular, during early spring, we could not exclude the loss of soil cohesion under the snow cover (Stahr and Langenscheidt, 2015). These soils, in fact, showed relatively low values of the Atterberg plastic and liquid limits, in particular at a depth of 15 cm (LP: 36-54 %; LL: 48-67 %), which could represent the ground surface where the topsoil had already been eroded and stripped away (Ceaglio et al., 2012). The soil VLWC registered at 15 cm depth in B (close to the water source, where many patches of soil erosion are present) reached the maximum values of 48 % in season 2010 (23 March) and of 51 % in season 2011 (13 February). These values were close to the Atterberg plastic and liquid limits for the subsoil. Therefore, the loss of cohesion might have contributed to the active snow gliding processes by the formation of a thin mud layer at the snow-soil interface, especially in the eroded areas, as observed in 2010 (Fig. 12). This thin mud layer might have reduced the roughness and the friction at the snow-soil interface and might explain the high amount of solid material transported by the glide-snow avalanches in this study site (Ceaglio et al., 2012).

5. Conclusion

The presence of water at the snow-soil interface is one of the key contributing factors to glide-snow processes. In this study we focused on how the liquid water at the snow-soil interface is generated, evolves and how it is related to glide-snow rates. With a newly established field site, we analyzed the different predisposing conditions for warm- and cold-temperature snow gliding events.

For warm-temperature events we found that the most significant variables were snow depth, settlement and air temperature.

For cold-temperature events we found that, together with snow depth, the volumetric liquid water content at the snow-soil interface and in soil played a fundamental role. Our results indicate that cold-temperature events are characterised by an upward movement of water from the soil to the snow. We determined a quantitative relationship between the glide-snow rate and the volumetric liquid water content at the snow-soil interface and at different soil depths. Glide-snow rates increased exponentially with increasing water content at the snow-soil interface and in the top 5 cm of the soil. This observations show the importance of considering the snow cover and the underlying soil as a continuous system, where the key contributing part is certainly represented by the snow-soil interface.

In addition, we found that some discontinuities between the topsoil and the underlying soil horizon may act as a gliding layer. Depending on the soil physical characteristics, especially the plastic and liquid limits, the presence of high liquid water content values could induce the reduction of the soil cohesion, favoring the formation of a soft slushy film and creating a predisposing condition for both snow gliding and soil erosion.

Our results confirm that it is paramount to observe and/or measure the snow and soil properties jointly, since together they represent a highly dynamic and connected porous medium, in order to enhance our knowledge on driving processes for snow gliding. Thermal and hydraulic processes are influencing the formation processes of glide cracks and avalanches. As our database is limited and site specific, some of our results might be influenced by the specific conditions we observed in both winter seasons. However, many results such as the exponential correlation of soil water content and glide-snow rates are probably generally valid. Nevertheless, more data from well-instrumented sites should be collected to corroborate our results.

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Figures:

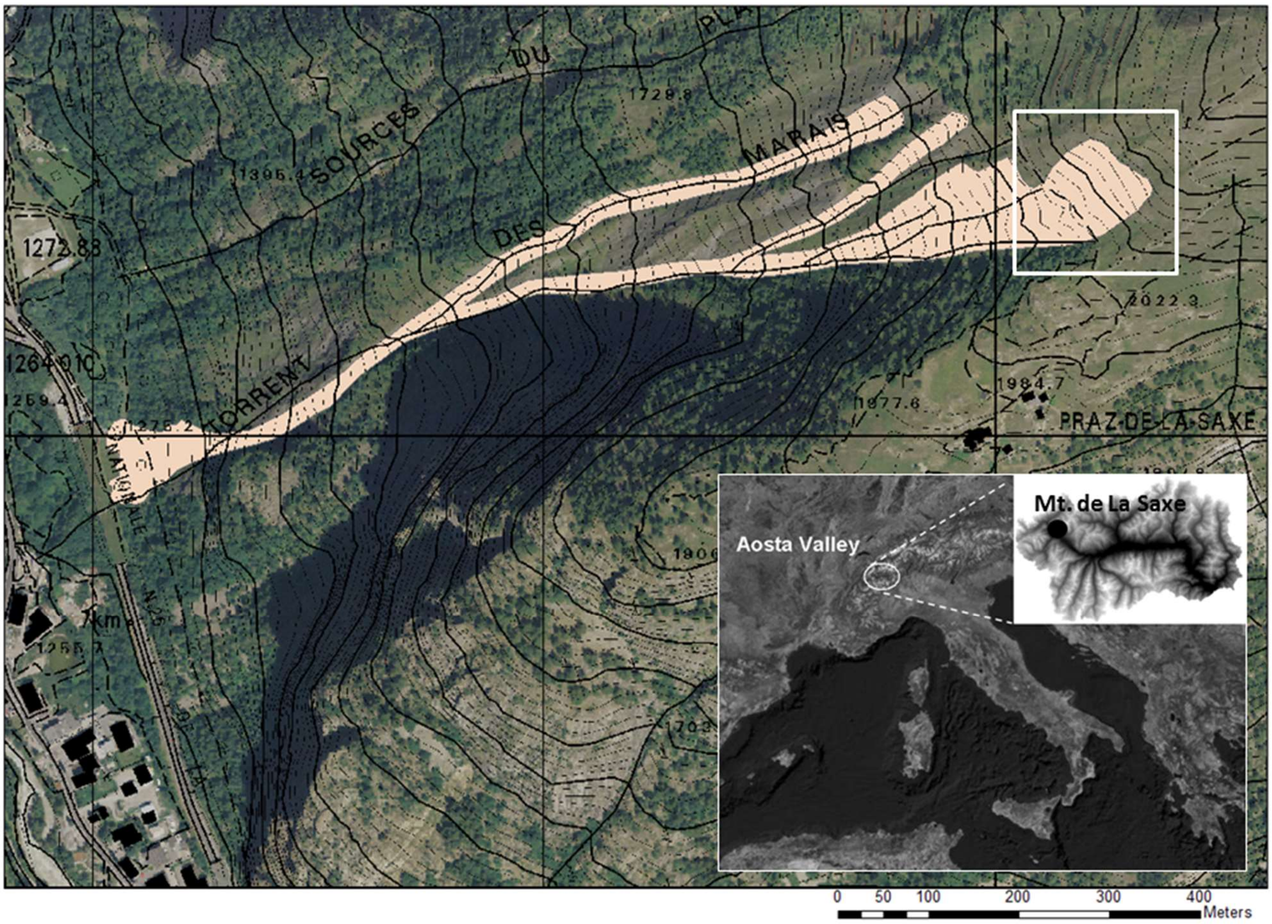


Fig. 1. Study area: the polygon shows the extension of the avalanche event occurred in 2009 as an example, with the release area highlighted within the white rectangle. In the inset the localization within the Aosta Valley and in Italy is shown.

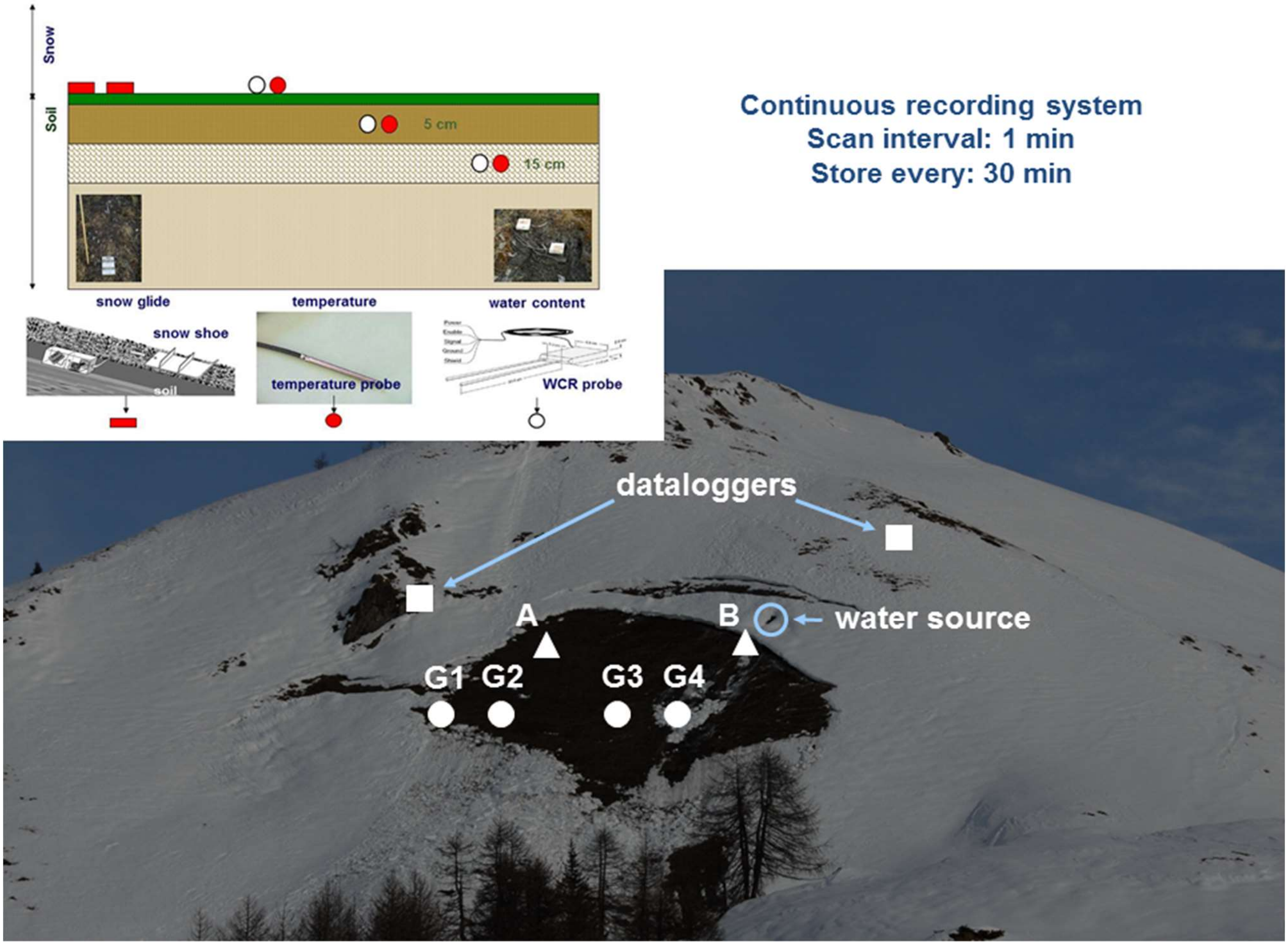
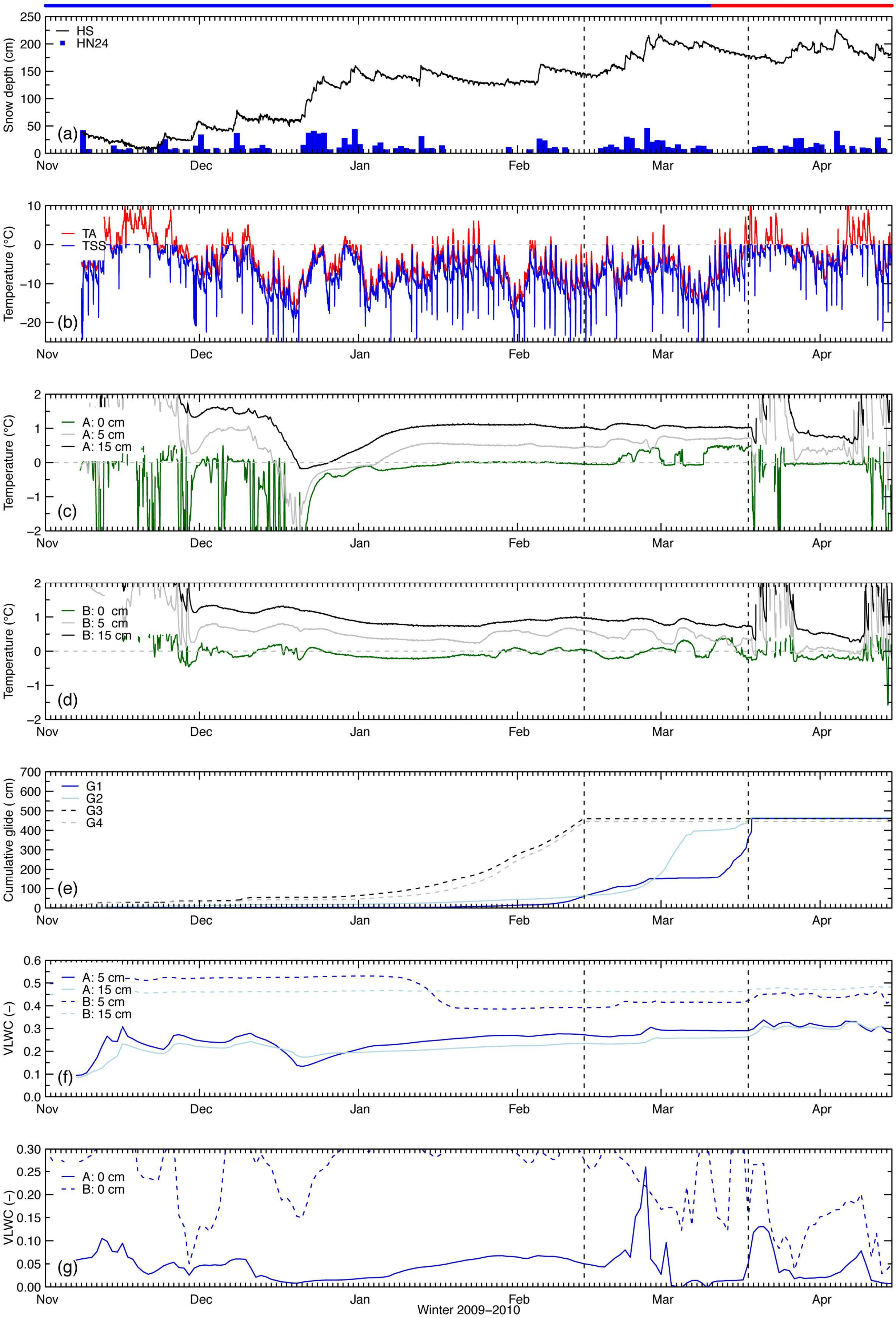


Fig. 2. General view of the monitoring site with the localization of the two pairs of glide-snow shoes (G1-G2 and G3-G4) and of the temperature and volumetric liquid water content sensors (A and B). The scheme in the upper-left corner shows the instrumentation. Photo taken by R. Cosson in Winter 2008.



Snow depth (cm)
HS
HN24
(a)
Temperature (°C)
TA
TSS
(b)
A: 0 cm
A: 5 cm
A: 15 cm
(c)
B: 0 cm
B: 5 cm
B: 15 cm
(d)
Cumulative glide (cm)
G1
G2
G3
G4
(e)
VLWC (–)
A: 5 cm
A: 15 cm
B: 5 cm
B: 15 cm
(f)
A: 0 cm
B: 0 cm
(g)
Nov
Dec
Jan
Feb
Mar
Apr
Winter 2009–2010

Fig. 3. Winter season 2009-2010: (a) Snow depth (HS), simulated 24 h new snow sum (HN24); (b) measured air temperature (TA) and simulated snow surface temperature (TSS) at the location of the AWS *Pré-Saint-Didier Plan Praz*. Soil temperature at plot A (c) and B (d), (e) glide-snow distance and volumetric liquid water content (VLWC) measured within the soil (f) and at the snow-soil interface (g) for both A and B. G1-G2 and G3-G4 refer to the two pairs of glide-snow shoes as in Fig. 2. Dashed lines identify significative dates: 14 February - end of cables for the pair G3-G4; 18 March - snow avalanche release. Blue and red colored lines on top indicate periods of cold-temperature (blue) and warm-temperature events (red).

Fig. 4. Glide crack and snow avalanche recorded during winter season 2010. Photos taken on 17 March (up) and 23 March 2010 (bottom, by R. Cosson).

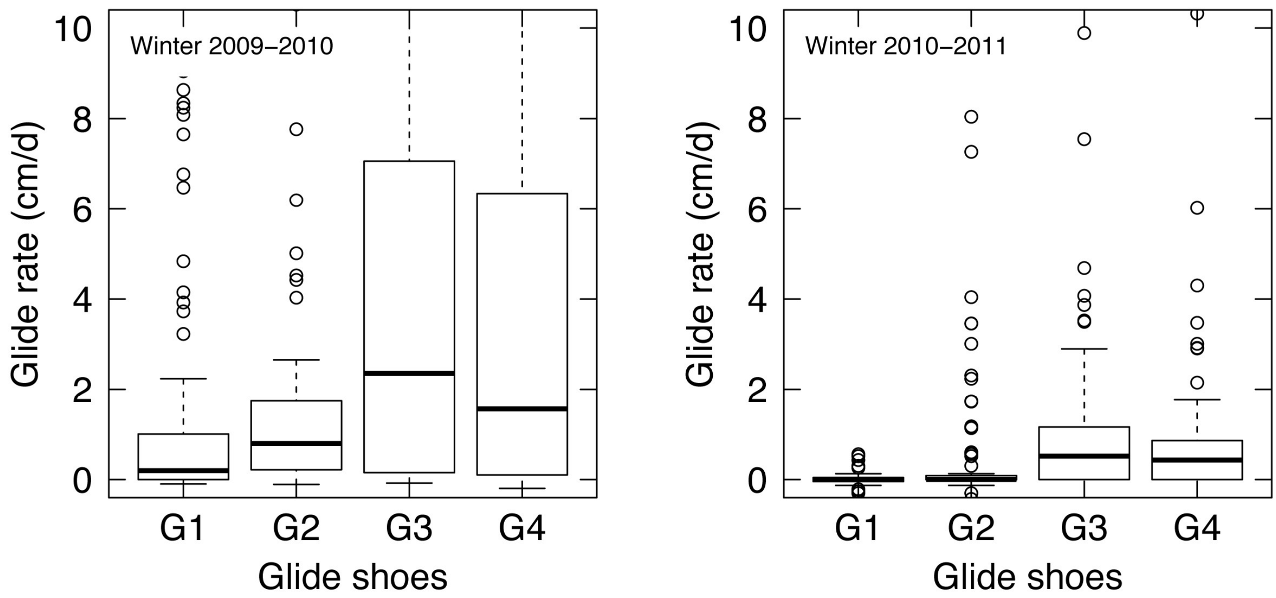


Fig. 5. Daily average glide rates for the four different glide shoes in the two monitoring seasons (left: 2009-2010; right: 2010-2011). Data from 8 November 2009 to 14 February 2010 for G3-G4 and from 8 November 2009 to 18 March 2010 for G1-G2 in season 2010; data from 8 November 2010 to 30 April 2011 for G1-G2-G3-G4 in season 2011.

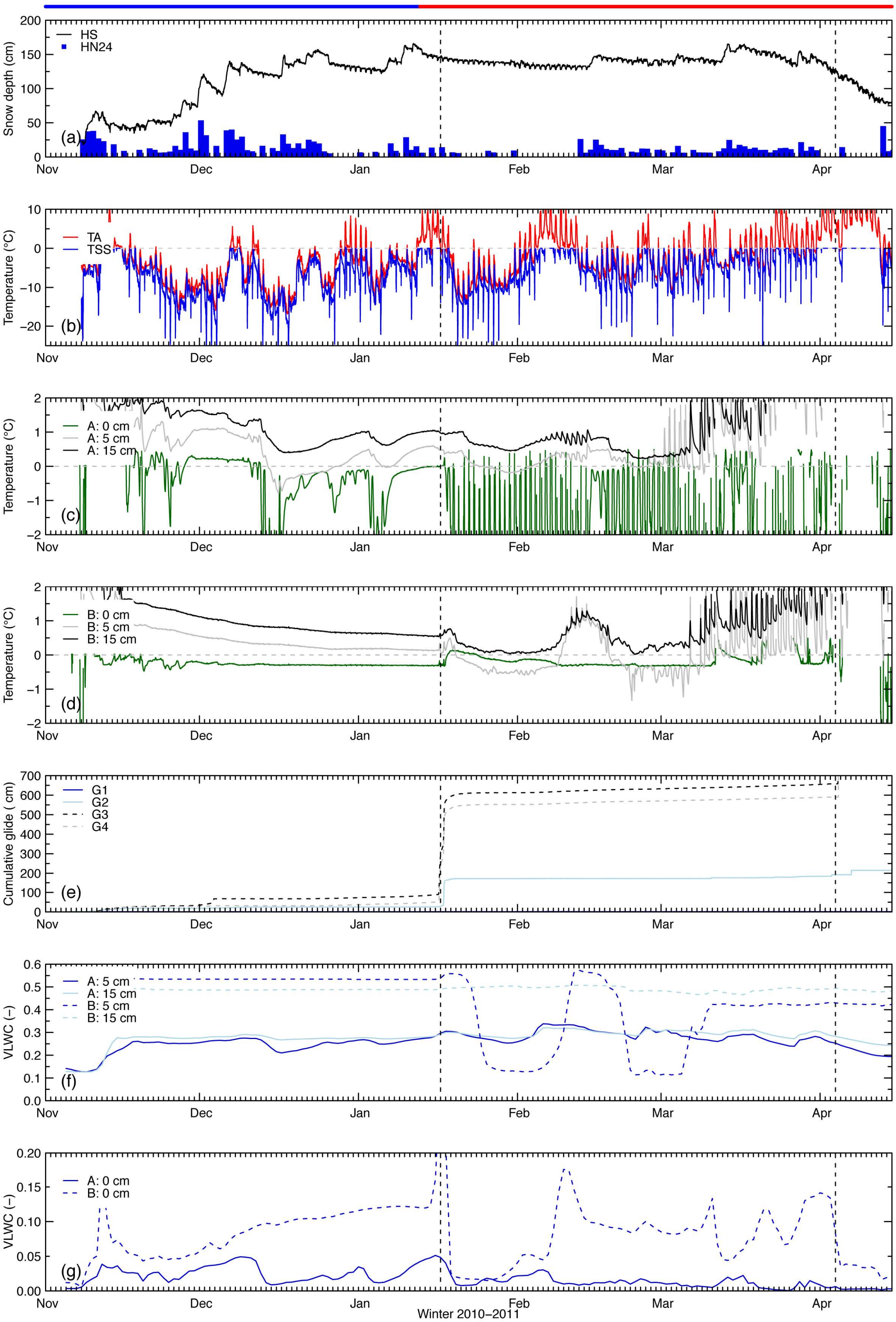

Snow depth (cm)
HS
HN24
(a)
Temperature (°C)
TA
TSS
(b)
A: 0 cm
A: 5 cm
A: 15 cm
(c)
B: 0 cm
B: 5 cm
B: 15 cm
(d)
Cumulative glide (cm)
G1
G2
G3
G4
(e)
VLWC (–)
A: 5 cm
A: 15 cm
B: 5 cm
B: 15 cm
(f)
A: 0 cm
B: 0 cm
(g)
Nov
Dec
Jan
Feb
Mar
Apr
Winter 2010–2011

Fig. 6. Same representation as in Fig. 3, but for the winter season 2010-2011. Dashed lines identify significative dates for strong glides-snow movements: 17 January 2011 and 4 April 2011. Blue and red colored lines on top indicate periods for cold-temperature (blue) and warm-temperature events (red)

Fig. 7. Glide crack and snowmelt during winter season 2011. Photos taken on 3 February (up) and 23 March 2011(bottom).

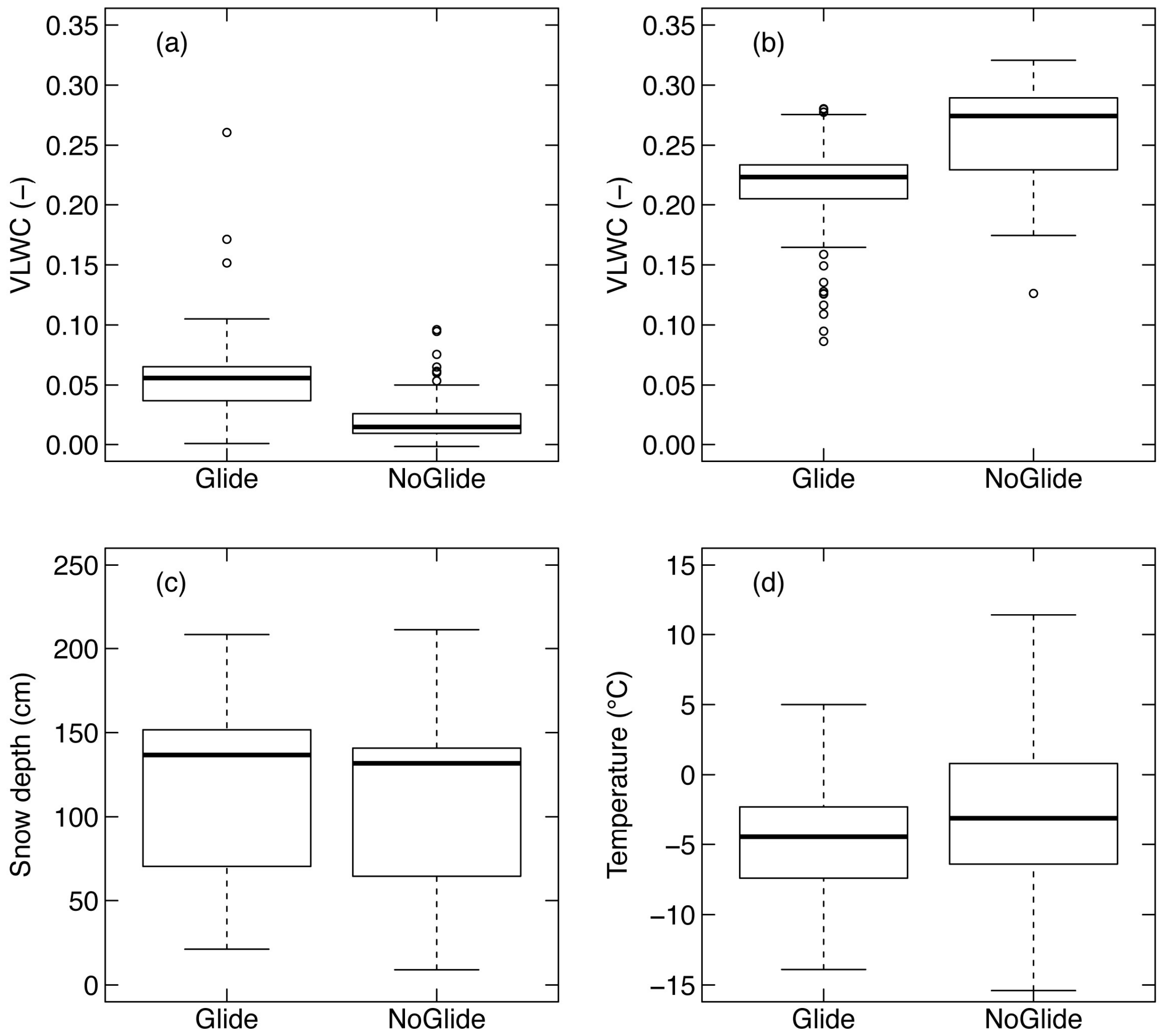


Figure 8. Comparison between gliding (Glide) and non-gliding (NoGlide) periods during cold-temperature events: (a) volumetric liquid water content at the snow-soil interface (VLWC) and (b) at 15 cm soil depth, (c) snow depth and (d) daily mean air temperature.

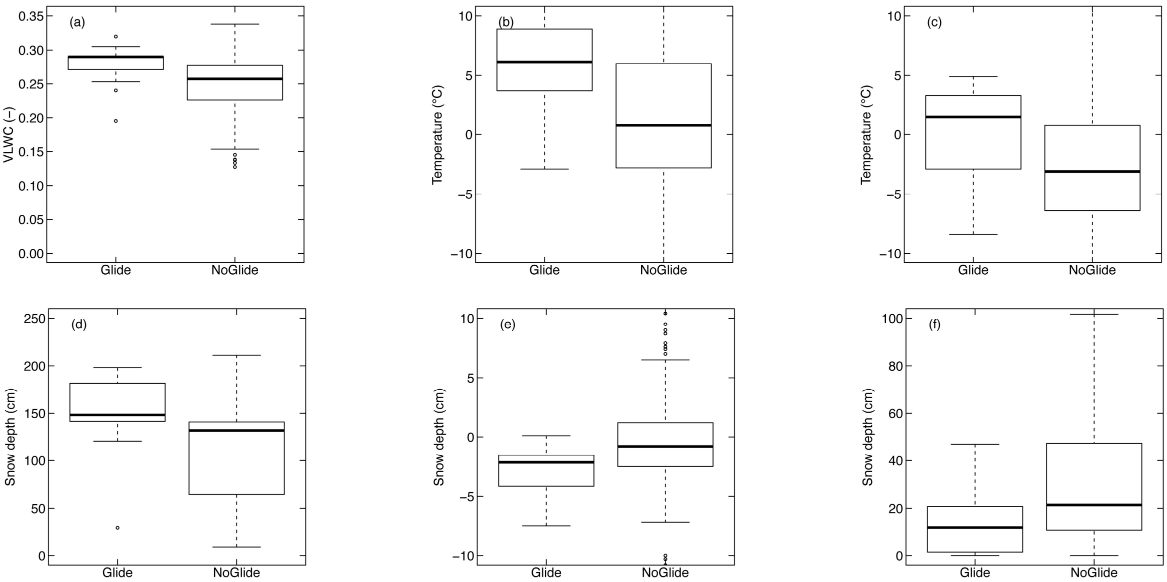


Figure 9. Comparison between gliding (Glide) and non-gliding (NoGlide) periods during warm-temperature events: (a) volumetric liquid water content (VLWC) at 5 cm soil depth, (b) daily maximum air temperature, (c) daily mean air temperature, (d) snow depth, (e) 24-hour difference in snow depth and maximum simulated new snow depth summed over five days.

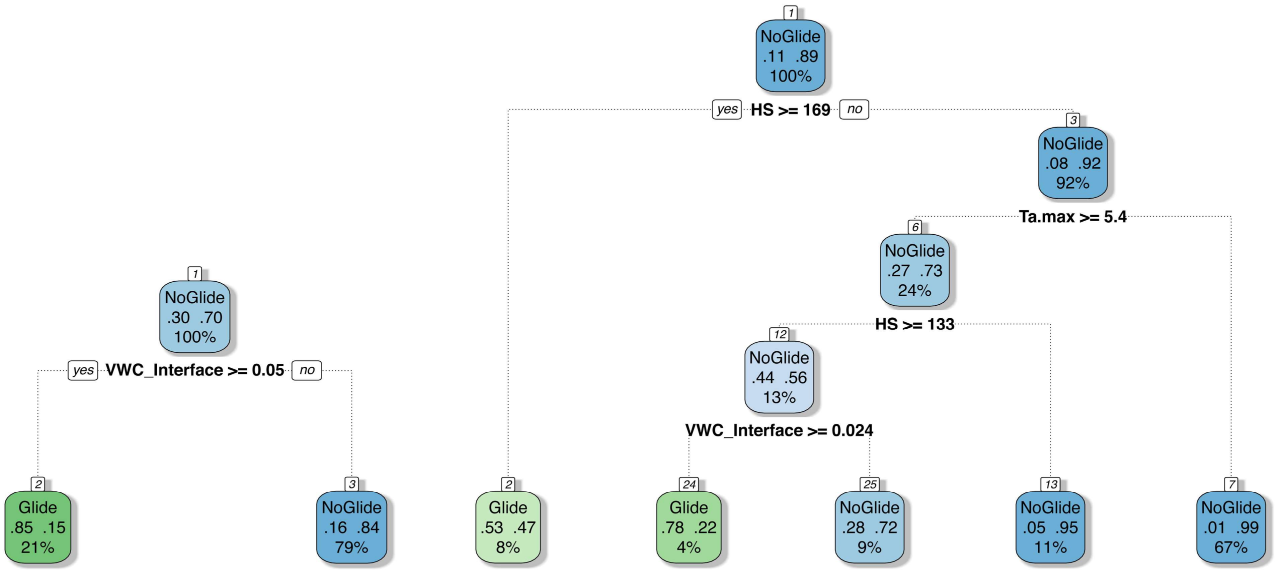


Figure 10. Classification Trees for cold (left) and warm (right) temperature events, considering all the variables shown in Table 2.

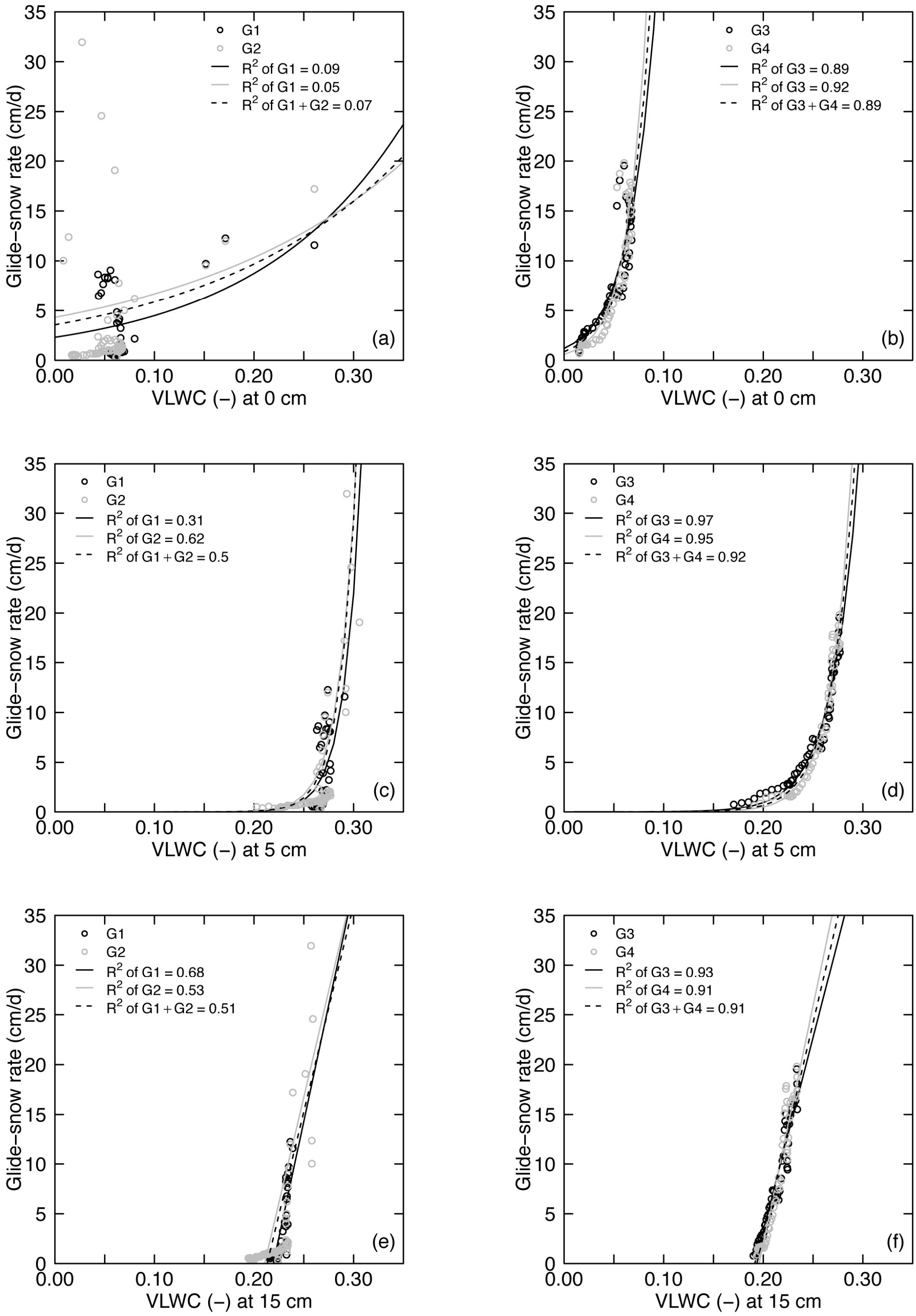


Fig. 11. Fitting models between daily glide-snow rates and volumetric liquid water content (VLWC) measured in plot A at the snow-soil interface and at 5 and 15 cm soil depths during the cold-temperature snow gliding event of season 2010 [data: 21 Jan. – 26 Feb. for G1 (N=37), 31 Dec. – 7 Mar. for G2 (N=67), 26 Dec. – 13 Feb. for G3 (N=50), 29 Dec. – 13 Feb. for G4 (N=47)].

Fig. 12. On 2 April 2010 in the study area the soil at the bottom of the snowpack appeared liquid and mixed with the snow in a continuous system.

Tables

Table 1. Parameters measured at the AWS *Pré-Saint-Didier - Plan Praz* (2044 m a.s.l.).

Automatic weather station of Pré-Saint-Didier - Plan Praz 2044 m a.s.l., UTM - 32T ED50 E: 340864 N: 5069401 Characteristics: flat, grassy area		
Sensor	*Parameter*	*Unit*
Thermometer	Air temperature	°C
Rain gauge	Rain precipitation	mm
Snow gauge	Snow depth	cm
Solarimeter	Short wave (305 e 2800 nm) solar radiation (total, incident and reflected)	W/m^2
Anemometer	Wind speed (average and gusts); wind direction	m/s degree
Hygrometer	Relative humidity	%
Barometer	Atmospheric pressure	Pa
Snow thermometer	Snow temperature	°C

Table 2. Summary statistics showing median values of various variables for gliding days (Gd) and non-gliding days (NonGd). For each variable, distributions were contrasted (U-test, cross-tabulated), and the level of significance p is given ($^{*}p<0.05$, $^{**}p<0.01$).

	All events			**Cold events**			**Warm events**		
Variables	Gd	NonGd	p-value	Gd	NonGd	p-value	Gd	NonGd	p-value
Temperature at 0 cm (°C)	0.0	-0.1	0.01*	0.0	-0.1	0.061	0.4	-0.1	0.017*
VLWC at 0 cm (%/100)	**0.05**	**0.02**	**<0.001****	**0.06**	**0.01**	**<0.001****	0.01	0.01	0.889
Temperature at -5 cm (°C)	0.6	0.5	0.204	0.5	0.5	0.467	0.7	0.6	0.117
VLWC at -5 cm (%/100)	0.27	0.26	0.226	0.26	0.26	0.721	**0.29**	**0.26**	**<0.001****
Temperature at -15 cm (°C)	1.1	1.0	0.157	1.1	1.0	0.267	1.0	1.0	0.249
VLWC at -15 cm (%/100)	**0.23**	**0.27**	**<0.001****	**0.22**	**0.27**	**<0.001****	0.28	0.27	0.183
Avg Ta (°C)	-3.7	-3.1	0.228	**-4.5**	**-3.1**	**0.005****	**1.5**	**-3.1**	**0.007****
Max Ta (°C)	0.6	0.8	0.461	-0.2	0.8	0.010*	**6.2**	**0.8**	**0.001****
Min Ta (°C)	-6.8	-5.7	0.111	**-7.7**	**-5.7**	**0.005****	-2.7	-5.7	0.075
HS (cm)	**141**	**132**	**<0.001****	137	132	0.039*	**148**	**132**	**<0.001****
ΔHS24h (cm)	-1.6	-0.8	0.083	-1.1	-0.8	0.792	**-2.2**	**-0.8**	**<0.001****
HN24 (cm)	2	4	0.100	2	4	0.573	**0**	**4**	**0.005****
HN3d (cm)	9	12	0.255	12	12	0.884	**7**	**12**	**0.003****
HN5d (cm)	20	21	0.109	25	21	0.744	**12**	**21**	**0.002****
HN7d (cm)	31	34	0.062	37	34	0.564	**20**	**34**	**0.002****

Table 3. Correlations (r) between daily glide-snow rate (G) and volumetric liquid water content (VLWC) measured in plot A (Fig. 2) during the cold-temperature snow gliding event of season 2010 (data in periods: 21 Jan. – 26 Feb. for G1, 31 Dec. – 7 Mar. for G2, 26 Dec. – 13 Feb. for G3, 29 Dec. – 13 Feb. for G4) at the snow-soil interface (I) and at 5 and 15 cm depth in the soil (S5 and S15 respectively). $^{*}p<0.05$, $^{**}p<0.01$; n.s. not significant.

	VLWC I	**VLWC S5**	**VLWC S15**
G1	.451**	.536**	.825**
G2	n.s.	.567**	.697**
G3	.866**	.873**	.962**
G4	.858**	.884**	.956**

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