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

2

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20

21 **Abstract**

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

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

48

49 **1. Introduction**

50 Snow gliding, defined as the slow downhill movement of the entire snow cover on the ground, may
51 lead to the formation of folds and cracks within the snowpack (In der Gand and Zupancic, 1966).

52 Eventually, the movement may speed up and a crack may develop into a glide-snow avalanche
53 (McClung and Schaerer, 2006). However, a glide crack does not necessarily result in glide-snow
54 avalanche release, and in case it does, the time span from crack opening to the avalanche release
55 may vary from a few seconds up to several months (Feick et al., 2012). Due to this high temporal
56 variability, glide-snow avalanches still represent a major point of uncertainty for forecasting
57 programs at all scales (Peitzsch et al., 2012; Reardon and Lundy, 2005; Stimberis and Rubin, 2004).

58 Glide processes in snow and glide-snow avalanche release have been studied since the 1930s and
59 are summarized in three recent reviewing publications (Ancey and Bain, 2015; Höller, 2014; Jones,
60 2004) which conclude that snow gliding is favoured by a smooth ground surface (in der Gand and
61 Zupancic, 1966; Leitinger et al., 2008; McClung and Schaerer, 2006; Newesely et al., 2000), a
62 lowermost layer of wet snow (in der Gand and Zupancic, 1966; McClung and Clarke, 1987) and a
63 temperature at the snow-soil interface close to 0 °C (McClung and Clarke, 1987). Snow gliding can
64 typically be observed on slopes with incline of at least 15° (McClung and Schaerer, 2006). Based
65 on McClung and Clarke (1987), an enhanced gliding speed is connected to increased liquid water
66 content at the snow-soil interface. Since monitoring the snow-soil interface is very demanding,
67 different methods for tracking gliding speed were developed in the past (van Herwijnen et al.,
68 2013).

69 As the presence of water is the key-contributing factor to snow gliding conditions, it is important to
70 know how the liquid water content at the snow-soil interface evolves. The main processes
71 associated with producing water are melting at the snow surface and rain-on-snow events. In fact,
72 Clarke and McClung (1999) related most observed glide-snow avalanches to either snowmelt or

73 rain-on-snow events using air temperature as a proxy and consequently called these glide-snow
74 avalanche warm-temperature events. However, glide-snow avalanches have also been observed
75 after prolonged periods of dry weather with sub-freezing temperatures, so-called cold-temperature
76 events, which could not be explained with air temperature (Clarke and McClung, 1999). More
77 recently, different processes that may lead to the presence of water at the snow-soil interface were
78 investigated (Dreier et al., 2016; Mitterer and Schweizer, 2012). The results of both analyses
79 underlined again the importance of differentiating between cold and warm-temperature events
80 (Clarke and McClung, 1999), which seem to be driven by different soil, snow (Mitterer and
81 Schweizer, 2012) and meteorological factors (Dreier et al., 2016).

82 All reviewing articles further conclude that there is a general lack of understanding of the exact
83 glide-snow avalanche release mechanism, especially concerning the interaction of the two porous
84 media (snow and soil). Höller (2014) concludes that *“The increasing number of glide-snow
85 avalanches in certain winter periods might be associated with the soil and ground surface
86 conditions in late autumn and early winter; however, this assumption is primarily based on
87 observations and not yet confirmed by relevant investigations. In this context, the soil conditions
88 and the conditions at the snow–soil interface should be investigated.”*. In fact, snow and soil are
89 connected and represent a highly dynamic system, characterized by layered particles of different
90 grain size and shapes with appreciable quantities of air and water. The strata encountered in a
91 snowpack are in some ways analogous to the horizons that make up a soil profile. The interactions
92 between the two domains are so strong that they must be considered a continuous system (Guymon,
93 1978). The presence of discontinuities in the physical properties of both snow and soil strata
94 represents a potential triggering factor for snow movements and soil erosion, respectively (Chiaia
95 and Frigo, 2009; Stanchi et al., 2014, 2012). First attempts in modelling the water transport
96 behavior at the snow-soil interface (Mitterer and Schweizer, 2012) showed that a strong pressure
97 gradient at the snow-grass interface causes an upward flux of water. Water in the model moved
98 from the soil towards the snowpack. Consequently, if the substrate is a wet porous medium (i.e.

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

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

106 **2. Data and methods**

107 **2.1. Study area**

108 The study area, located in the Aosta Valley Region (NW-Italy), very close to the Mont Blanc
109 Massif, includes the so-called *Torrent des Marais - Mont de la Saxe* avalanche path. The avalanche
110 path runs on a WSW-facing slope from 2115 m to 1250 m a.s.l. (Fig. 1). The selected avalanche
111 release area, at an elevation of about 2100 m a.s.l., is typically characterized by intense snow
112 gliding and the formation of large glide cracks, often developing into a glide-snow avalanche,
113 mainly during springtime. However, from time to time also in late autumn glide-snow avalanches
114 were observed. The crack or avalanche crown width typically ranges between 30 and 100 m. A
115 groundwater source is present in the south-eastern part of the crack zone. The slope, characterized
116 by a mean angle of 30°, is covered by abandoned pastures and patches of bare soil providing a
117 smooth surface favourable to snow gliding (Newesely et al., 2000). The bedrock is mainly black
118 argillic schists, calcareous sandstones and, in some places, porphyritic granites. The soils in the
119 study area (Haplic Cambisol (Humic, Dystric) according to IUSS, 2006) appeared frequently
120 disturbed by snow gliding and snow avalanche phenomena, with the removal of the upper horizons
121 (5-20 cm) and the consequent exposure of the subsoil (Ceaglio et al., 2012). In the study area, at
122 about 2000 m, the long-term mean precipitation is 730 mm yr⁻¹ (1992-2012), and the mean annual
123 air temperature is +2.8 °C (1992-2012); the average cumulative snowfall is about 630 cm (2002-
124 2012).

125 **Data collection**

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

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

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

148 These sensors were installed in a place representative of the soil conditions of the study site (A in
149 Fig. 2). Another system with the same set of sensors was placed very close to the groundwater
150 spring (B in Fig. 2) in order to measure soil conditions in a waterlogged area with evidence of soil

151 erosion; Stahr and Langenscheidt (2015) reported that these kind of conditions might potentially
152 cause snow gliding. The data loggers were set to record measurements every minute and to store
153 average (maximum in case of snow gliding) values every 30 minutes.

154 Soils were sampled (3 replicates) at 5 and 15 cm depth within plots A and B and analyzed in
155 laboratory in order to determine soil physical properties according to standard methods (SISS,
156 1997): skeleton content (%), Atterberg plastic (LP, %) and liquid (LL, %) limits. The Atterberg
157 Limits, determined through the cone penetrometer method, represent the soil moisture content
158 values determining the transition from the semi-solid to the plastic state, and from the plastic to the
159 liquid state, respectively (Lal and Shukla, 2004; Stanchi et al., 2012). The use of Atterberg Limits
160 has been extended to the field of natural hazard assessment and investigation, mainly either for
161 unstable phenomena involving the first decimeters of soil as shallow landslides or for the evaluation
162 of soil erosion susceptibility to snow avalanches (Confortola et al., 2011; Stanchi et al., 2014,
163 2012).

164 **2.3. Methods**

165 During the winter season 2010, the snow gliding data registered by the glide-snow shoes G1 and G2
166 were analysed from 8 November 2009 until 18 March 2010, the day when a glide-snow avalanche
167 released. For the glide-snow shoes G3 and G4 the data were analysed from 8 November 2009 until
168 14 February 2010, when the maximum cable length was reached. During the winter season 2011,
169 snow gliding data registered by all the glide-snow shoes were analysed from 8 November 2010 until
170 30 April 2011, when the site was almost snow free, with only few snow patches left.

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

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

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

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

198 We assumed that the distinction between a cold and a warm-temperature event is related to the
199 origin of liquid water at the snow-soil interface: in a cold-temperature event the necessary wet
200 snow-soil interface originates either from snow melting at basal layers of the snowpack or from

201 suction; in a warm-temperature event the water originates from melting processes at the snow
202 surface, percolates through the snowpack and ponds at the snow-soil interface.

203 **3. Results**

204 **3.1. Winter season 2010**

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

210 A glide crack was observed during the field work on 1 February 2010; its opening probably started
211 in the last days of January. The glide crack finally evolved into a glide-snow avalanche on 18
212 March 2010 (Fig. 4). On this day the highest peak of daily glide-snow rate was registered with the
213 glide-snow shoe G1 (100.9 cm/d) (Fig. 3). Unfortunately, the cables of glide-snow shoes G3 and G4
214 already reached their maximum length on 14 February 2010, after a long period of continuous and
215 gradual gliding; therefore they did not record the avalanche event. The snow gliding started one
216 week earlier for the glide-snow shoes G3-G4 than for the other pair and the daily glide-snow rate
217 was higher for the prior pair than for the latter one (see also boxplots in Fig. 5), with a mean daily
218 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.

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

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

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

231 The glide-snow avalanche recorded on 18 March 2010 was classified as a warm-temperature event.
232 It occurred after a substantial rise of air temperature (daily averages from -13.3 °C to +3 °C from 9
233 to 18 March), which produced a strong snowpack settlement of 25 cm (Fig. 3). From 10 to 18
234 March, the snowpack glided downwards 303.5 cm in G1 and 64.8 cm in G2, reaching the total cable
235 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
236 G2. The maximum glide-snow rate was recorded from G1 between 15:30 and 15:35 on 18 March
237 2010, when the glide-snow shoe in G1 moved downwards by 47.4 cm, indicating the time of the
238 glide-snow avalanche release.

239 **3.2. Winter season 2011**

240 The winter season 2011 started with earlier and heavier snowfall events than the season 2010, but
241 the cumulative snowfall (548 cm) was lower. The air temperature was higher than the average
242 (dataset for period 2002-2011), especially during February and from mid March until the end of
243 April, when daily average air temperatures exceeded 0 °C several times. The snow-soil interface
244 temperature was not constantly around 0 °C as in 2010, but showed an oscillating behavior related
245 to thawing/freezing episodes (Fig. 6). A strong temperature decrease at the snow-soil interface was
246 registered in A after a glide crack started to open on 17 January, which very likely exposed the soil
247 where the probes were buried (Fig. 7). Between 16 and 17 January 2011 the glide-snow shoes
248 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
249 G3 and G4, respectively (Fig. 6). The only other significant glide-snow movement was registered
250 on 4 April from glide-snow shoes G3-G4 (as the other couple of glide shoes were already free of
251 snow): the daily glide-snow rate was 113.9 cm/d in G3 and 776.6 cm/d in G4.

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

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

263 We classified the two important snow gliding events of this season as warm-temperature events.
264 Both events occurred after a consistent rise in air temperature with exceptional values for the period
265 (mean daily temperatures of +3.5 °C at 2000 m a.s.l. with a maximum of 11.4 °C on 16 January
266 2011; mean daily temperatures of +7.5 °C with a maximum of 12.3 °C on 3 April 2011), producing
267 a strong wetting and settlement of the snowpack.

268 **3.3. Gliding versus non-gliding periods**

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

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

285 **3.4. Correlation of snow gliding with meteorological and soil variables for the cold-** 286 **temperature event**

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

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

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

301 **3.5. Soil characteristics**

302 Focusing on the soil physical properties, the topsoil (0-10 cm depth) differed significantly from the
303 deeper soil horizons (10-20 cm depth). It was constituted by a organo-mineral horizon with hard,

304 medium granular structure and 10% content of sub-angular fine gravel with abundant fine roots.
305 The underneath horizons had a soft, medium granular structure and were characterized by 35-70%
306 of angular coarse gravel and very few fine roots. These differences in soil properties were reflected
307 in the plastic (LP) and liquid (LL) limits, that in the topsoil resulted higher (L LP: 65-67%; L: 76-
308 82%) than in the underlying soil horizon (LP: 36-54%; LL: 48-67%), which represents the ground
309 surface in many eroded patches in the study site; consequently, considering the soil moisture
310 content recorded in this study, the possibility of a significant reduction of soil cohesion in the
311 subnivean zone was considerable, in particular close to the groundwater source. During a field
312 survey in spring 2010, we observed the presence of a thin mud layer at the snow-soil interface while
313 digging a snow pit in the south-eastern part of the study area, closer to the groundwater source (Fig.
314 12).

315 **4. Discussion**

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

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

327 During gliding periods of warm-temperature events, air temperature (daily mean and maximum)
328 was significantly higher, and the decrease of snow depth was significantly stronger, than during
329 non-gliding periods; moreover, in periods of gliding new snow amount was significantly lower than

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

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

348 Moreover, our analysis of VLWC and glide rate measurements shows that the amount of water at
349 the interface is correlated with an increase in gliding speed. In particular, in the case of the cold-
350 temperature snow gliding event in 2010, the glide-snow rate was strongly correlated with the
351 measured soil volumetric liquid water content (Tab. 3): faster gliding rates corresponded to higher
352 amounts of VLWC. These findings again agree with the recent results of Baumgärtner (2016), who
353 found a strong correlation between glide-snow rates and VLWC in the soil for data gathered in an
354 experimental site during the period October-January. For our data, we found an exponential relation
355 between glide-snow rates and VLWC at the snow-soil interface and at 5 cm soil depth and a linear

356 relation with VLWC values at 15 cm soil depth (Fig. 11). The exponential and linear relationship
357 between the glide-snow rates and the VLWC was better defined for the glide-snow shoes pair G3-
358 G4 than for G1-G2 which might be due to site specific conditions (e.g. position of the glide-snow
359 shoes pairs in the crack and vicinity to the water source).

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

378 In addition, we observed changes in VLWC which we attributed to freezing of water. At the
379 beginning of season 2010, VLWC measured in A at 5 cm soil depth was roughly 25 % and it
380 dropped abruptly to 14 % on 20 December 2009 (Fig. 3). These decrease occurred in a period of
381 prevailing low air temperatures and shallow snow cover, which are reflected in subfreezing

382 temperatures at the snow-soil interface and in the topsoil (Fig. 3). Snowfalls increased the total
383 snow depth and insulated the soil, where the VLWC increased to a value similar to the initial one.
384 Changes in VLWC are either attributed to water flow or to phase changes. Since the sharp decreases
385 in VLWC occurred during a cold period with soil temperatures below 0 °C, we think that freezing
386 processes led to this decrease in VLWC (Brooks et al., 2011). Since the relative permittivity of
387 water is about 20 times larger than that of ice, the significant drop in permittivity measured in A
388 suggests rather a phase change than water movement causing this change. Similarly, after the snow
389 depth increased, insulating the soil, the frozen water in the soil or snow could melt leading to an
390 increase in VLWC. During periods of low VLWC and sub-freezing soil temperatures, no gliding
391 was registered (Fig. 3), while the snowpack started again to glide as soon as the soil temperatures
392 had reached roughly 0 °C.

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

399 Abrupt VLWC changes occurred in plot B in 2011. We think that also in this case a water phase
400 change can explain the strong decrease registered in VLWC at 5 cm depth in plot B at mid January
401 2011 (Fig. 6). In this case, the opening of a glide crack occurred on 17 January (as also registered
402 by the glide-snow shoes) and possibly exposed the soil, where the sensors were buried, to the cold
403 air temperatures registered in the following period. Subsequently the soil temperature dropped
404 below 0 °C and the soil water froze. The same considerations on water phase changes are valid for
405 the other sharp changes registered for VLWC at 5 cm depth in plot B (Fig. 6).

406 Therefore the amount of water content is not only important itself for snow gliding, but it has also a
407 cascading effect on the soil thermal regime: it plays a major role in keeping the temperature at the

408 snow-soil interface close to 0 °C, which is in turn again a predisposing factor for snow gliding. In
409 other words, the strictly inter-connected water flow and thermal dynamics of both soil and snow
410 porous media influence glide-snow processes.

411 Due to the high soil volumetric liquid water content recorded especially in B throughout both winter
412 seasons, and in particular, during early spring, we could not exclude the loss of soil cohesion under
413 the snow cover (Stahr and Langenscheidt, 2015). These soils, in fact, showed relatively low values
414 of the Atterberg plastic and liquid limits, in particular at a depth of 15 cm (LP: 36-54 %; LL: 48-67
415 %), which could represent the ground surface where the topsoil had already been eroded and
416 stripped away (Ceaglio et al., 2012). The soil VLWC registered at 15 cm depth in B (close to the
417 water source, where many patches of soil erosion are present) reached the maximum values of 48 %
418 in season 2010 (23 March) and of 51 % in season 2011 (13 February). These values were close to
419 the Atterberg plastic and liquid limits for the subsoil. Therefore, the loss of cohesion might have
420 contributed to the active snow gliding processes by the formation of a thin mud layer at the snow-
421 soil interface, especially in the eroded areas, as observed in 2010 (Fig. 12). This thin mud layer
422 might have reduced the roughness and the friction at the snow-soil interface and might explain the
423 high amount of solid material transported by the glide-snow avalanches in this study site (Ceaglio et
424 al., 2012).

425 **5. Conclusion**

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

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

432 For cold-temperature events we found that, together with snow depth, the volumetric liquid water
433 content at the snow-soil interface and in soil played a fundamental role. Our results indicate that

434 cold-temperature events are characterised by an upward movement of water from the soil to the
435 snow. We determined a quantitative relationship between the glide-snow rate and the volumetric
436 liquid water content at the snow-soil interface and at different soil depths. Glide-snow rates
437 increased exponentially with increasing water content at the snow-soil interface and in the top 5 cm
438 of the soil. This observations show the importance of considering the snow cover and the
439 underlying soil as a continuous system, where the key contributing part is certainly represented by
440 the snow-soil interface.

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

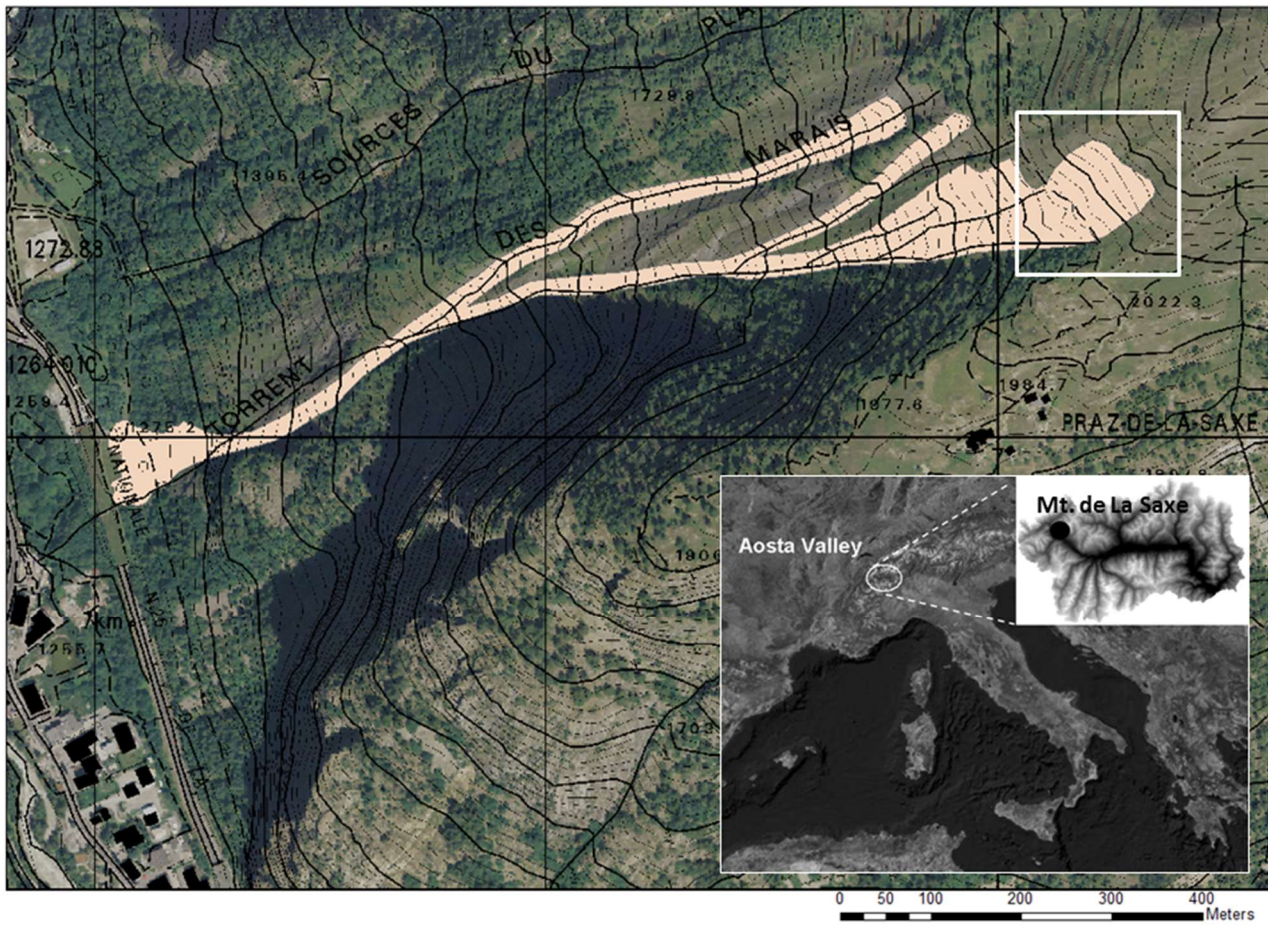
446 Our results confirm that it is paramount to observe and/or measure the snow and soil properties
447 jointly, since together they represent a highly dynamic and connected porous medium, in order to
448 enhance our knowledge on driving processes for snow gliding. Thermal and hydraulic processes are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

454

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459 morphoclimatic system dynamics to global changes and related geomorphological hazards"

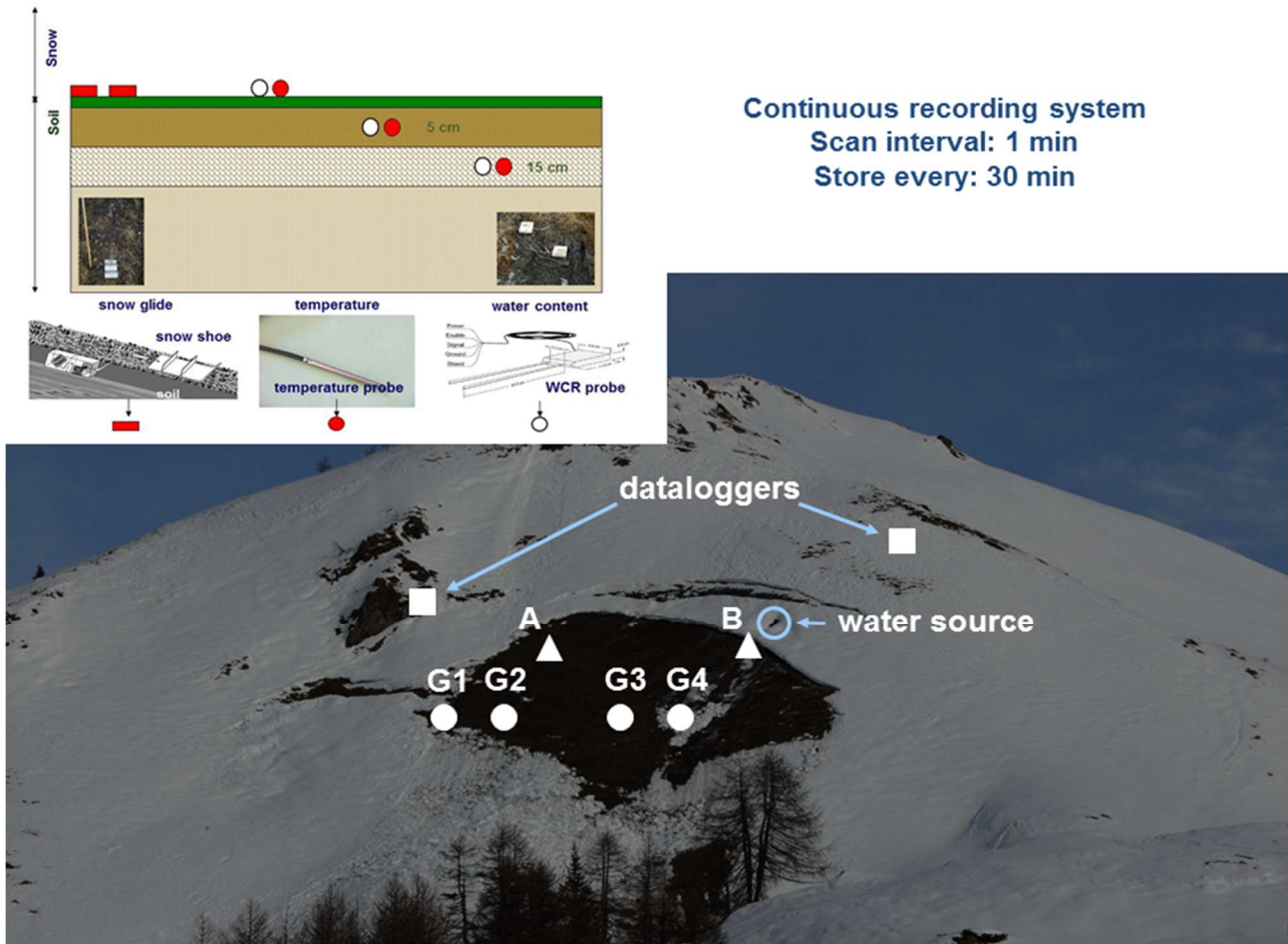
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462 (FMS) for her suggestions; Fabrizio Busa for technical assistance in realizing and maintaining the
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464 work and discussions.
465



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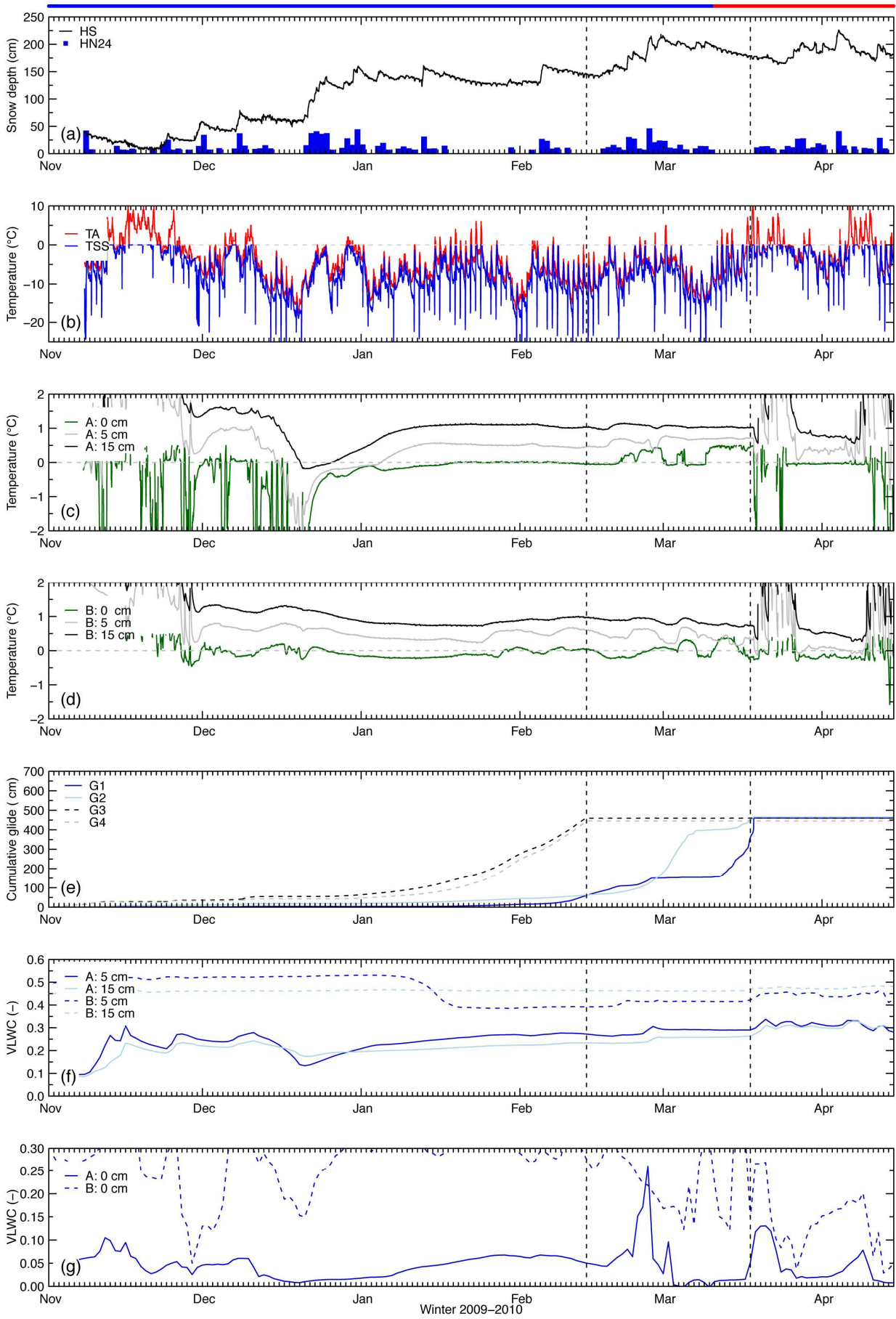
468 Fig. 1. Study area: the polygon shows the extension of the avalanche event occurred in 2009 as an
469 example, with the release area highlighted within the white rectangle. In the inset the localization
470 within the Aosta Valley and in Italy is shown.

471



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

477



479 Fig. 3. Winter season 2009-2010: (a) Snow depth (HS), simulated 24 h new snow sum (HN24); (b)
480 measured air temperature (TA) and simulated snow surface temperature (TSS) at the location of the
481 AWS *Pré-Saint-Didier Plan Praz*. Soil temperature at plot A (c) and B (d), (e) glide-snow distance
482 and volumetric liquid water content (VLWC) measured within the soil (f) and at the snow-soil
483 interface (g) for both A and B. G1-G2 and G3-G4 refer to the two pairs of glide-snow shoes as in
484 Fig. 2. Dashed lines identify significative dates: 14 February - end of cables for the pair G3-G4; 18
485 March - snow avalanche release. Blue and red colored lines on top indicate periods of cold-
486 temperature (blue) and warm-temperature events (red).
487

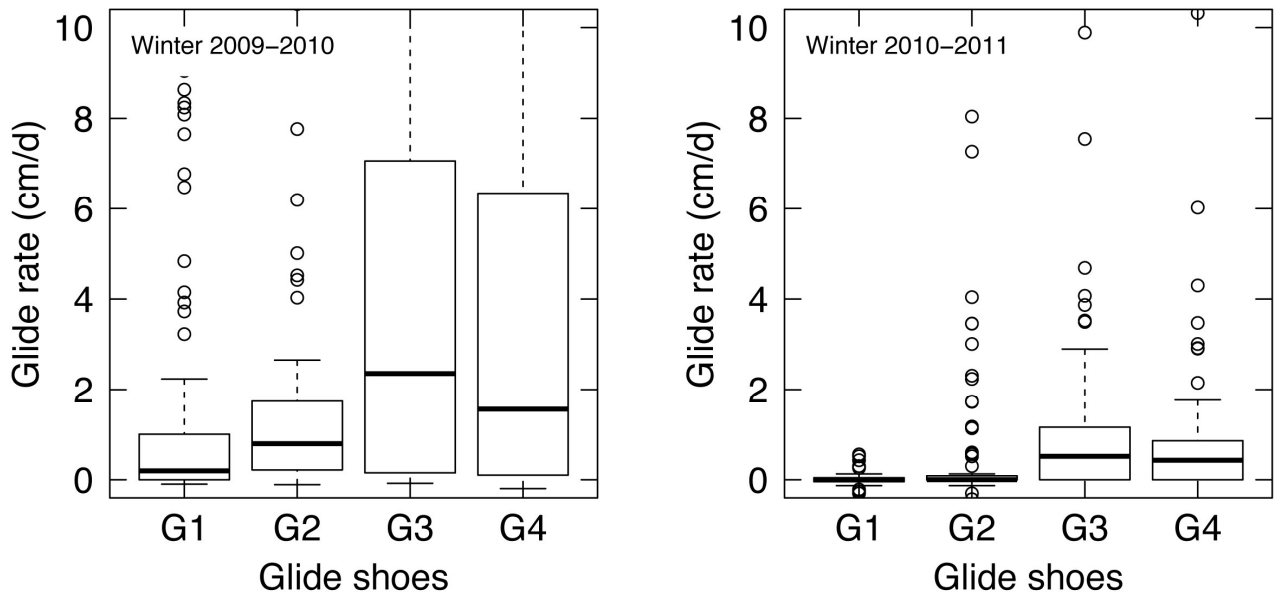


488

489 Fig. 4. Glide crack and snow avalanche recorded during winter season 2010. Photos taken on 17

490 March (up) and 23 March 2010 (bottom, by R. Cosson).

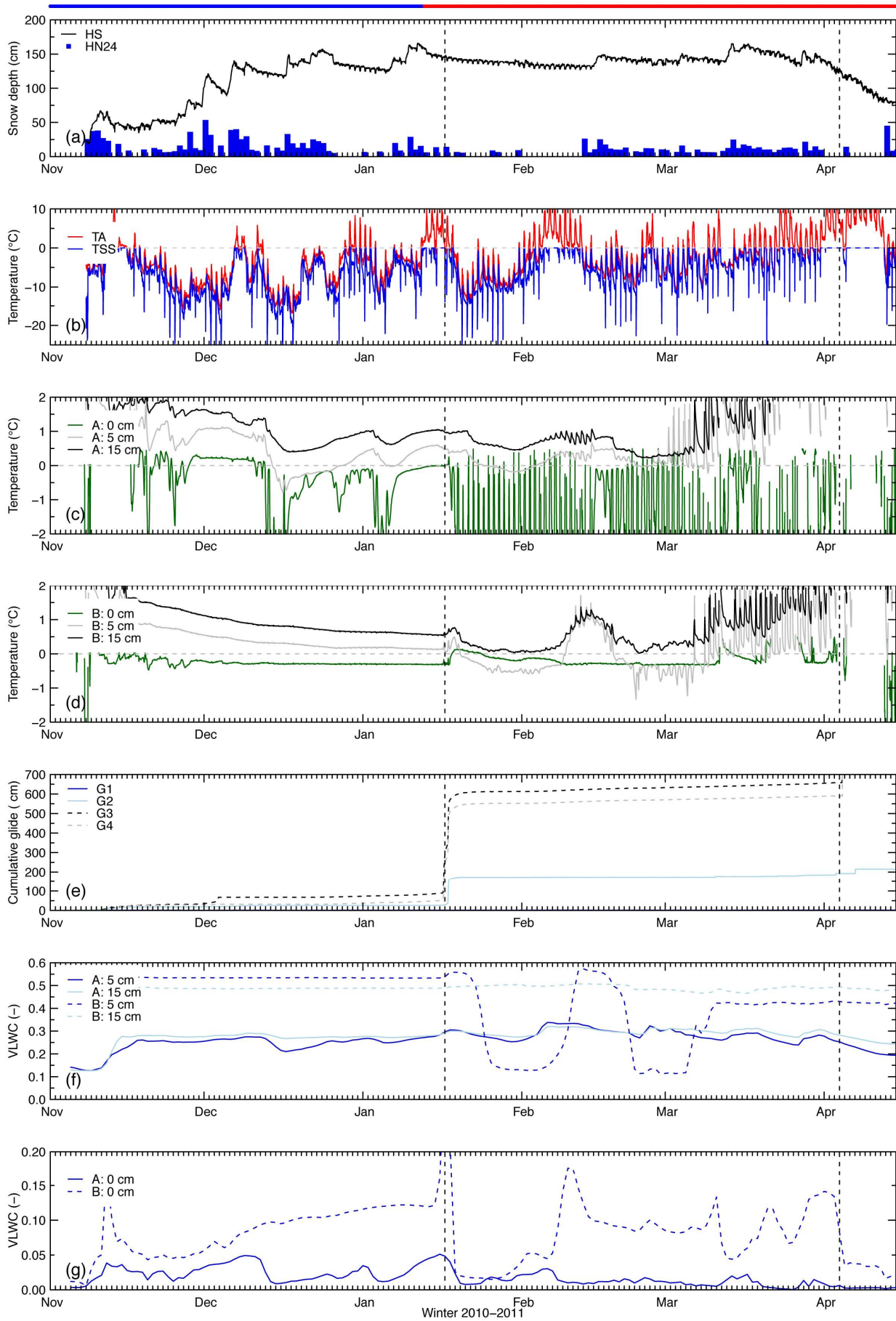
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492

493 Fig. 5. Daily average glide rates for the four different glide shoes in the two monitoring seasons
 494 (left: 2009-2010; right: 2010-2011). Data from 8 November 2009 to 14 February 2010 for G3-G4
 495 and from 8 November 2009 to 18 March 2010 for G1-G2 in season 2010; data from 8 November
 496 2010 to 30 April 2011 for G1-G2-G3-G4 in season 2011.

497



499 Fig. 6. Same representation as in Fig. 3, but for the winter season 2010-2011. Dashed lines identify
500 significant dates for strong glides-snow movements: 17 January 2011 and 4 April 2011. Blue and
501 red colored lines on top indicate periods for cold-temperature (blue) and warm-temperature events
502 (red)
503

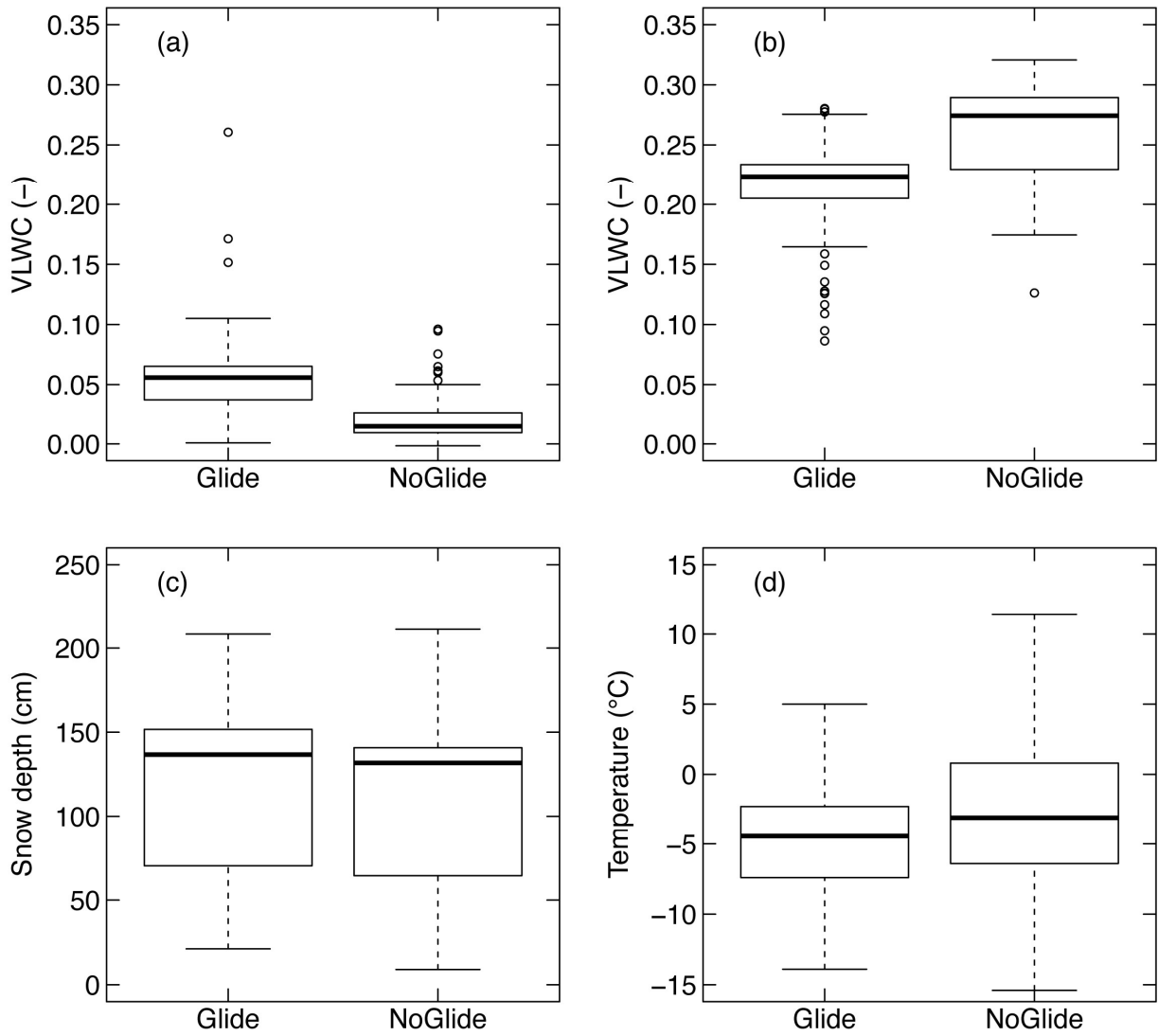


504

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

506 23 March 2011(bottom).

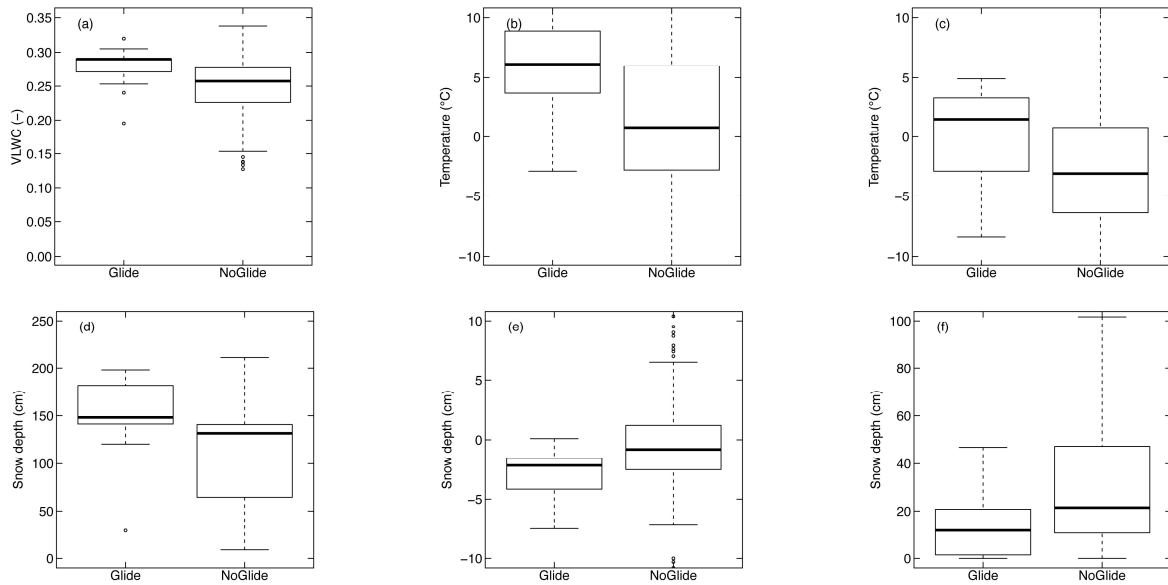
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508

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

512



513

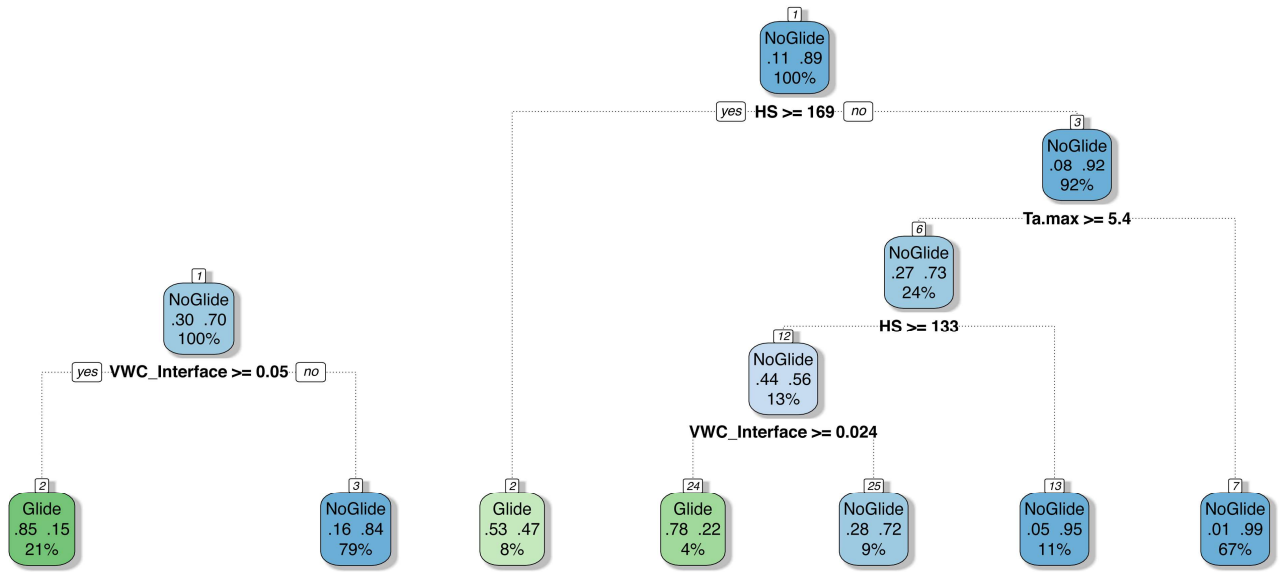
514 Figure 9. Comparison between gliding (Glide) and non-gliding (NoGlide) periods during warm-
 515 temperature events: (a) volumetric liquid water content (VLWC) at 5 cm soil depth, (b) daily
 516 maximum air temperature, (c) daily mean air temperature, (d) snow depth, (e) 24-hour difference in
 517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

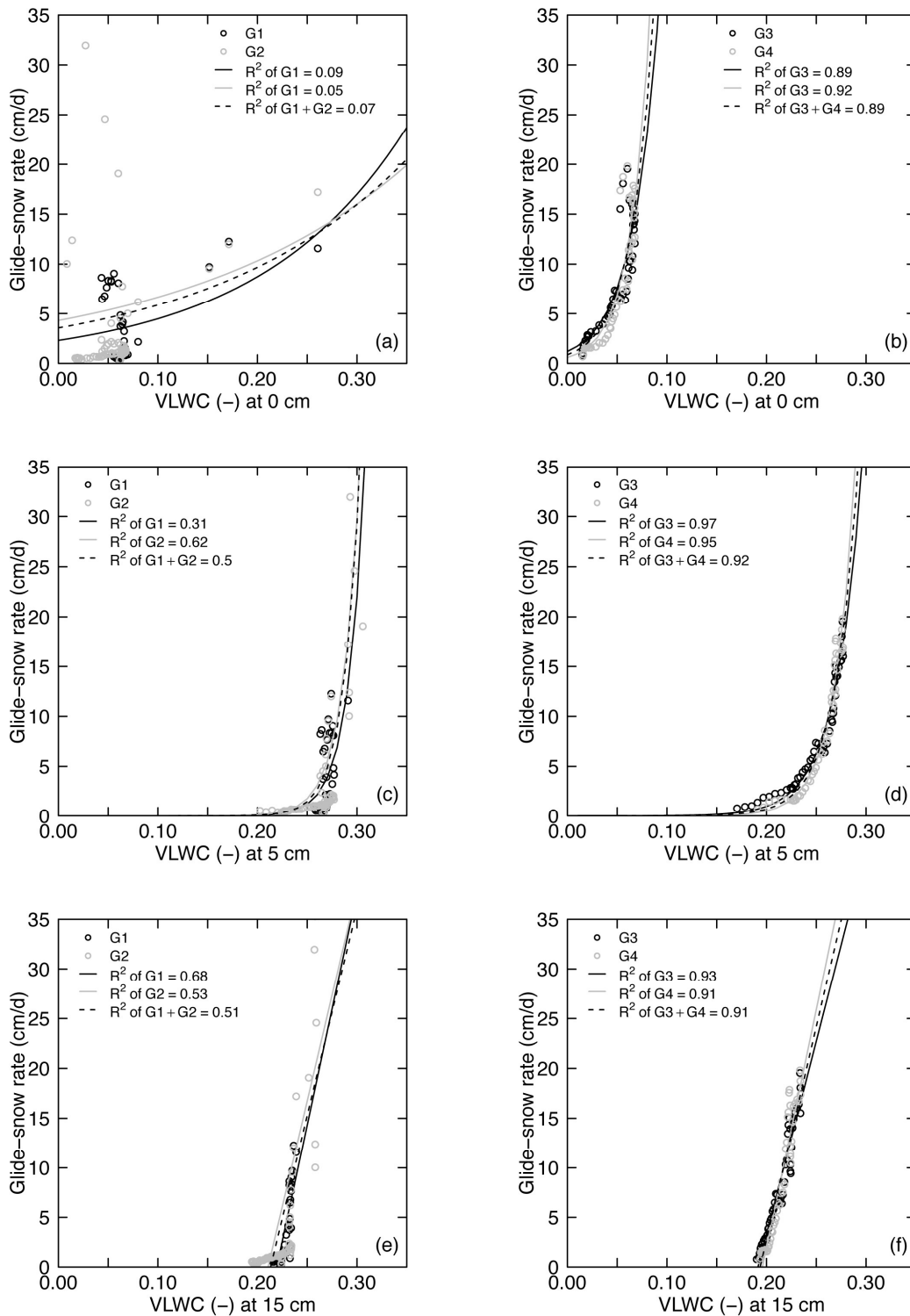
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519

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

522





523

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



528

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

531

532 **Tables**533 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		
<i>Sensor</i>	<i>Parameter</i>	<i>Unit</i>
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

534

535

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

Variables	All events			Cold events			Warm events		
	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**

539

540 Table 3. Correlations (r) between daily glide-snow rate (G) and volumetric liquid water content
 541 (VLWC) measured in plot A (Fig. 2) during the cold-temperature snow gliding event of season
 542 2010 (data in periods: 21 Jan. – 26 Feb. for G1, 31 Dec. – 7 Mar. for G2, 26 Dec. – 13 Feb. for G3,
 543 29 Dec. – 13 Feb. for G4) at the snow-soil interface (I) and at 5 and 15 cm depth in the soil (S5 and
 544 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**

545

546

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