A CHARACTERIZATION OF SNOW GLIDING AND POTENTIAL PREDISPOSING FACTORS IN A FULL-DEPTH SLAB AVALANCHE RELEASE AREA (VALLE D'AOSTA, NW ITALIAN ALPS)

E. Ceaglio*[,1,2,3], M. Freppaz[3], G. Filippa[3], S. Ferraris[4], E. Zanini[3], V. Segor[2]

[1] Fondazione Montagna Sicura - Montagne Sûre, Italy;
[2] Ufficio neve e valanghe, Assetto idrogeologico dei bacini montani, Regione Autonoma Valle d'Aosta, Italy;
[3] Dipartimento di Scienze Agrarie, Forestali e Alimentari and NatRisk-LNSA, University of Torino, Italy;
[4] Dipartimento Interateneo di Scienze, Progetto e Politiche del Territorio, Università e Politecnico di Torino, Italy.

ABSTRACT: In recent years many progresses have been made in the comprehension of the glide avalanches; however processes leading to this kind of phenomena are still poorly understood and therefore represent a major point of uncertainty for avalanche forecasting. In this study, we aimed to contribute to the snow gliding understanding, with particular attention to the snow/soil interface properties and meteorological parameters. The study area, located in the NW Italian Alps, consists of an avalanche site, running on a west exposed slope; in the release area, typically characterized by intense snow gliding, with the formation of a big glide crack often leading to the occurrence of a full-depth slab avalanche, a monitoring site was settled. Two plots were chosen and equipped with snow glide shoes; temperature and water content sensors were located at different soil and snow depths. Meteorological data were recorded by an automatic weather station; snowpack properties were collected by manual snow profiles. Data were gathered in two hydrological years, 2009-2010 and 2010-2011, characterized by different meteorological conditions. Preliminary results will be presented focusing on the relationship between the gliding process, the soil and snow properties and the weather conditions, in order to identify the main environmental factors controlling the development of snow gliding, and potentially provide moisture/temperature thresholds for the release of a gliding avalanche.

1. INTRODUCTION

The snow gliding, defined as the slow downhill movement of the snow cover on smooth or wet ground, can lead to the formation of folds and cracks, which are considerate as precursors of glide avalanches (full-depth slab avalanches of wet snow). Glide processes have been studied since the 30s' till nowadays (e.g. Jones et al., 2004), although they are not yet enough understood and they can be funny encountered in the "strange but true section" of snow phenomena, as defined by Reardon et al. (2006). Currently wet snow avalanches, including the gliding ones, represent a major point of uncertainty in the forecasting activities because of their hard predictability (Baggi and Schweizer, 2009; Peitzsch, E.H., et al., 2012; Reardon and Lundy, 2004; Simenhois and Birkeland, 2010). The glide cracks monitoring could represent an essential step towards glide avalanche risk assessment (Feck et al., 2011; Peitzsch, E.H., et al., 2012).

Studies have shown that the rate of gliding is very sensitive to the amount of free water present at the snow/ground interface (e.g. Clarke and McClung, 1999; Lackinger, 1987). In particular the formation of a soft slushy soil film may influence the gliding mechanism. Sources of free water at the interface level include: (1) rainfall; (2) melt at the interface resulting from the summer heat stored by the soil; (3) snowpack melt by solar radiation; (4) melt from geothermal hot spots and groundwater outflows (e.g. Jones, 2004). The latter case is seldom observed and investigated (Jones, 2004), but, even if rare, site with geothermal hot spots and groundwater outflows could be used as experimental sites to investigate how water content and temperature at the snow/soil interface may regulate the gliding. Most of the research have studied the glide processes in two different ways: a) investigating key parameters, such as water content, in the snow and at the snow/ground interface, often on rocky slopes characterized by conditions very similar to those where gliding avalanches usually occur (e.g. Clarke and McClung, 1999; Mitterer at al., 2011; Stimberis and Rubin, 2004) or b) investigating the link between avalanche release activity and meteorological parameters (e.g. Clarke and McClung, 1999; Peitzsch, E.H., et al., 2012; Simenhois and Birkeland, 2010). Some of those have directly

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* Corresponding author address: Ceaglio E., Fondazione Montagna Sicura - Montagne Sûre, Valle d'Aosta (I); tel: +39 (0)165 776852; fax: +39 (0)165 776813; email: eceaglio@fondms.org

investigated the avalanche release areas (e.g. in der Gand and Zupancic, 1966; Lackinger, 1987; Stimberis and Rubin, 2004; Wilson et al., 1996), but few works focused on the role played in the glide process by the soil properties. The aim of this study was to contribute to the comprehension of the glide processes, in particular: 1) to quantify the intensity of the snow movements in a gliding avalanche release area; 2) to investigate the relationship between the glide process and contributing factors, including physical properties of soil/snow interface and meteorological parameters.

2. MATERIALS AND METHODS

2.1. Study area

The study area, located in the Valle d'Aosta Region (NW-Italy), very close to the Mont Blanc Massif (4810 m asl), consists of an avalanche site called "Torrent des Marais - Mont de la Saxe", running on a west exposed slope, from 2115 m to 1250 m asl. The long-term yearly mean precipitation in the study area is 840 mm yr^{-1} (1995-2010) and the mean annual air temperature is +2.8 °C (1993-2010) (Source: UCF-VDA). The average cumulative annual snowfall is 275 cm at 1250 m asl (period 1937-1995) and about 450 cm at 2000 m asl (Mercalli, 2003). The avalanche release area is typically characterized by intense snow gliding and by the formation of a big glide crack, often leading to the release of a wet snow, full-depth slab avalanche (gliding avalanche), mainly during springtime and sometimes also in late autumn (Fig. 1).

Fig. 1: glide sequence in winter 2009.

The crack/avalanche crown width usually ranges between 30 m and 100 m, depending on the intensity of the glide processes. On the left flank of the crack a groundwater source is present. The slope is characterized by a mean steepness equal to 30°, covered by a pasture almost abandoned. The soils are frequently disturbed with the removal of the upper horizons, the consequent exposure of the subsoil, and many signs of old and recent erosion, mainly due the snow related processes, are present (Ceaglio et al. 2012). The bedrock is constituted mainly by black argillic schists, calcareous sandstones and, in some places, by porphyritic granites.

2.2. Data collection

General information about the winter season was obtained from the "Snow and Weather Reports" of "Winter 2009-2010" and "Winter 2010-2011", published by the Snow and Avalanche Warning Service of the Valle d'Aosta Region. Weather and snow data were provided by an automated weather station (2044 m asl, 8.5 km far from the avalanche release area) managed by the Ufficio Centro Funzionale (UCF) - Valle d'Aosta Region; the station has been active since 2002 and it's considered well representative for the area, especially for the snow depth at 2000 m asl. The parameters available from this automatic station were: air temperature (°C), snow depth (cm), rain (mm), and solar radiation (W m^{-2}).

In order to determine the physical properties of the snow cover, several snow profiles were described in the left side of the study area, in a safe area where the avalanche rarely releases. Moreover, from the observation network of avalanche forecasting, we chose a series of snow profiles carried out every week in a flat study plot (2114 m asl), 9.5 km far from the avalanche release area, that we considered representative of the snow conditions and physical properties of the study area. A typical snow profile, according to the AINEVA standards (Cagnati, 2003), included: total depth, temperature by depth and identification of layer boundaries, and, for each layer, hand hardness, grain types and mean size, water content and snow density.

In the starting zone a monitoring site was settled with snow glide shoes, located at the snow/soil interface and connected to potentiometers (Sommer®), as developed by ind der Gand (1954). The potentiometers were calibrated in order to convert the electric signals (V), emitted when the snow shoes glided, into downward movements (cmd^{-1}), caused by the snow gliding. Wires connecting shoes to the potentiometers were about 4.5 m long in the winter 2010 and about 20 m long in the winter 2011. Consequently the maximum snow gliding detectable for each winter was different. Two plots (A and B) were equipped with two glide shoes, called in this work A1-A2 and B1-B2 (Fig. 2). The B plot was closer to the groundwater source, on the left flank of the crack. Besides the glide shoes, temperature sensors (Campbell - 107 Temperature Probe) were placed at the bottom of the snowpack (Sn), at the snow-soil interface (I) and in the soil, at depth of 5 (S5) and 15 cm (S15). Moreover soil volumetric water content probes (Campbell-CS616 - Water Content Reflectometers) were placed in the soil at the same spots (S5 and S15) (Fig. 3). All sensors were connected to central dataloggers (Campbell-CR1000), which were located in a safe position outside the avalanche release area and supplied by long duration batteries and solar panels. The electric wires were cabled underground and reinforced with spikes and ropes in order to minimize the possibility to be torn off by the strong snow movement forces and by the potential release of an avalanche.

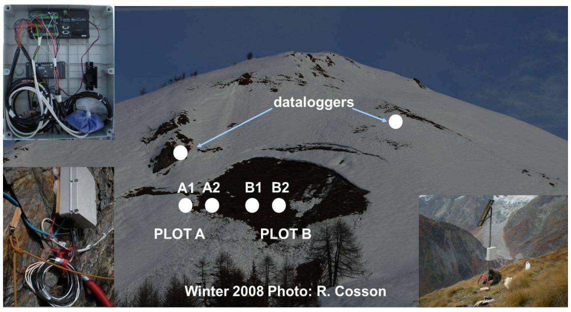

Fig. 2: monitoring site in the glide crack area (A1-A2 and B1-B2 points indicate the glide shoes).

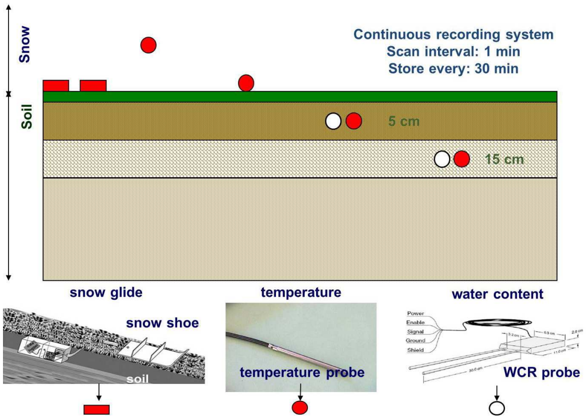

Fig 3: instruments placed in each plot (NB: water content probes in B were put only from 2011).

The data loggers were set to scan measures of different parameters every minute and to store the average value every half an hour. All the shown data are referred to the hydrological years 2009-2010 and 2010-2011; in both years, for simplicity often called in this work as winter 2010 and winter 2011, the time period considered was between November the 8th (0.00 am) and April the 30th (11.30 pm). Datasets were analyzed using the freeware software R.

3. RESULTS

3.1. Snow and weather condition

The winter season 2010 was characterized by a high frequency of weak snowfalls and long periods of low temperatures. Consequently a very complex snowpack layering was usually present, with prolonged unstable conditions. Winter 2011 started with heavy snowfalls since late October throughout November and December, which was the snowiest and coldest month of the season, while the following months were very dry, so that only in middle of March new snowfalls occurred. Generally, during the season, the snowpack was well to moderate bonded. In winter 2010 the cumulative value of fresh snow, at 2000 m asl, was in line with the average historical data; the same was found for snow depth and the number of days with snow on the ground. The air temperature, compared to the historical series, was lower from December to February and higher during springtime, starting from the middle of March (Segor, 2010). On the other side, in 2011, the seasonal cumulative value of fresh snow was lower than the historical value, while the average snow depth and number of days with snow on the ground was comparable with the historical values. The seasonal air temperature was higher than the historical data, especially during February and from the middle of March; only in December and in the first decade of January temperatures were lower than the reference values (Segor, 2011). The main differences between the two winters, in the study area, can be gathered from graphs in Fig. 4, where snow depth and air temperature from the automatic weather station are reported.

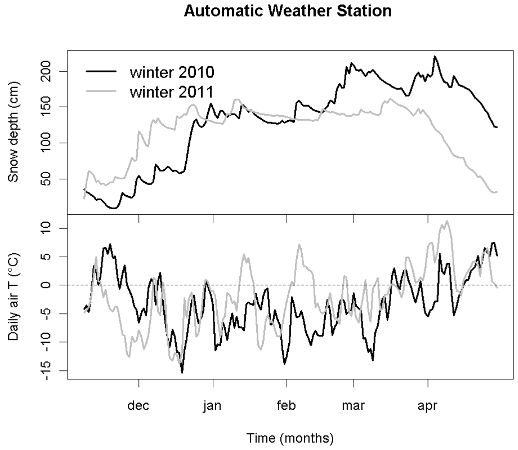

Fig. 4: snow depth and air temperature from the automatic weather station (2044 m asl).

From the analysis of the manual snow profiles (Table 1), in winter 2010, the mean snow depth resulted equal to 100 cm, with a maximum of 142 cm on March the 4th. The bottom snow layer (0-20 cm) reached isothermal conditions on April the 19th. In the first 20 cm of snow above the soil, facets were the main grain type before the onset of a destructive gradient, then rounded crystals were prevalent, and the snow density increased from 280 to 360 kgm^{-3}, with a maximum value of 420 kgm^{-3} reached on April the 2nd. Winter 2011 had an average snow depth equal to 80 cm, with a maximum of 100 cm recorded on January the 11th. The bottom snowpack layer (0-20 cm) reached isothermal conditions on March the 15th. Facets were the main grain type represented and the snow density increased from 280 kgm^{-3}, before the onset of a destructive gradient, to 330 kgm^{-3}, with a maximum value of 380 kgm^{-3} reached on April the 29th.

Noticeable Dates	**2009-10**		**2010-11**	
Snow pack temperature gradient <0.05 ℃ cm^{-1} (destructive metamorphism)	February, 18th		February, 15th	
Isothermal condition in the bottom layer (0-20 cm)	March, 19th		March, 15th	
Snow pack properties	**Before 18th Feb**	**After 18th Feb**	**Before 15th Feb**	**After 15th Feb**
Snow depth (cm)	103	99	79	81
*Grain type in the bottom layer (0-20 cm)	FCso	MFcl	FCso	FCso/xr
Mean grain size (mm) in the bottom layer (0-20 cm)	1.9	1.5	1.2	1.8
Hand hardness index in the bottom layer (0-20 cm)	2.5	3.0	2.5	3.0
Water content index in the bottom layer (0-20 cm)	1	2	1	1
Snow/soil interface temperature (℃)	0.0	0.0	0.0	0.0
Snow temperature at 10 cm above the ground (℃)	-0.3	-0.1	-0.4	-0.2
Snow temperature at 20 cm above the ground (℃)	-1.0	-0.3	-1.7	-0.4
Snow density (kgm^{-3}) in the bottom layer (0-20 cm)	280	360	270	330

Table 1: snow cover physical properties, mainly referred to the bottom layer (0-20 cm), detected from snow profiles of the study plots Morgex-Les Ors and Mont de la Saxe, during winter 2010 (n=19+4) and 2011 (n=16+2). Mean values, before and after the onset of a destructive metamorphism, are reported, except for grain types (categorical variables marked with an asterisk), whose modal values are shown. For grain type the new International classification for seasonal snow on the ground is used (Fierz et al.). Modified from Phillip and Schweizer (2007).

3.2. Temperature

In early winter 2010, with a snow depth lower than 50 cm, the influence of air temperature on soil and snow/soil interface temperatures (S5, S15, I), was higher in the A plot than in the B one.

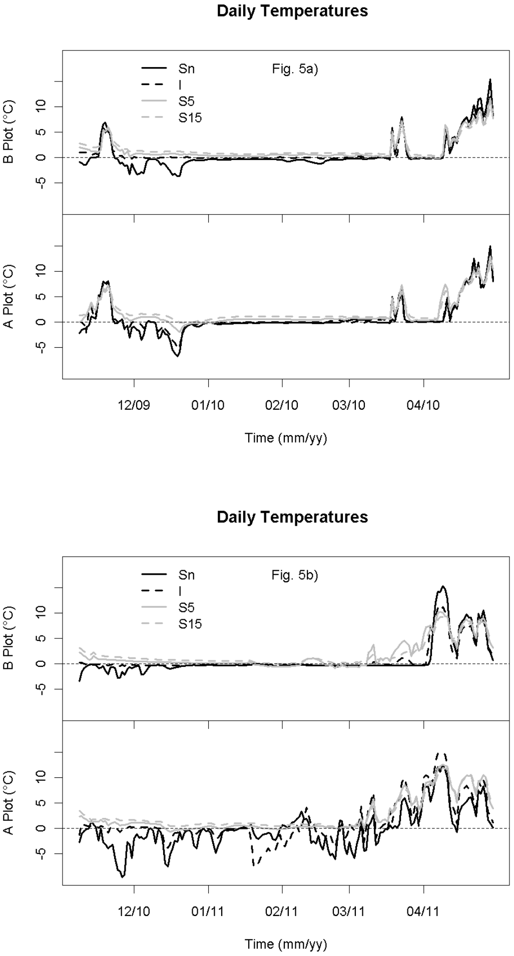

Fig. 5: winter 2010 (a) and 2011 (b) daily temperatures (Sn= snow, I=snow/soil interface, S5= soil at 5 cm depth, S15= soil at 15 cm depth).

After the onset of a consistent (> 1 m) snowpack in late December, the temperature recorded at the different depths, both in snow and soil, was close to 0℃ in both plots. A crack opening was observed in January, when consequently small temperature fluctuations were recorded first in B and then in A plot. On March the 19th temperatures showed two very sharp peaks, followed by a new settlement at 0℃, and later consistently raised (Fig. 5a).

At the beginning of winter 2011, characterized by lower air temperatures and more snow than in winter 2010, soil (S5, S15) and interface (I) temperatures were steadier to 0℃ than in winter 2010. During the whole season, in the A plot, Sn and I temperatures were continuously oscillating between positive and negative values, showing a significant correlation with the air temperature ($r=0.789$, $p<0.05$ and $r=0.597$, $p<0.05$, respectively). Since March, S5 and S15 temperatures, both in B and A plots, started to rise and on April the 5th, all temperatures showed a sharp increase towards positive values (Fig. 5b).

3.3. *Water content*

In winter 2010, water content values in S5 and S15 had similar trends during the season, with higher variability in S5. The amount of water at 5 cm was generally higher than at 15 cm. At the beginning of the season many peaks were registered, while from late December the VWC gradually increased, reaching two main peaks in February (VWC-S5=30%) and in March (VWC-S5=32%).

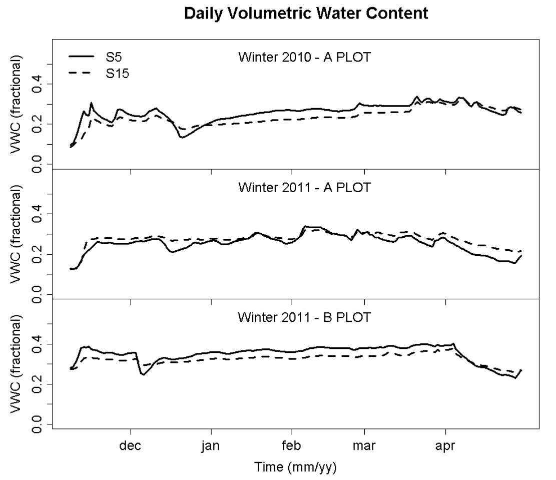

Fig. 6: water content in winter 2010 and 2011 (S5= soil at 5 cm depth, S15= soil at 15 cm depth).

In winter 2011, the A plot showed no clear trend, both in S5 and S15 and the maximum peak was reached on February the 6th, with a value equal to 34%. The B plot generally showed higher values of water content and less variability than the A plot. In B from December the VWC slowly increased up to 40%, value reached on April the 4th, and then quickly decreased (Fig. 6).

3.4. *Snow glide rates*

In winter 2010, thanks to field observations, a glide crack was monitored from the middle of January and a gliding avalanche occurred in the middle of March (Fig. 7). In the B plot, from middle of December, when the snowpack reached 100 cm, snow glide began to gradually and continuously increase until February the 14th, when the device reached the maximum cable extension (Fig. 9a). The total movement in B1 and B2 subplots until that time was equal to 460 cm and 446 cm, respectively. The two glide shoes moved with almost the same velocity: the mean daily rates were equal to 5 cmd^{-1} and 4 cmd^{-1}, and the maximum in both plots, was reached on February the 11th, with mean values equal to 19 cmd^{-1} and 20 cmd^{-1}.

Fig. 7: glide crack and avalanche during winter 2010.

In the A plot the gliding began later, in the second half of January, and the cumulative total movements, measured on March the 18th, were 461 cm (A1) and 466 cm (A2). On the same date a glide rate equal to 47 cm was registered in A1 between 3.35 pm (GMT) and 3.40 pm (GMT) reaching the maximum cable extension, while in A2 the maximum cable extension was already reached 1 hour before and therefore could not register this further movement. The snow glide in the A plot showed a mean daily rate of 3 cmd^{-1} and 4 cmd^{-1}, in A1 and A2 respectively; the maximum rate was detected on March the 18th, with 101 cm (A1), and on March the 2nd, with 47 cm (A2). In the B plot, considering only the period with active snow movement (until February the 14th), a significant correlation between glide rates and the volumetric water content in the soil at 5 cm was observed (B1: $r=0.45$, $p<0.05$, B2: $r=0.46$, $p<0.05$). However, focusing on the time period since December the 15th, when the snow depth exceeded 1 m and glide rates in B plot started to gradually increase, the correlation with the water content in the soil improved, both at 5 cm (B1: $r=0.80$, $p<0.05$, B2: $r=0.77$, $p<0.05$) and at 15 cm depth (B1: $r=0.81$, $p<0.05$, B2: $r=0.82$, $p<0.05$). In the A plot, during the time period from January the 13th, when the movement started, and March the 18th, the glide rate in A2 resulted significantly correlated with the soil water content at 5 cm ($r=0.57$, $p<0.05$) and at 15 cm ($r=0.55$, $p<0.05$) depth.

In winter 2011, after the heavy snowfalls of November and early December, on December the

6th a ground avalanche released without involving the monitoring site area: here, during the winter, a glide crack formed, visible at least since February the 3rd, but without the subsequent release of a gliding avalanche. On March the 23rd the snow cover was inconsistent on the study area and many patches of soil were already present: sensors in A plot came to surface, while the B plot was under 20-40 cm of snow (Fig. 8).

Fig. 8: glide crack and snow melt during winter 2011.

Thanks to the glide shoes cable length equal to 20 meters it was possible to measure the total snow gliding in both plots (Fig. 9b). In the B plot the total movement was equal to 773 cm (B1) and 1412 cm (B2). The A plot showed a lower movement than the B plots, with 227 cm of total gliding in A2 and no recorded movement in A1. The snow glide rate was equal to 4 cmd^{-1} and 8 cmd^{-1} in B1 and B2, respectively, and equal to 1 cmd^{-1} in A2. A first sharp increase in the snow gliding velocity was recorded between January the 16th and the 17th.The maximum rate was registered in B1 and it was equal to 42 cm in 30 min, between 3.30 and 4.00 pm (GMT) of January the 17th. After a long time period of almost no movements, in 30 hours the snowpack glided downward for 473 cm in B1 and 449 cm in B2. In A2 the movement started later on the afternoon of January the 17th, with 133 cm of gliding in 8 hours and the maximum velocity of 25 cm, registered in 30 min between 4.00 and 4.30 pm (GMT). On April the 4th, another very sharp increase of glide rates was recorded in the B plot (the A plot was already snow free), with 777 cm (B2) of gliding in 1 minute, at 01.59 pm (GMT), and 103 cm (B1) between 11.44 and 11.46 am. In winter 2011 no correlations were found between snow glide and the snow/soil parameters recorded.

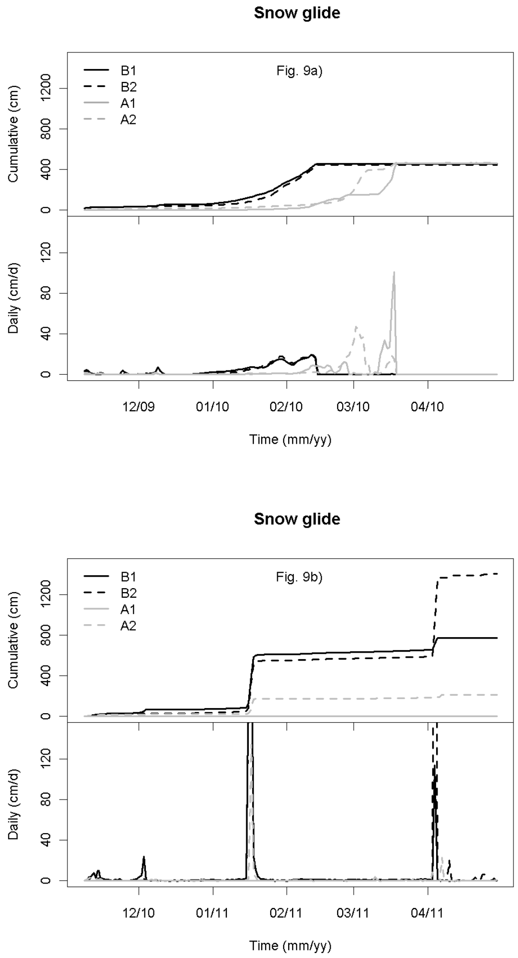

Fig. 9b: snow glide (daily and cumulative) in winter 2010 (a) and 2011 (b).

4. DISCUSSION

Winter 2010 was generally characterized by more snowfalls and lower air temperature than 2011. The snowpack was deeper (100 cm on average vs 80 cm on 2011) and denser. In winter 2011, the destructive temperature gradient and onset of the wetting front occurred earlier; however, temperatures at the bottom layer of the snowpack (10 and 20 cm), were generally lower. On average, the snowpack bottom remained dry with facets hardly shifting to melt forms. This was probably due to the thinner snow pack and to the shorter time of snowpack persistence. The onset of a low gradient in both years occurred in the middle February, but in 2011 the snow melt occurred 1 month earlier.

Temperature patterns in A and B were very similar in winter 2010, and the soil, except during the beginning of the season, was well insulated by the snowpack, which was thick enough (>100 cm). In contrast, in 2011, the A plot seemed to be less insulated by the snow cover compared to the B plot, and it was strongly influenced by the air temperature. The combination of a thinner snowpack in A and moister soil in B resulted in different seasonal patterns of soil temperature. The spring rise of temperatures may either indicate complete snowmelt or the input of warm air from the open cracks. The water content was generally higher in 2011 than in 2010 and was more irregular, without the clear increasing trend that can be seen in 2010.

The snow gliding in winter 2010 was very intense and sustained throughout the season, but movements in the two monitored plots behaved very differently, probably because of their different position in the crown of the forming glide crack and subsequent avalanche. The glide crack likely began from the B plot, then enlarging towards the A plot, so that the snow shoes in B were soon included in the movements with almost the same intensity, while the A subplots were only involved later in the spring. Consistent with this explanation, a clear difference was visible also between the two subplots A1 and A2, because A1 was closer to the right flank of the gliding slab. The gliding avalanche probably occurred on March the 18th at 03.40 pm GMT because, besides the increased glide velocity and the great rate registered in 1 minute, the subsequent sharp increase of soil temperatures, indicated that the soil became bare. The glide rates recorded during 2010, seemed to be highly related to the number of snowfalls and amounts of snow at the ground, but more analyses have to be done on the meteorological parameter.

In winter 2011, the two registered glide peaks correspond to periods of warm air temperature and high atmospheric pressure. Besides these episodes the winter was characterized by long time periods of almost no movements, probably related to the low amounts of snowfalls and to the thin snowpack. The snow shoes trend confirmed that the snow gliding usually starts from B and end or even never reached (like in this winter) the point A1. The sudden movement registered on April the 4th was probably indicative of the collapse of the last snow patch present in the B plot.

5. CONCLUSION

Very intense and sustained snow movements followed by the release of an avalanche in snowy and cold winter 2010 contrasted to episodic snow movement and the lack of an avalanche release in the less snowy and warmer winter 2011, indicating that meteorological patterns regulate soil properties such as temperature and moisture, which in turn drive the snow movements. The fact that glide rates were well correlated with the water content in the soil, corroborate this hypothesis, and confirm how the soil could be considered an extension of the snowpack, contributing to the snow movements. The soil water content could be considered as an indirect measurement of the amount of free water in the basal snow layer and at the snow/soil interface, generally quite difficult to detect. More efforts in this direction, trying to collect other significant cases of strong snow glide movements, should be done, in order to detect soil water content thresholds for snow gliding and avalanche release to occur. Moreover it would be interesting to investigate the potential contribution of the soil liquefaction processes and of a soft slushy soil film to the gliding mechanism.

ACKNOWLEDGMENTS

This project is carried out as part of Operational programme 'Italy - France (Alps - ALCOTRA)', Project “DynAval - Dynamique des avalanches: départ et interactions écoulement/obstacles”.

We would like to thank: Ufficio neve e valanghe (Regione Autonoma Valle d'Aosta – Assessorato opere pubbliche, difesa del suolo e edilizia residenziale pubblica – Dipartimento difesa del suolo e risorse idriche – Assetto idrogeologico dei bacini montani) and Fondazione Montagna Sicura, in particular Paola Dellavedova for her support; Ufficio centro funzionale (Regione Autonoma Valle d'Aosta – Assessorato opere pubbliche, difesa del suolo e edilizia residenziale pubblica – Dipartimento difesa del suolo e risorse idriche), in particular Fabio Brunier, for the meteorological data;

A special thanks to all the friends helping me in the instrumentation of the monitoring site, especially to Fabrizio Busa and Renzino Cosson for their great support.

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