Dear Editor,
In this PDF file I merge the following: 1) my response to the reviewers and 2) the changes in the revised version of the manuscript.

Response to C. Ancey

Dear Christophe, thanks for your suggestions..
We answer step by step in the following… the text is actually the comments which we have inserted directly in your PDF file through the comment tool. You find this file in the discussion.

- To answer to your question about the short period for monitoring the test sites... it was a founding issue. And actually also the delay in time was related to that and the involved persons. The research was planned within the MRRTeam project, but after that, unfortunately, we were not supported again for continuing the research.
  In fact, we think that longer monitoring would produce more data to deepen the research questions. Moreover, we think that a collaboration between researchers with test sites all over the mountains would produce results which consider all the different driving factors (vegetation included).

- Empirically, in a few ski resorts, the ground is drained, with a positive influence on gliding rates. This has been, for instance, attempted in Saint-François-Longchamp (Savoie, France), with success. → Interesting as managing practice... does exist a reference about this experience? I did not find anything on the web.

- We have tried to improve the English... if not good enough yet, we will pay a native speaker to improve it.

- Use of acronyms should be limited to standard abbreviations. → Ok, we now limit the use of acronymous, if not standard.

- Page 2: although liquid water is present in most documented cases of snow gliding, it happens sometimes that dry snow covers also glide. This has been, for instance, observed by Damien Margueritat in Chamonix/Le Brévent (Margueritat, D., Retour d'observations sur les plaques de reptation, Neige & Avalanches, 152, 18-22, 2016). → A dry snowpack can surely glide, but, to do that, liquid water should be present at its base. This is the definition of a cold event and I believe that to glide there should be liquid water at the snow soil interface... It was interesting to read the paper you suggested where you found two cases of gliding in case of cold snowpack until the base of the snow cover.
  I insert this citation in the Introduction...

- On the one hand, these adjectives are borrowed from common language (boiling water is warm, ice is cold), and scientifically they do not tell us much. On the other hand, snow gliding arises from multiple scenarios, and to a large extent is history dependent. I urge the authors to be more specific in their introduction. → FROM THE TYPICAL AVALANCHE PROBLEMS (EAWS, 2018): "...Glide snow avalanches can occur both with a cold dry snowpack and with a warm wet snowpack. ..." Other authors (Dreier et al., 2016; Clarke and McClung, 1999) speak about warm and cold-temperature events. Maybe the term "temperature" should always be written instead of using only warm and cold...... Fromm et al. (2018) divided into periods I and II, which indicate periods of rising and declining snowpack. We think it is interesting to check driving factors for those two scenarios.

- We've improved the figures, which we've changed also according to the suggestions of the other reviewer.

Response to anonymous reviewer #2

Many thanks for the very useful suggestions to improve our manuscript. I will answer point by point in the following for the major comments, while minor revisions are included in the revised version of the manuscript. The text is actually the comments which we have inserted directly in your PDF file through the comment tool. You find this file in the discussion.

Page2, line 11: We've inserted this reference.

Page2, line 26: Ok, we've produced a figure to show the position of the automatic and manual measuring stations for the snow and weather parameters. Doing so, we realized that the official name of D'Ejola is actually Gressoney-L.T.

Page2, line 28: We actually wrote "cumulative snowfall".... which, yes, it is the sum of new snow.

Page3, line 4: Ok, we've produced a figure to show the position of the automatic and manual measuring stations for the snow and weather parameters.

We consider these stations representative of the study site. Gabiet in particular is just on the opposite side of the valley at little higher altitude.

Weissmatten is 12 km south but, from previous analyses, we realized how the time evolution of the snow depth for our sites is similar to what measured at Weissmatten.

What probably is not clear from the previous version of the paper is that we had information about the conditions of the sites as we collaborated with the Director of the ski-run, who weekly, even daily sometimes, report us the conditions of the area.

This comment is valid also for the following remark (Page 3, line 6).

Page 3, line 7: We used the snow profiles made weekly at the official measuring site of the Regione Valle d'Aosta to obtain existing periodical data from already existing measuring sites. We think these data are useful to follow the seasonal evolution of the snowpack in the area. However, we also made ad-hoc snow profiles at the sites, especially after some specific gliding events.

We add a sentence regarding these specific snow profiles in the manuscript.

Page 3, line 11: We did not have in mind to use two glide shoes as replications. In fact, the glide shoes in the same test site behaved differently... we discuss this fact in the Results and Discussion section.

Our sites were not dedicated only to gliding (for which we would have used a higher number of glide shoes, according of course to the available budget, to make replications - as for example in some Austrian test sites) but aimed also at catching the glide avalanches, which can interfeer with both or only one glide shoe.

Page 3, line 14: Yes, thanks!

Actually we know this and in fact, parallel to this paper, we made a specific campaign to find a way to correlate the values measured by the WCR in the snow with values determined starting from snow density and Denoth equation. We forgot to mention this work. We add now a sentence to tell that we corrected the value registered by the probe placed in the basal snowpack layers following the corrections found by Godio et al (2018) during a specific experimental campaign performed in the vicinity of the manual measuring site Sant'Anna.

Page 3, line 20: Actually it was not clear from the text (that we have changed according to your suggestion) that we also went to the site for specific field work, for example in case of significant gliding events and for resetting the instrumentation.

In such occasions we made specific observations which helped us to choose the periods of anlayses.

Moreover, also the Director of the ski-run gave us information on the specific local conditions.

For example, after a glide avalanche, the site was free of snow therefore the time from the glide avalanche and the following snowfall was not considered in the analyses as the site were snow free.

Page 3, line 23: We went into the field to recover the glide shoes involved in the events and to replace them close to the potenziometer, which we also checked. We add a sentence at the end of the Data collection section.

Page 4, line 18: yes!

Page 4, line 23: You are right, better not to generalize.

We've changed the sentence and highlight better the event when this fact is clearly visible.

Page 4, line 30: we made it!

Page 4, line 38: we've add the missing reference.

Page 5, line 7: 1) Thanks. We have changed 24 to 21.

2) We've changed a bit the text to be clearer. We've actually not written that the site was free of snow. S2 was free of snow just after the event on November 21st or covered by little snow.

Page 5, line 10: See the previous comments about AWS and snow measuring sites.

This value come from the manual measuring site Lake Gabiet, which is representative of the site.

Also the Director told us it was snowing again.....

Page 5, line 22: You are right, the sentence is confusing. It is not a proper cooling but an impediment for the soil to warm up. We've changed the sentence.

Page 6, line 22: Yes, we have decided to merge Results and discussions.

We have asked the Editor, who also in the pre-discussion process told us to separate the sessions. But we made a version with separate sections which we liked less.... we think it comes natural to discuss already the results. In this way we also avoid repetitions. We've discussed with the Editor and finally he let us free to decide if merging or not.

Page 6, line 38: Yes, we know!

We've in fact cited that work in Ceaglio et al. (2016):

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."

But, it is true, we should do it also here. We've cited that work.

Concerning the Figures, we have changed them accordingly to all your suggestions.

Figures 4 – 7: The glide measurements indicate extraordinary values (about 2000 cm (20 m) in Fig. 4 and 5) and up to 15000 cm (150 m) in Fig. 6 and 7. I am wondering if such values can be measured with the Sommer-device, since the length of the wire is only 4 m in total. → Concerning the measuring device by Sommer, the latest version has a cable of 20 m! But MANY THANKS: in Fig. 6 and 7 there is a "0" too much......... the correct values were an order of magnitude lower. We corrected the graphs of the cumulative glide.

Figure 6: According to Fig.6 the liquid water content in the snowpack is approximately 20. → Yes, we realized that this value is much too high. However, the period in white is a period of no data anlyses, therefore these values did not affect our results.

I explain to you what happened...

After the event of November 2014, we could not reset the glide shoes due to unsafety conditions in both sites. Therefore, we also could not check the position of the WCR probe. Therefore such high values, close to values registered in the soil, might be explained by the fact that the WCR probe moved during the avalanche and finally was accidentally inserted in the soil.

Not to make confusion we could eventually cancel the data after the event on November 2014...

But, then, we should do that for all graphs....

I would leave as it is now, stressing the fact that white periods represent periods of no analyses when the recorded values at the two sites might be unrealistic.

We add a sentence about the unrealistic values from VLWC (and eventually other sensors) in periods of no analyses in the Data analysis section.

Table 1: THANKS! you are right!

In particular for the beginning of the seasons and in Fig. 7 for S2 for which the period of analyses continued also after the event in November 2014.

The number of data (N) are the number of the days when the analyses have been performed. As we analized daily rate N gives an indication of the data we could use in the analyses. N does not represent anything in term of snow gliding, it is not the number of the days when gliding was registered. We just wanted to give a number to show how much data we have for statistics.

Concerning the warm and cold periods in the figures and in the table: in the Table we can give more details as we can report the different periods for S1 and S2, while in the figure we've drawed an indication of warm and cold periods which cannot take into account this distinction... however we think it is useful as overview on warm and cold periods.

Snow gliding and glide snow avalanches: recent outcomes from two experimental test sites in Aosta Valley (NW Italian Alps)

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Abstract. Snow gliding and glide snow avalanches are gaining importance among scientists as global warming might induce conditions favourable to those phenomena. Our aim is to analyse such processes with a particular focus on the potential driving factors associated to the soil conditions. We equipped two experimental test sites in Aosta Valley Region (NW-Italy) with glide-snow shoes, temperature and volumetric liquid water content (VLWC) sensors in the soil and in the basal snowpack layer; snow and weather parameters were also collected by automatic weather stations and in manual snow measuring sites.

In the two monitoring seasons 2013-14 and 2014-15 we registered 9 glide snow avalanches: 2 cold and 7 warm-temperature events, which were characterized by different snow and soil conditions. In the only warm glide snow avalanche event, which presented a continuous gliding before, the daily glide rate showed a significant exponential relationship with the soil VLWC. We also found, though without a general trend, that gliding and non-gliding periods (either considering warm and cold periods separately or together) were characterized by significantly different predisposing factors.

This study contributes to assess the importance of soil VLWC, which seems to be one of the most important driving factors for gliding processes. Therefore, it supports the need, already suggested by other scientists, of analysing such processes with an interdisciplinary approach which integrates snow and soil sciences.

1 Introduction

Snow gliding processes have recently gained importance among scientists as climate change might influence the snow cover and the related processes, leading to a reduction of dry snowpacks and an increase of wet ones (Castebrunet et al., 2014). Already in the past, scientists have studied snow gliding and glide snow avalanches - see reviewing papers by Holler (2014) and Ancey (2015) - but current and future climate change might generate scenarios prone to such processes, therefore they are gaining again importance. In fact, raise of the air temperature and of the snowfall limit (Hartman et al., 2013) may influence the snow cover, which might become denser and wetter, also due to more frequent rain on snow events, in particular close to 2000 m asl (Morán-Tejeda et al., 2018).

A deep knowledge of the most important driving factors of such phenomena deserves attention, in order to be able to eventually predict and manage them in the optimum way. Already In der Gand and Zupancic (1966) states that snow gliding occurs on a smooth ground surface, a lowermost layer of wet snow and a temperature at the snow-ground surface of 0 °C. Based on different driving factors, some scientists elaborated models to predict snow gliding distances (e.g. Leitinger et al., 2008) or to identify areas prone to snow gliding (e.g. Maggioni et al., 2016).

The approach commonly used for studying snow gliding and glide snow avalanches starts from the distinction between cold and warm temperature events (Clarke and McClung, 1999). This distinction is based on 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 water suction from the soil; 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. However, Margueritat (2016) recently registered cases of snow gliding in winter time (cold-temperature events) without a basal layer of wet ground grains, but in certain cases with a basal layer made of faceted particles.

The most recent studies by Ceaglio et al. (2017) and Fromm et al. (2018) underline the importance of soil moisture as a driving factor for snow gliding. In particular, Ceaglio et al. (2017) found a strong relation between glide snow rate and moisture at the snow-soil interface for cold temperature events, with a possible contribution also of soil liquefaction, while Fromm et al. (2018) found that soil moisture and temperature had a significant influence on snow gliding in both warm and cold periods.

As in Ceaglio et al. (2017) and Fromm et al. (2018), this work, using an experimental approach, starts from data gathered in two test sites and aim at giving a contribution to the on-going scientific discussion on the most important driving factors for snow gliding and glide snow avalanches. Our goal is to quantify the linkages between soil water content and snow gliding processes and to assess the factors predisposing the glide avalanche release, under different meteorological and snowpack conditions (warm vs cold events).

2 Data and methods

2.1 Study area

The study area is located within the MonterosaSki resort in the NE of the Aosta Valley Region (NW Italian Alps), in the Mont Rose Massif, close to the LTER site Istituto Mosso (https://deims.org/17210eba-d832-4759-89fa-9ff127cbdf6e). From the data taken at the weather station Gressoney-L.T. (1837 m asl), which has the longest time series among the different weather stations present in the area (Fig. 1a), the long-term mean precipitation (including the snow water equivalent) is 1111 mm yr^{-1} (years 1927-2017), the mean annual air temperature is 4.2 °C (years 1971-2017) and the average cumulative snowfall is 398 cm (years 1981-2010).

Two test sites were equipped in the study area for measuring snow gliding and snow and soil properties (Fig. 1b). The site “Pista Nera” is a slope at about 2230 m asl with an average inclination of 40° with an ESE aspect. The soil is classified as Cambisol and is characterized by a Liquid Limit (LL) in the topsoil (0-10 cm depth) and in the underlying soil horizon (10-20 cm depth) equal to 53 % and 47 %, respectively. The slope is covered by a mountain grassland (*Festuca scabriculmis*) with sparsely low dwarf shrubs (*Juniperus nana*, *Calluna vulgaris* and *Rhododendron ferrugineus*). The site “Sant’Anna” is a slope at about 2120 m asl with an average inclination of 36° with an E aspect. The soil is classified as Regosol, with a Liquid Limit of 84 % and 76 % in the topsoil and in the underlying soil horizon, respectively. The dominant plant species are *Festuca rubra s.l.* and *Agrostis tenuis*. The glide snow avalanches releasing from the "Pista Nera" site can reach the ski run below (Fig. 1b and 2) and therefore needs a careful monitoring.

2.2 Data collection

The data were collected during the hydrological years 2013-2014 and 2014-2015. Snow and meteorological parameters (snow depth, precipitation, air temperature, wind speed and direction) were provided by the automatic weather station (AWS) "Gressoney-S.J. – Weissmatten", which is operational since 2002 and placed 12 km further south from the study site at 2038 m asl (Fig. 1a). The new snow amount in 24h was gathered from the manual snow measuring site "Gressoney-L.T. – Lake Gabiet" (2370 m asl) 4 km east from the study sites (Fig. 1a).

To describe the physical properties of the snowpack, we used the weekly snow profiles made at the manual snow measuring site Sant'Anna, very close (less than 1 km) to the study sites (Fig. 1a), by the *Corpo Forestale Valdostano* (Forestry Office). Moreover, after specific gliding events, we performed ad-hoc snow surveys at the study sites. Observations were performed according to Fierz et al. (2009).

In the two test sites, instrumentation was installed for measuring snow gliding and snow and soil properties (Fig. 3). In each test site, two glide-snow shoes, connected to potentiometers (Sommer®), were placed within the area where glide-cracks were observed in the past. 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 in the basal layer of the snowpack and at two different soil depths (5 cm and 15 cm). The scheme of the instrumental set-up for both sites is given in Fig. 3. Moreover, a web-cam was continuously monitoring the possible glide cracks formation and evolution in the "Pista Nera" site.

The Responsible of the ski-area security monitored the specific conditions at the study sites: for ex., when a glide avalanche occurred, he informed us in order that we could record the characteristics of the event and reset the instrumentation. The reset of the instrumentation consisted in the check of the positions of the temperature sensors and the WCR probes and, when possible in term of safety standards, in the repositioning of the glide shoes involved in the avalanche.

2.3 Data analysis

During the two monitoring seasons, we selected different periods for the analyses of the data registered by each single glide shoe in the two test sites (Tab. 1). In fact, the four glide shoes showed different patterns (see later in section 3). Moreover, the periods for the analyses were also chosen according to the specific snow conditions observed at the sites, which influenced the significance of the registered temperature and volumetric liquid content (VLWC) parameters. For example, after a glide avalanche event, identified as a large sudden glide shoe movement and/or from field survey, the instrumentation was reset but the site remained with no snow until the next snowfall, therefore this period could not be considered for analysis. In periods of no analyses the data registered by the WCR probe in the basal snowpack layer might show unrealistic values.

We considered daily values, which were obtained by averaging the 30 minutes 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.

As WCR probes were mainly designed to measure volumetric liquid water content in soils, we were able to transform the values recorded by the instrument place in the basal snowpack layer following the corrections found by Godio et al. (2018) during an experimental campaign made in the vicinity of the manual measuring site of Sant'Anna.

We performed statistical analyses to investigate the difference between cold and warm gliding events in terms of driving factors (snow and soil temperature and VLWC, air temperature, snow height, new snow in 24h). We assume that the distinction between a cold and a warm temperature event is related to the origin of the liquid water at the snow-soil interface as in Ceaglio et al. (2017).

Concerning glide-snow avalanche events, we explore possible differences between driving factors measured at the moment of the events (semi-hourly data) for warm and cold events, applying the Wilcoxon-Mann-Whitney test.

We executed 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^{-1} for at least one glide shoe) and periods of no gliding. Initially, we considered the whole dataset at once and then we classified into cold- and warm-temperature periods in the two test sites, in order to investigate the potential differences in the driving factors.

We also checked potential relationships between glide rate and soil VLWC.

Beside the above mentioned quantitative analyses, we also made a qualitative description of the two monitoring seasons, trying to explain some patterns found in the registered values for specific days.

3 Results and discussion

Predisposing factor for glide avalanche events

Figures 4-7 report the pattern of the registered variables along the two monitoring seasons in the two test sites. In total, we registered 9 glide snow avalanches. Other events occurred during the first season, but were only observed through field surveys without measurements by the glide-snow shoes. Among the measured events, 2 have been classified as cold events and 7 as warm events (among which 1 was related to a rain-on-snow episode). Often the events occurred suddenly without an appreciable snow gliding before.

The two cold glide-snow avalanche events were recorded in late fall 2013 in both sites, while the warm events were recorded both in fall and spring. In literature (e.g. Dreier et al., 2016), cold events were usually associated to the beginning of the winter season, while warm ones only to the end. But the beginning of season 2014-15 was meteorologically an exception. In fact, November 2014 was the second warmest (air temperature 3.1 °C above the average) and the rainiest (378 % more than the average) November of the previous 57 years in NW Italian Regions (ARPAP, 2015). The conditions were not typically winter; the first available snow profile (December 17th) described a wet snowpack with melt forms in the basal layer. We classified the registered gliding events occurred in November 2014 as warm; on November 30th a glide avalanche due to a rain-on-snow (ROS) event occurred. For such events soil VLWC was around 35 % in "Sant'Anna", while in "Pista Nera" it started around 15 % (November 5th) and raised up to 22 % on November 30th. The soil was not frozen in both sites. In comparison to 2013-14 the soil showed the same values of VLWC in “Sant’Anna”, while in “Pista Nera” the soil was wetter in November 2014 than in November 2013. Soil in “Sant’Anna” was in general wetter than in “Pista Nera” in both seasons.

Analysing the patterns of air temperature and snow height, we could appreciate the fact that the warm temperature events often occurred after a snowfall followed by an increase in air temperature, resulting in a decrease in the snow depth. This clearly occurred for the event in March 2014 in “Pista Nera” (Fig. 4). For warm events this might describe the situation in which snow melting occurred at the snow surface with percolating water through the snowpack down to the snow-soil interface with a lowering of the basal friction. The same occurred for the cold events in November 2013 at both sites, but with a less sharp decrease in the snow depth.

Comparing “Sant’Anna” and “Pista Nera” after the first snowfall at the end of November 2013, it is interesting to notice how this snowfall caused a snow gliding phenomenon in “Pista Nera” site earlier than in “Sant’Anna”. In “Pista Nera” a glide avalanche occurred on the 21st, while in “Sant’Anna” on the 24th. From the analysis of the collected data, soil temperature in “Pista Nera” (2.9 °C) was 1 °C warmer than in “Sant’Anna” (1.8 °C), while soil moisture was about the half in “Pista Nera” (19 %) than in “Sant’Anna” (35 %). Probably, the reason of the earlier movement in “Pista Nera” than in “Sant’Anna” lies in the average inclination of the sites, which is 40° for “Pista Nera” and 36° for “Sant’Anna”, and in the vegetation characteristics. Vegetation in “Pista Nera” is more favourable than that in “Sant’Anna” to gliding: though the presence of sparse lignified shrubs, “Pista Nera” presents longer grass, not grazed, while “Sant’Anna” is usually grazed by dairy cows. The differences in inclination and vegetation between the sites might also explain why in March 2014 the combination of a snowfall followed by an increase in air temperature produced a glide avalanche only in “Pista Nera” and not in “Sant’Anna”. However, despite some differences between the two sites, their characteristics make them to belong both to classes which present a low basal friction, favourable to snow gliding (Feistl et al., 2014).

The complexity of the experimental test sites, with couples of glide shoes which behaved differently, could gave us the possibility of trying to explain some differences between the glide shoes.

For example, at the beginning of season 2013-14, in “Pista Nera” a glide avalanche occurred on November 21st involving glide shoe S2 in its movement (Fig. 4). This avalanche occurred after the first consistent snowfall of more than 1 m of new snow (Fig. 4). After this first event, no snowfall occurred until December 19th when 30 cm of new snow fell again. Glide shoe S2, which was reset on November 27th, did not move anymore until the last small and fast movement in April 2014. The data of soil temperature and moisture showed that the soil remained frozen until January 14th. The instruments were closer to S2 than S1, representing then the situation of no (or little, i.e. 30 cm from the snowfall on December 19th) snow at ground between the event on November 21st (which denudated the soil) and January 14th. Therefore, after the event on November 21st, S2 did not move because one of the necessary conditions for gliding was not present (snow-soil interface at 0 °C). Instead S1, which was not involved in the glide avalanche of November 21th, remained below 1 m of snow plus 30 cm from the snowfall on December 19th, when it started moving again continuously. At the location of S1 the snow at ground was more than 1 m and possibly the soil was not frozen, favouring a continuous and gradual snow gliding, as registered by S1.

A simple descriptive statistics of the variables registered at the moment of the glide avalanche events (box-plots in Fig. 8) showed that the cold glide snow avalanche events were characterized, in average, by: i) a slightly higher soil VLWC (26.9 % and 25.3 %) than in case of warm events (25.6 % and 24.9 %) at 5 cm and 15 cm depths, respectively; ii) a lower VLWC (0.6 %) in the snowpack basal layer than in case of warm events (2.5 %); iii) a slightly higher soil temperature at 5 and 15 cm depths (difference of 0.1 and 0.3 °C respectively) than in case of warm events. Though it seems that there exist some little differences between the predisposing factors registered at the moment of the cold and warm glide-snow avalanche events, the differences are not statistically significant (Wilcoxon-Mann-Whitney test). The fact that in cold event, registered at the beginning of the season, soil temperatures were higher than in warm events, might be explained by the heat stored by the soil during the Summer; while for the warm events in late spring the longer presence of the snowpack did not allow the soil to warm up and soil temperatures remained lower. Minor VLWC values in the basal snowpack layer during cold events represent the fact that the snow cover was cold, being formed by the first probably cold and dry snowfalls, while in spring the VLWC of the basal layer of the snow cover is the result of percolating water from above layers (the available water is more than that of cold snowpack at the beginning of the season). For the warm events at the beginning of season 2014-15, the VLWC in the snow was related to the melting of the first snowfalls occurred in November with warm air temperature (see Fig. 6 and 7).

Gliding vs non-gliding periods

In "Sant'Anna" and "Pista Nera" the differences between gliding and non-gliding periods in terms of the measured parameters (Tab. 2 and 3) were highly significant when considering the whole dataset together, while in "Pista Nera" significant differences were found only in cold periods and in "Sant'Anna" only in warm periods. Some differences could be reasonably explained with what we think the snow gliding process is, also according to existing literature (e.g. Höller, 2014 and Ancey, 2015), while others are difficult to understand. For example, in "Pista Nera" the VLWC in the snow was significantly higher for gliding than for non-gliding period when considering the whole dataset or cold periods. This was also found by Fromm et al. (2018) and Ceaglio et al. (2017). Instead, in "Sant'Anna" there was no difference in the VLWC of snow during cold periods; a little significant difference was found in warm periods, but the VLWC of snow was higher in non-gliding than in gliding periods, revealing how other predisposing factors could contribute to the snow gliding process.

The multivariate CART analyses produced results, for the whole data set or dividing warm and cold periods, which show how different variables (e.g. air temperature, soil temperature and VLWC) appear in the decision process (splitting nodes) but without a general trend.

Predisposing factors for snow gliding

In "Pista Nera" for the warm gliding periods at the end of the season, the daily glide rate showed a significant ($p < 0.001$) exponential relationship with the soil VLWC at both depths (Fig. 9). Conversely, we did not find any relationship between the glide rate and the soil VLWC in the continuous cold gliding period in "Pista Nera", as we have recently found in another experimental test site in the same region (Ceaglio et al., 2017). The difference between those findings and the results presented here might be related also to the soil properties of the two different test sites, in particular to the Atterberg Liquid Limits. The Atterberg Liquid Limits (LL) represent the soil moisture content value determining the transition from the plastic to the liquid state (LL) (Lal and Shukla, 2004; Stanchi et al., 2012). The LL for the deeper soil horizon (10-20 cm depth) in the site of Mt de La Saxe (in Ceaglio et al., 2017) was around 48–67 %, and the registered soil VLWC was around 50 %. In "Pista Nera" (where we registered a cold gliding period in 2013-14 which did not show any relationship between the glide rate and the VLWC) the LL was 53 % (topsoil) and 47 % (underlying horizon), values never measured by the WCR sensors (Fig. 4). In Mt de La Saxe soil liquefaction was possible (and actually observed on field), while in "Pista Nera" not at all. Therefore, in Mt de La Saxe a further driving factor for snow gliding in cold periods might have been soil liquefaction, which did not occur in "Pista Nera" in 2014.

For "Sant'Anna" we did not found any relationship between the daily glide rate and the soil VLWC for the identified both warm and cold periods.

4 Conclusions

In this study, through a 2 years field campaign, we analysed the predisposing factors for snow gliding and glide snow avalanches.

From the data registered in two monitoring seasons at two experimental test sites in Aosta Valley, even if the differences are not significant, we found that cold glide-snow avalanche events occurred with a higher VLWC in the soil and a lower VLWC in the basal snowpack layer than in warm events.

Significant differences were instead found between the predisposing factors during gliding and non-gliding periods, considering the whole dataset together or dividing cold and warm gliding periods. However, no general trend during cold or warm periods was found in the two test sites.

Our analysis on the potential driving factors for gliding processes underlined the importance of soil VLWC, in particular for warm glide events. Though we could not find a clear and generalizable trend, the example of the warm gliding periods in 2014 in the site Pista Nera shows how the glide-snow rate increased exponentially to the VLWC in the soil.

In conclusion, among the parameters considered in this study, which sometimes showed contrasting effects, our findings contribute to assess the importance of soil water content in snow gliding processes. Therefore, this result supports the need, already suggested by other scientists (e.g. Höller, 2014), of analysing such processes with an interdisciplinary approach which integrates snow and soil science.

An effort which should be done by scientists would be to share all the data collected in the different experimental test sites, in order to create a common rich database and to be able to analyse the driving factors for snow gliding processes, including also site characteristics. Doing so, the results obtained in the different test sites might be generalized.

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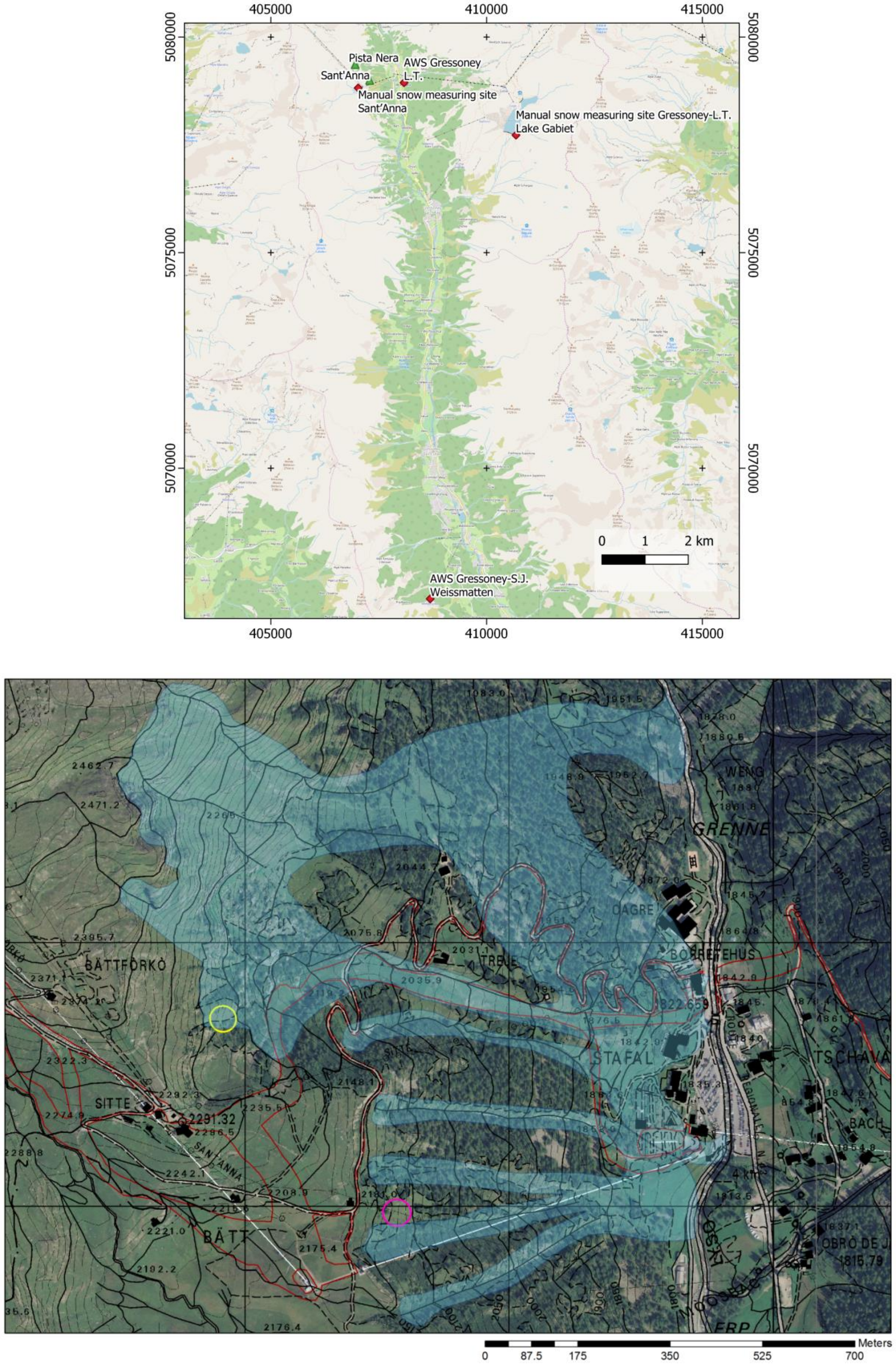


Figure 1: (a) Location of the two test sites (green triangles), the automatic weather stations and the manual snow measuring sites (red diamonds). (b) Location of the two test sites "Pista Nera" and "Sant'Anna", shown with the yellow and pink circles (in red the ski runs of the MonterosaSki resort are reported, while the light blue polygons represent the perimeter of the maximum avalanche events registered in the Avalanche Cadastre of the Aosta Valley Region).

Figure 2: Winter view of the study area: in the circles the location of the two test sites "Pista Nera" (PN) and "Sant'Anna" (SA).

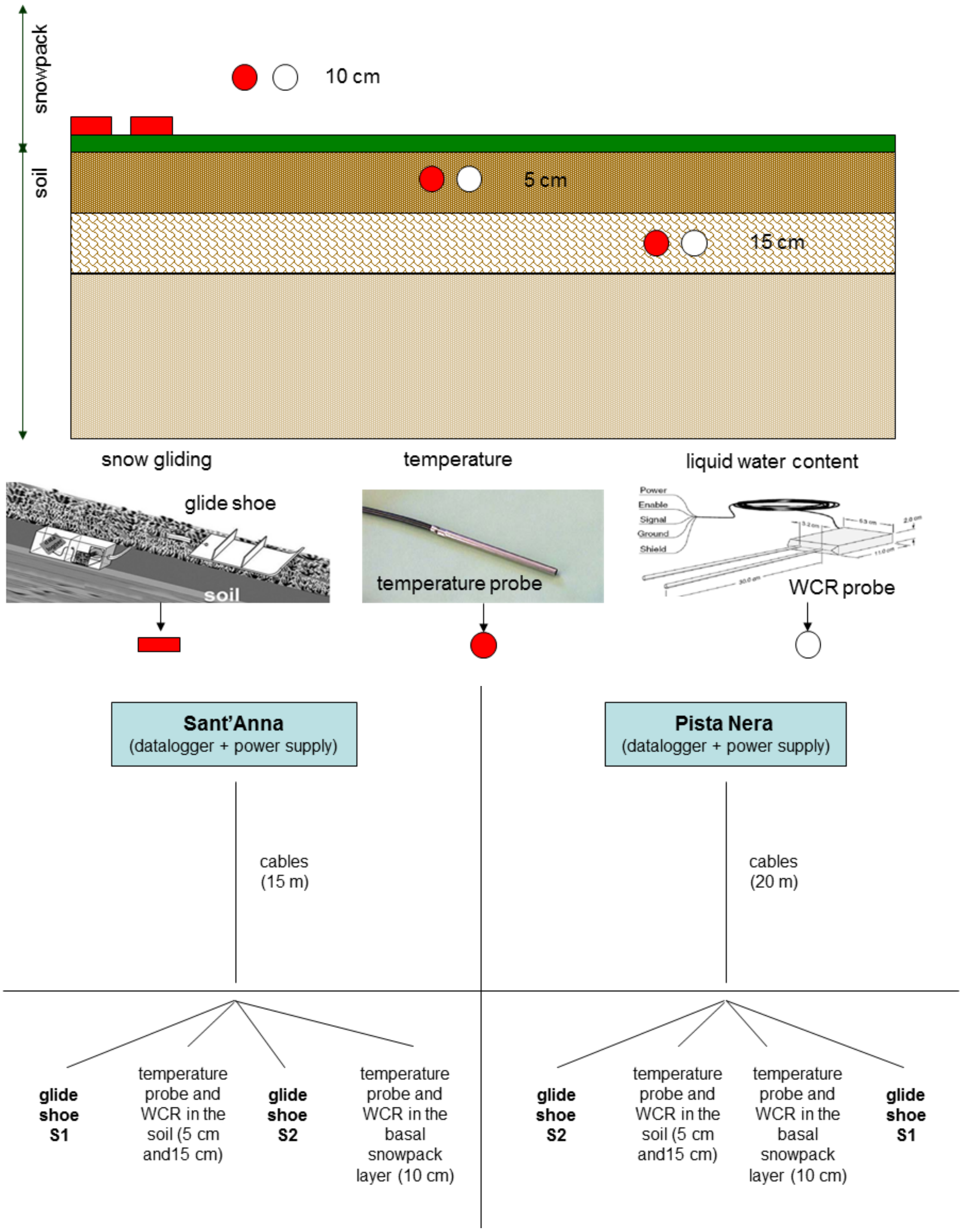


Figure 3: Set-up of the experimental test sites.

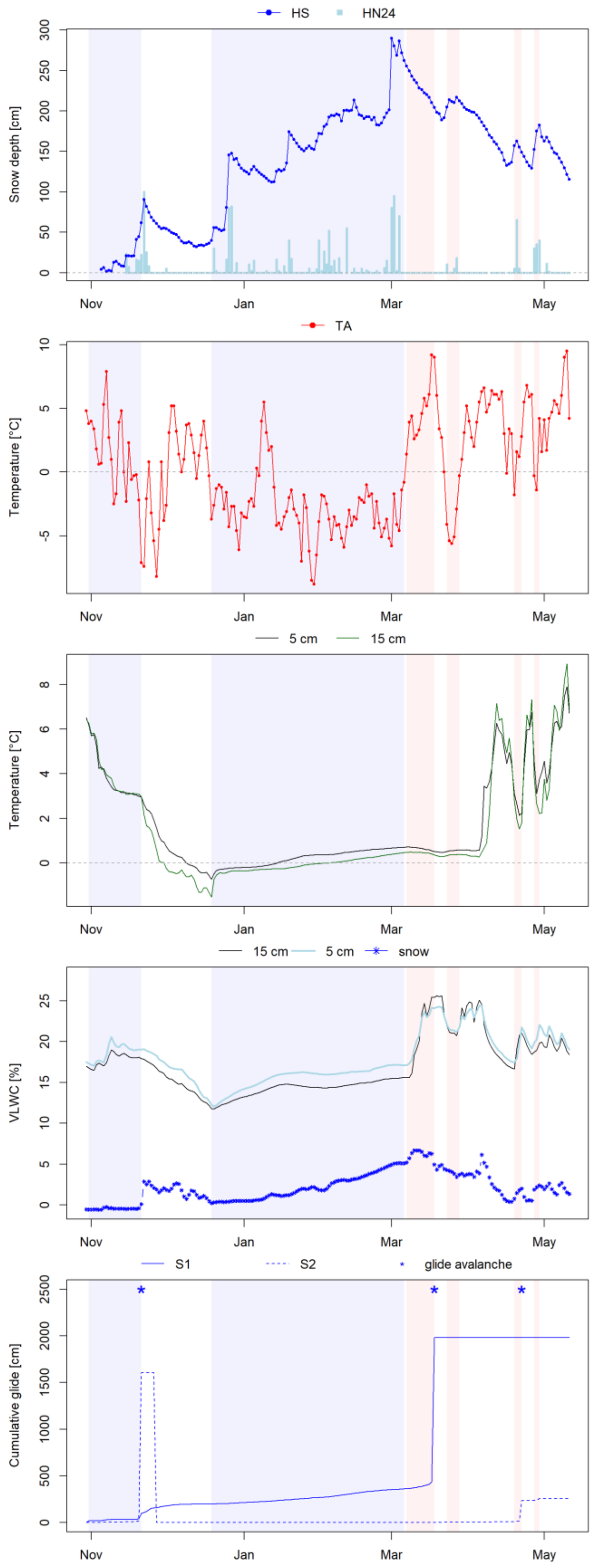


Figure 4: Site "Pista Nera", winter season 2013–2014: (a) Snow depth (HS) from AWS Weissmatten and new snow sum (HN24) from manual snow measuring site Gabiet; (b) air temperature (TA) from AWS Weissmatten; (c) soil temperature; (d) VLWC measured within the soil and in the basal snowpack layer; (e) cumulative glide. Warm and cold periods are highlighted in orange and blue, respectively; periods reported in white are periods of no data analyses for either S1, S2 or both (see Table 1 for details).

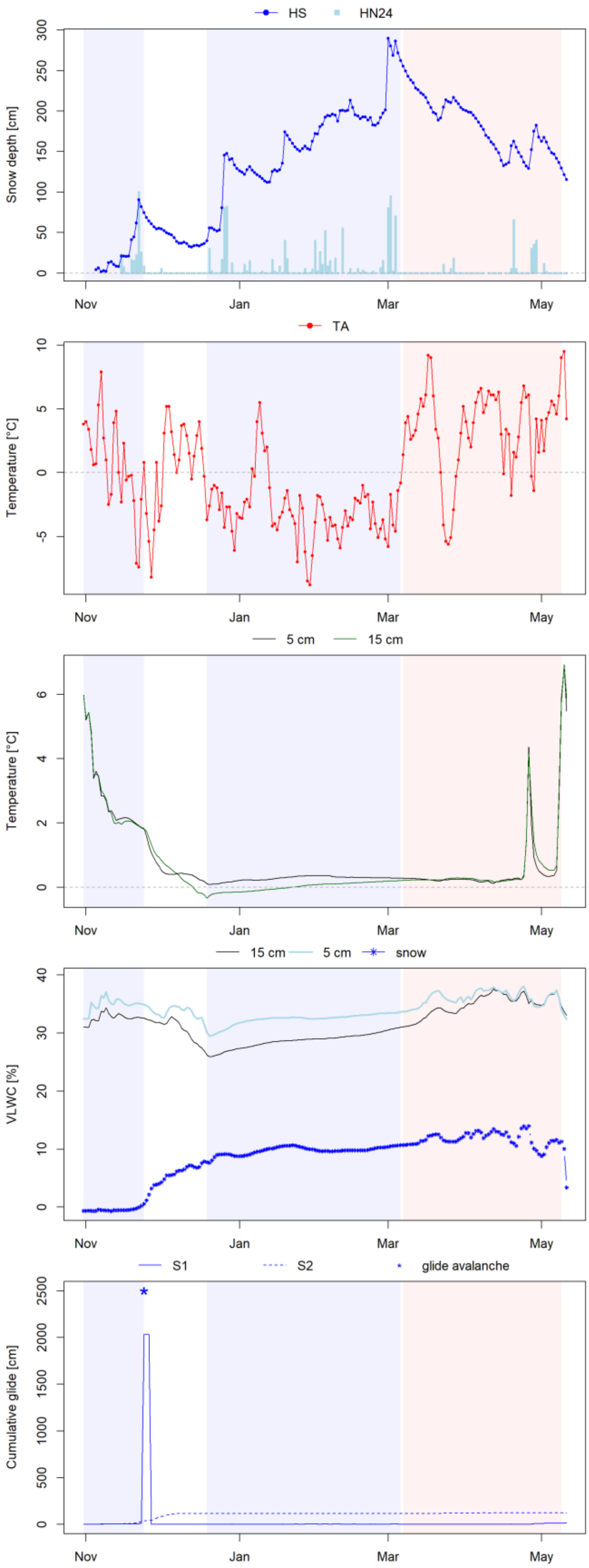


Figure 5: Site "Sant'Anna", winter season 2013–2014: (a) Snow depth (HS) from AWS Weissmatten and new snow sum (HN24) from manual snow measuring site Gabiet; (b) air temperature (TA) from AWS Weissmatten; (c) soil temperature; (d) VLWC measured within the soil and in the basal snowpack layer; (e) cumulative glide. Warm and cold periods are highlighted in orange and blue, respectively; periods reported in white are periods of no data analyse for either S1, S2 or both (see Table 1 for details).

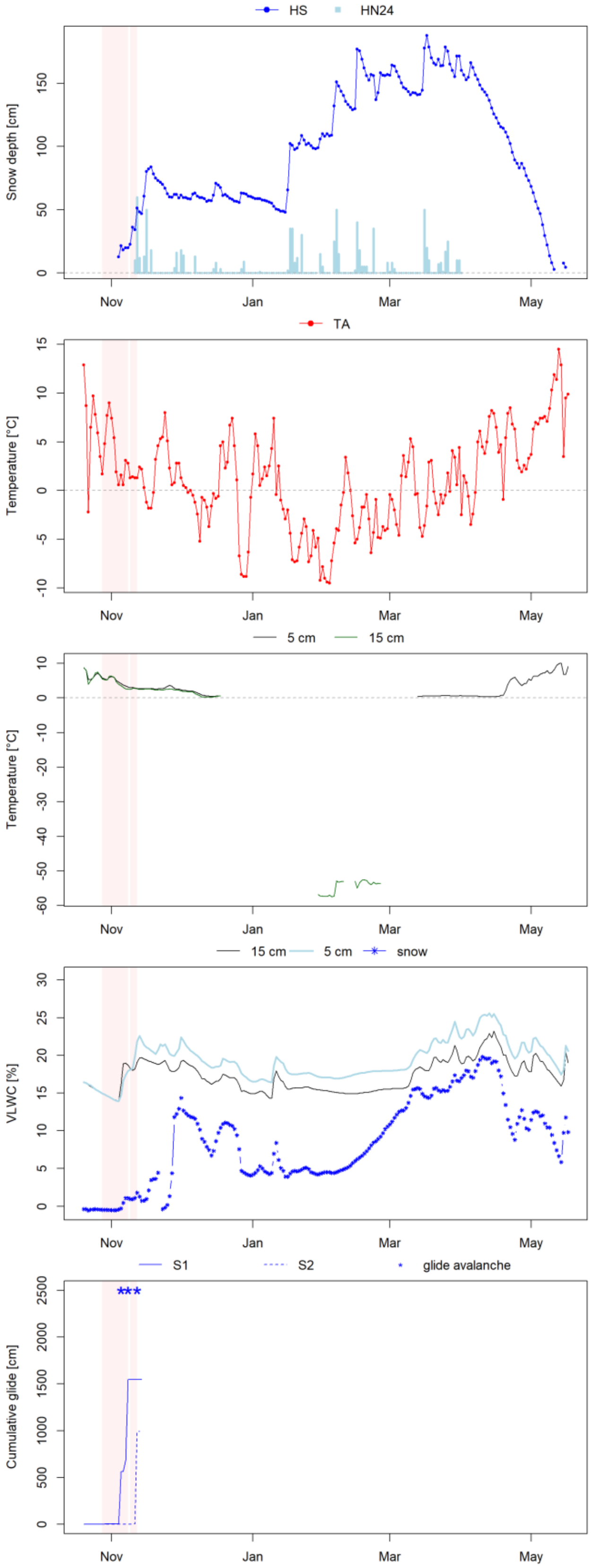


Figure 6: Site "Pista Nera", winter season 2014–2015: (a) Snow depth (HS) from AWS Weissmatten and new snow sum (HN24) from manual snow measuring site Gabiet; (b) air temperature (TA) from AWS Weissmatten; (c) soil temperature; (d) VLWC measured within the soil and in the basal snowpack layer; (e) cumulative glide. Warm and cold periods are highlighted in orange and blue, respectively; periods reported in white are periods of no data analyses for either S1, S2 or both (see Table 1 for details) (the period 9-12.11.2014 is no analyses for S1).

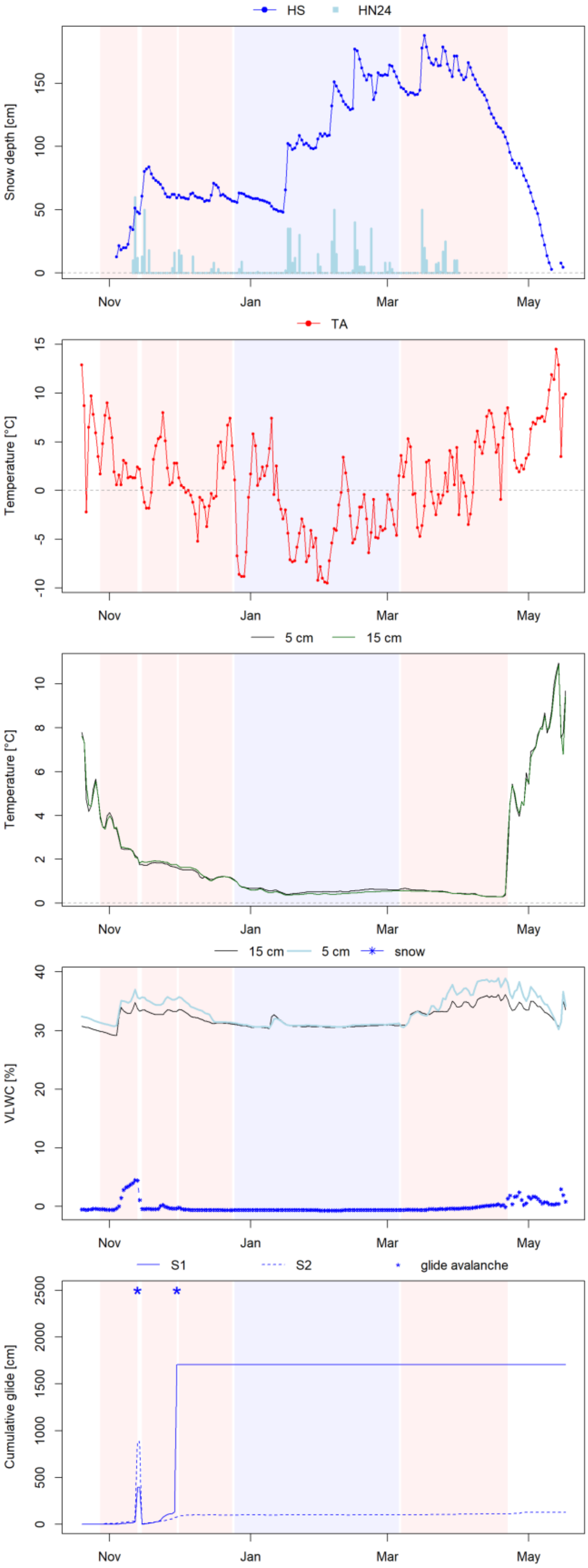


Figure 7: Site "Sant'Anna", winter season 2014–2015: (a) Snow depth (HS) from AWS Weissmatten and new snow sum (HN24) from manual snow measuring site Gabiet; (b) air temperature (TA) from AWS Weissmatten; (c) soil temperature; (d) VLWC measured within the soil and in the basal snowpack layer; (e) cumulative glide. Warm and cold periods are highlighted in orange and blue, respectively; periods reported in white are periods of no data analyses for either S1, S2 or both (see Table 1 for details) (from 1.12.2014 to the end of the season no analyses for S1).

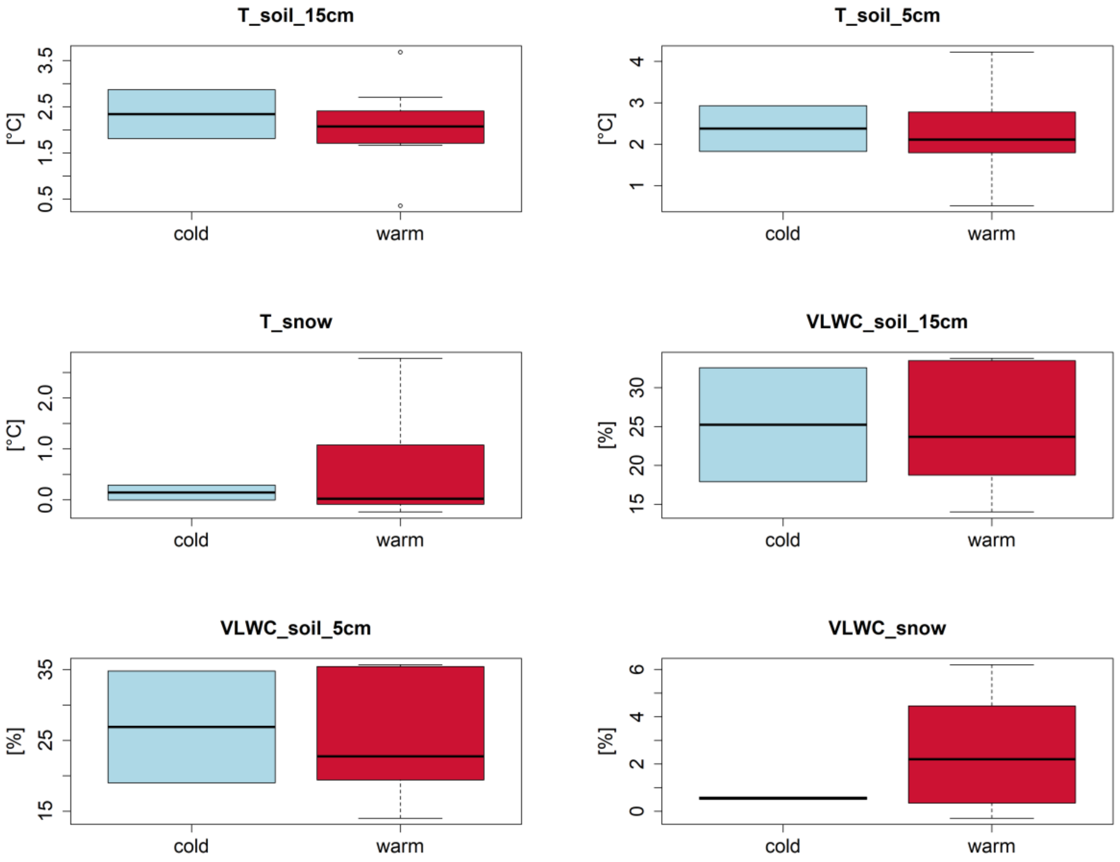
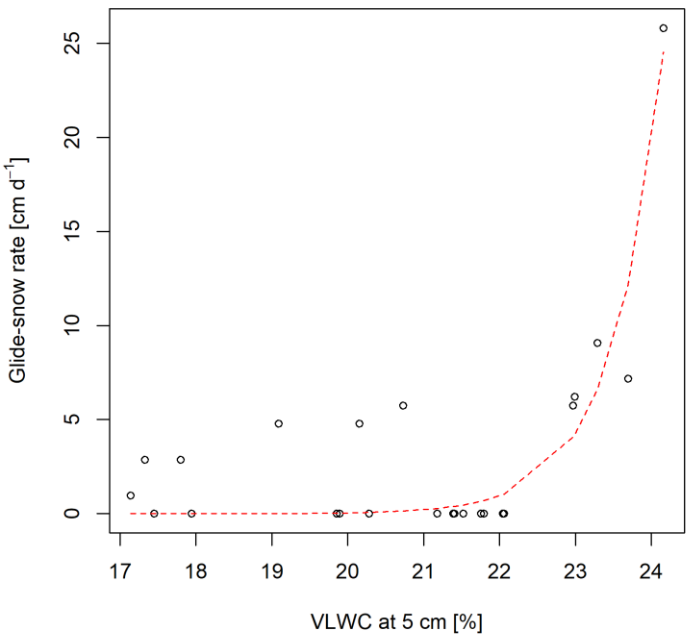


Figure 8: Boxplots of the parameters registered at the moment of the cold and warm glide snow avalanche events (values registered 30 min before the events).



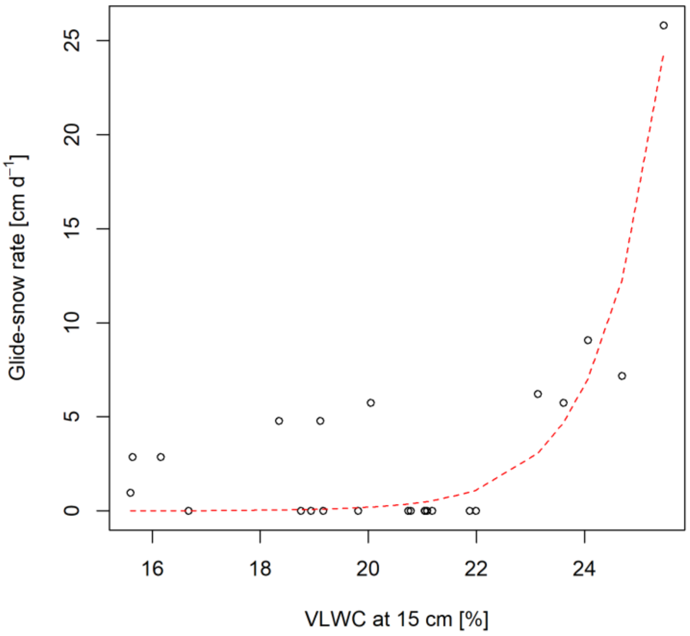


Figure 9: Fitting model between daily glide-snow rates for S1 and volumetric liquid water content (VLWC) measured in Pista Nera at 5 cm (left) and 15 cm (right) soil depths during the warm-temperature events of season 2014.

Table 1. Periods of analyses for each single glide shoe in the two test sites during the two monitoring seasons. Dates are in day/month/year; N indicates the number of data in the corresponding period.

Period	Glide-snow shoe	Cold/warm	N
PISTA NERA			
31/10 – 21/11/2013	S1 and S2	cold	22
19/12/2013 – 6/03/2014	S1 and S2	cold	78
7 – 18/03/2014	S1 and S2	warm	12
23 – 28/03/2014	S1 and S2	warm	6
19 – 22/04/2014	S1 and S2	warm	4
27 – 29/04/2014	S1 and S2	warm	3
28/10 – 8/11/2014	S1 and S2	warm	12
9 – 12/11/2014	S2	warm	4
“SANT’ANNA			
31/10 – 24/11/2013	S1 and S2	cold	25
19/12/2013 – 6/03/2014	S1 and S2	cold	78
7/03 – 09/05/2014	S1 and S2	warm	64
28/10 – 13/11/2014	S1 and S2	warm	17
15 – 30/11/2014	S1 and S2	warm	16
1 – 24/12/2014	S2	warm	24
25/12/2014 – 6/03/2015	S2	cold	72
7/03 – 22/04/2015	S2	warm	47

Table 2. Pista Nera: summary statistics showing median values of various variables for gliding days (Gd) and non-gliding days (NonGd). For each variable, distributions were contrasted (Mann-Witney U test), and the level of significance p is given. Temperatures are in °C, VLWC are in %, snow height are in cm.

Variables	All data			Cold periods			Warm periods		
	Gd	NonGd	p-Value	Gd	NonGd	p-Value	Gd	NonGd	p-Value
T_snow	-0.19	-0.22	0.173	-0.2	-0.2	0.684	0.75	-0.22	0.354
VLWC_snow	1.8	0	<0.001***	1.81	0	<0.001***	1.8	3.57	0.585
T_soil5cm	0.55	3.13	0.022*	0.37	3.15	0.043*	2.7	0.58	0.288
VLWC_soil5cm	16.3	19.12	0.085	16.18	17.67	0.06	18.29	21.29	0.727
T_soil15cm	0.23	3.11	0.007**	-0.01	3.2	0.043*	2.21	0.38	0.202
VLWC_soil15cm	14.8	18.11	0.04*	14.65	17.26	0.048*	18.75	20.89	0.601
TA	-1.9	-0.8	0.291	-2.9	-0.3	0.001**	2.8	-2.15	0.009**
HN24	0	2.5	0.838	2	0	0.805	0	5	0.474
HS	157	56	0.084	156	21	<0.001***	163	212	0.394

Table 3. Sant'Anna: summary statistics showing median values of various variables for gliding days (Gd) and non-gliding days (NonGd). For each variable, distributions were contrasted (Mann-Witney U test), and the level of significance p is given. Temperatures are in °C, VLWC are in %, snow height are in cm.

Variables	All data			Cold periods			Warm periods		
	Gd	NonGd	p-Value	Gd	NonGd	p-Value	Gd	NonGd	p-Value
T_snow	-0.05	-0.07	<0.001***	-0.05	-0.06	0.619	-0.05	-0.08	<0.001***
VLWC_snow	-0.27	4.5	0.378	-0.41	-0.51	0.846	-0.25	10.8	0.026*
T_soil5cm	0.6	0.38	<0.001***	0.53	0.44	0.1	0.64	0.31	<0.001***
VLWC_soil5cm	34.58	32.67	<0.001***	32.45	32.01	0.115	35.33	35.36	0.676
T_soil15cm	0.55	0.37	<0.001***	0.46	0.38	0.139	0.93	0.29	<0.001***
VLWC_soil15cm	32.86	30.88	<0.001***	30.75	30.5	0.066	33.52	33.53	0.378
TA	-0.1	-0.65	0.593	-3.5	-2.6	0.361	1.35	3.6	0.002**
HN24	0	0	0.044*	0	0	0.568	0	0	0.001**
HS	127	144	0.001**	123	130	0.164	139	156	<0.001***