



**Short-term variability  
of rock glaciers**

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# Short-term velocity variations of three rock glaciers and their relationship with meteorological conditions

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Abstract

In recent years, strong variations in the speed of rock glaciers have been detected, raising questions about their stability in a changed climate. In this study, we present continuous time series over three years of surface velocities of six GPS stations located on three rock glaciers in Switzerland. Intra-annual velocity variations are analyzed in relation to local meteorological factors, such as precipitation, snow(melt), as well as air and ground surface temperatures. A main focus of this study lies on the abrupt velocity peaks, which have been detected at two steep and fast moving rock glacier tongues.

The continuous measurements with high temporal resolution revealed that all rock glaciers experience clear intra-annual variations in movement where the timing and the amplitude is rather similar between individual years. The seasonal decrease in velocity was typically smooth, starting one to three months after the seasonal decrease in temperatures, and was stronger in years with colder temperatures in mid winter. The seasonal acceleration always started during the zero curtain period, often was abrupt and rapid compared to the winter deceleration, and at two stations it was interrupted by short velocity peaks, occurring immediately after high water input from snowmelt or heavy precipitation. The findings of this study suggest that both, the seasonal acceleration and the short velocity peaks are strongly influenced by water infiltration, causing thermal advection and increase in pore water pressure, and that likely no velocity peak was solely caused by high temperatures. In contrast, the amount of deceleration in winter seems to be mainly controlled by winter temperatures.

1 Introduction and related work

Rock glaciers are a wide-spread landform in alpine permafrost terrain related to creep of frozen debris or sediment. They shape and alter the landscape and contribute to the transport of sediment. In recent years, strong variations in movement speed of rock glaciers have been detected with a general trend of increasing velocities over

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the past decade (e.g., Delaloye et al., 2008a), raising questions about their stability in a changing climate (Harris et al., 2001; Kääb et al., 2007; Roer et al., 2008). Where such rock glaciers end in channels or gullies, they may increase the potential of debris flows due to enhanced debris transport (e.g., Delaloye et al., 2013; Graf et al., 2013).

Further, rock glaciers can contribute to discharge through ice melt, especially in warmer conditions (e.g., Krainer et al., 2007; Burger et al., 1999; Azócar and Brenning, 2010), as they can store significant volumes of ice for extended periods (cf., Johnson, 1981; Arenson et al., 2002).

We define rock glaciers by morphology, irrespective of the origin of ice, as lobate or tongue-shaped debris–ice mixtures, frequently with steep sides and snouts and longitudinal and/or transverse ridges and furrows, that are slowly creeping downslope (cf. Vitek and Giardino, 1987). The ice within rock glaciers may include buried surface ice (including glacier ice, e.g., Potter, 1972) or ice formed in the ground (e.g., Wahrhaftig and Cox, 1959; Humlum et al., 2007). Rock glaciers with periglacial origins, typically have an ice-content of 50–90 % (Potter, 1972; Barsch, 1977; Haeberli et al., 1998). In addition, the permafrost body is permeable (Johnson and Nickling, 1979; Vonder Mühll, 1992; Arenson et al., 2002; Buchli et al., 2013) and air-voids and liquid water can occur throughout the rock glacier body (Wagner, 1992; Arenson et al., 2002; Buchli et al., 2013).

Horizontal displacement of alpine rock glaciers is typically between several centimeters to one meter per year (Haeberli et al., 2006). Vertical displacement amounts to only 10–60 % of the horizontal displacement, with typical values of a few centimetres to decimetres per year (Haeberli, 1985; Roer, 2005). Within a single rock glacier, maximum velocities typically occur along the central flow line and decrease towards the margins (e.g., Barsch, 1992; Haeberli, 1985; Roer et al., 2005). For several rock glaciers it has been observed that velocities correlate with slope angle (Francou and Reynaud, 1992; Sloan and Dyke, 1998; Konrad et al., 1999) and velocities are generally higher in areas with extensive rather than compressive flow (Arenson, 2002). The movement observed at the rock glacier surface might be the result from movements occurring

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at different depth (Fig. 1). However, the few existing studies on borehole-deformation measurements in rock glaciers all reveal that within the permafrost body a thin layer with distinct rheological properties (e.g. lower viscosity) exists, where 50–97 % of the horizontal deformation takes place (Wagner, 1992; Haeberli et al., 1998; Hoelzle et al., 1998; Arenson et al., 2002; Buchli et al., 2013, Fig. 1). Below this shear horizon typically no, and above only limited internal deformation occurs. Hence, surface displacement measurements appear to be a good approximation of the slope movement of the entire rock glacier.

In recent years an increasing number of studies have detected temporal variations in rock glacier movement (e.g., Kaufmann and Ladstädter, 2007; Krummenacher et al., 2008) and distinguish between three time-scales: decennial, inter-annual, and intra-annual (e.g., Kääb et al., 2007; Perruchoud and Delaloye, 2007; Delaloye et al., 2010). Most studies are at the inter-annual time scale (e.g., Krummenacher et al., 2008; Perruchoud and Delaloye, 2007) and observations of intra-annual variations in velocities are rare, mainly because of limitations in measurement techniques. However, to analyse direct influences of meteorological factors on short-term velocity fluctuations, measurements with a high temporal resolution (e.g. daily) are required. The few studies of intra-annual variability were either based on measurements with low temporal resolutions (~ 1–4 months, Haeberli, 1985; Kääb et al., 2003; Roer, 2005; Perruchoud and Delaloye, 2007; Krummenacher et al., 2008) and/or had relatively short observation periods typically of a few months (Roer, 2005; Krainer and He, 2006; Buchli et al., 2013). Measurements made in a borehole at the Furggwanghorn rock glacier (Valais, Switzerland) from October 2010 to May 2011 form the longest published time-series of displacement measurements with daily resolution, known to the authors (Buchli et al., 2013).

Long-term time series of surface velocity observations from Austria (Kaufmann and Ladstädter, 2007) showed that rock glacier velocities were relatively high between 1950 and 1970, decreased until the beginning of 1990s, and since then have again accelerated. In various studies in the Alps a significant acceleration of rock glacier velocities

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since the 1980s has been reported (e.g., Roer et al., 2005; Kääb et al., 2007; Kaufmann and Ladstädter, 2007; Lugon et al., 2008; Delaloye et al., 2008a), and, for about 15 rock glaciers in the Alps, exceptionally high velocities of up to  $10 \text{ m a}^{-1}$  have been measured within the last decade (Delaloye et al., 2008b; Roer et al., 2008). This acceleration is often suggested to be linked to increasing permafrost temperatures (at  $> 20 \text{ m}$  depth) and related changes in the rheological properties (Delaloye et al., 2010; Roer et al., 2008) as well as hydrological effects (Roer et al., 2008). In general, long-term climatic effects, such as a warming of the entire rock glacier body, are thought to be the main factor influencing the long-term variability of rock glacier movement (Delaloye et al., 2010).

Annually repeated measurements over the last years at 16 rock glaciers of variable size and morphology located in six different regions of the European Alps, suggest that most rock glaciers have strong inter-annual velocity variations that are rather similar and synchronous (Delaloye et al., 2008a, 2010; PERMOS, 2013), and that have been suggested to be caused by external climatic factors rather than by internal characteristics (Delaloye et al., 2010). In most studies, the temperature of the upper permafrost layers, respectively the effect of slow diffusion of annual surface thermal anomalies deeper into permafrost (e.g., Hoelzle et al., 1998; Delaloye et al., 2008a, 2010) and changes in pore water pressure caused by snow meltwater infiltration (Ikeda et al., 2008; Krainer and He, 2006; Delaloye et al., 2010) are mentioned as the main controlling factors for the inter-annual velocity variations of rock glacier movements.

An overview of previous studies on intra-annual variability of rock glacier movements is given in Table A1. For various rock glaciers, an intra-annual (seasonal) variability in velocity was observed, sometimes more than 50 % of the mean annual velocity (e.g., Haeberli, 1985; Hausmann et al., 2007; Perruchoud and Delaloye, 2007), but this often varied significantly from year to year (Delaloye et al., 2010). For individual rock glaciers, it was found that the seasonal fluctuations occur mostly at the same time of year (Delaloye et al., 2010) with highest velocities in autumn or late summer, and lowest velocities in winter (Kääb et al., 2005; Perruchoud and Delaloye, 2007; Buchli

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et al., 2013). However, maxima in velocity have also been observed in spring (Haeberli, 1985; Krummenacher et al., 2008; Buchli et al., 2013), and minima in velocities in mid summer (Lambiel et al., 2005). The observed decrease in rock glacier velocities in winter was typically smooth and gradual and started a few weeks to months after the initiation of the seasonal cooling of ground surface temperatures (GST, Delaloye et al., 2010). The observed acceleration either occurred rapidly during the snowmelt-period (Krummenacher et al., 2008; Perruchoud and Delaloye, 2007; Buchli et al., 2013) or progressively and lagging the temperature increase (3–4 months after meltwater infiltration started, Kääb et al., 2005). For various rock glaciers velocity fluctuations have been observed to lag GST by few weeks to months (Kääb, 2005; Delaloye et al., 2010; Buchli et al., 2013) suggesting that changes in temperature above the shear horizon are a main controlling factor in seasonal velocity variations (timing and amplitude, Kääb et al., 2005; Lambiel et al., 2005; Delaloye et al., 2010). Additionally, timing and thickness of the snowcover (as a proxy for melt water infiltration) has been suggested as relevant factor influencing intra-annual variability of rock glacier velocities (Krainer and He, 2006; Perruchoud and Delaloye, 2007; Buchli et al., 2013). In the study of Buchli et al. (2013) on the Furggwanhorn rock glacier, in addition to the seasonal cycle two strong peaks in velocities were detected during the snowmelt period.

In this study, we present continuous time series of surface velocities of six GPS stations located on three differing rock glaciers in the Mattertal, Switzerland. Velocities are derived from GPS measurements over two to three years with a temporal resolution of one day and a spatial accuracy in the sub-cm range (Wirz et al., 2014). Intra-annual velocity variations are compared to local meteorological and snowpack factors (later on referred to as *meteorological factors*), such as GST, air-temperature, precipitation, as well as snow cover duration and snowmelting period (both extracted from GST data). In comparison to previous studies on intra-annual variability of rock glaciers, our data has both a very high temporal resolution and a comparably long temporal coverage, encompassing more than two complete years. All three rock glaciers have a distinct morphology, and for two, exceptionally high movement rates at their tongues were de-

tected by InSAR (Delaloye et al., 2008b; Strozzi et al., 2009a) and later revealed by GPS measurements (Delaloye et al., 2013; Wirz et al., 2015).

This paper addresses the following research questions:

- Do continuous GPS measurements with high temporal resolution confirm previous observations on intra-annual variability of rock glacier movement?
- What are important meteorological factors influencing the intra-annual variability of rock glacier movement and what might be the underlying processes?

A focus of this paper lies on the identification and interpretation of short peaks in velocities (over few days). In contrast to previous work (cf. Wirz et al., 2015) this paper has a stronger focus on meteorological factors and other processes influencing observed short-term variability of rock glaciers, as well as access to an additional year of data.

## 2 Study site and data

### 2.1 Description of the study site

The study site is located above the villages of Herbriggen and Randa on the orographic right side of the Mattertal in the Swiss Alps (see Fig. 2). Permafrost is likely to exist beneath much of the study area, especially above 2850 m a.s.l. (Boeckli et al., 2012). The main lithology is gneiss belonging to the crystalline Mischabel unit (Labhart, 1995).

Climate in the study area can be described as inner-alpine continental, with an average annual sum of precipitation of 523 mm and mean annual air temperature of 5.2 °C (long-term climatic mean obtained from the closest MeteoSwiss station, located in Grächen, at 1550 m a.s.l. 9 km away from the study site calculated for the period 1961–1990). Over the experimental period of this study (20 August 2011–19 August 2014) the MAAT in Grächen was approximately one degree warmer and the mean annual sum of precipitation was approximately 100 mm higher than the long-term climatic mean. During this period a local weather station installed at the study site at

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2697 m.a.s.l. measured the MAAT to be about 0.5 °C and the average annual sum of liquid precipitation was measured at about 630 mm. Due to a limitation of the instrument used (Vaisala WXT520) only liquid and not solid precipitation was measured.

Within the project PermaSense (<http://www.permasense.ch>) a total of 18 GPS stations were installed on various landforms within the study site (Wirz et al., 2015). Six of these stations are located on three active rock glaciers within the bounds of the study site. These active rock glaciers and their associated measurements constitute the core subjects studied within this paper.

The rock glacier Breithorn (R2) is situated between the mountains Breithorn and Gugla, and extends into the Bielziggi torrent (see Fig. 2). It stretches from approximately 2550 to 2850 m.a.s.l., is about 600 m long, 130 wide and about 40 m thick (Delaloye et al., 2013). It has a convex profile-curvature: approximately 100 m above the front the slope angle rapidly increases from about 20 to 35 °. GPS station R2a<sup>2</sup> is located on the flatter part of the rock glacier at 2704 m.a.s.l. that also moves more slowly than the steeper frontal part where GPS R2b is located at 2650 m.a.s.l. (Wirz et al., 2015). Since about 1995 this tongue has accelerated to about 2–3 m a<sup>-1</sup>. The cause of this acceleration is attributed to a combination of effects of topography, geometry of the landform and increased permafrost temperatures over the last two decades (Delaloye et al., 2013).

The rock glacier Steintälli (R6) consists of two superimposed lobes of different sediment lithology (see Fig. 2). The rock glacier is approximately 550 m long and 160 m wide, and each lobe is about 25 m thick (derived from DEM2 analysis). The upper lobe currently overrides the lower lobe. The GPS station at position R6a is located at 3020 m.a.s.l., with a slope angle of 20° on the upper lobe while position R6b is located on the lower lobe at 2991 m.a.s.l. and has a slope angle of 15°.

<sup>1</sup>Slope angles were derived from a digital elevation model with a cell size of 25 m (DEM25).

<sup>2</sup>The names for the different rock glaciers and GPS stations were adopted from Wirz et al. (2015).

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The rock glacier Dirru (R7) is composed of various lobes and fronts (see Fig. 2), originating from different rock glacier generations (Delaloye et al., 2013). The currently active lobe, which is located on the orographic right side of Dirrugrat, has a total length of more than a kilometer, is about 60 to 120 m wide, and is approximately 20 m thick (Delaloye et al., 2013). It has a convex profile and slope angles increase from about 15° in the upper part to more than 30° in the lower part towards its front. Since the 1970/80s this frontal steep part has progressively accelerated and reached surface velocities above 5 m a<sup>-1</sup>, potentially indicating a phase of destabilization (Delaloye et al., 2013). From 2008 to 2010 velocities measured at the front of R7 using manually executed annual GPS surveys have decreased slightly (Delaloye et al., 2013) with recent increases observed since 2011 (Wirz et al., 2015). The GPS station at position R7a is located on the upper flatter part at 2772 m a.s.l. The GPS at position R7c was installed on a small longitudinal ridge at 2673 m a.s.l. more or less in the middle of the steep fast-moving tongue.

## 2.2 Instrumentation of the study site

The main instrument used on the study site are custom built GPS stations designed for long-term observation in harsh high-mountain environments. These stations allow to measure continuously position and inclination angles with sub-cm accuracy, at high temporal resolution and with wide temporal and spatial coverage (Wirz et al., 2013). Each GPS station consists of a low-cost single-frequency GPS receiver (u-blox LEA-6T) with active antenna (Trimble Bullet III) and a two-axis inclinometer (VTI SCA830-D07) mounted on a mast 1–1.5 m above ground (Beutel et al., 2011; Buchli et al., 2012; Wirz et al., 2015). The GPS stations are installed on large boulders assumed to be carried along with the displacement of the entire slope. Nonetheless, an inference has to be made from this point measurement at the surface to the behavior at depth or in a larger area around the measurement. During a first phase of the project GPS stations used a simple data logger that required manual retrieval with a subsequent migration to a wireless data transfer using a low-power wireless sensor network, that

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allow data access in real-time (Beutel et al., 2011). For increasing the positioning accuracy a local GPS reference is located on a non-moving position adjacent to the rock glaciers concerned in this study. This strategy using a central GPS reference collocated in the vicinity of the moving positions under investigation allows to apply specialized differential GPS processing techniques using short baselines (0.2 to 1.5 km).

Near-surface ground temperature (GST) is measured next to each GPS station within a radius of about 7 m using five miniature temperature loggers (Maxim iButon DS1922L, cf. Gubler et al., 2011). These temperature loggers were distributed in small voids between the surrounding boulders at depths of approximately 5 to 30 cm to prevent direct solar exposure.

Air temperature and liquid precipitation is locally measured at the study site, next to the rock glacier Dirru, using an automatic integrated weather station (Vaisala WXT520). An additional weather station was mounted in summer 2013 above the rock glacier Breithorn, but this data is not used in this study as it covered less than one year. Three webcams distributed within the study site provide additional information about (actual) surface characteristics, such as snow cover extent and occurrence of water at the rock glacier fronts (e.g., Fig. 8). One weather station is located next to the rock glacier Dirru and one above the rock glacier Breithorn.

All measurements used in this study has been collected to a central database storage with web frontend available online (<http://data.permasense.ch>).

### 2.3 GPS and inclinometer data

GPS sensors as well as inclinometers are sampled continuously at 30 s and 2 min intervals respectively. From this primary raw data daily position solutions and inclinometer values are computed. For the post-processing of the raw GPS to positioning data a static approach based on a single-frequency differential carrier-phase technique has been used. It is implemented using the *Bernese* software (Limpach and Grimm, 2009; Dach et al., 2007). The SD of the GPS position solutions derived is typically about 1.5 mm in the horizontal and about 3.5 mm in the vertical direction and related

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covariances are small ( $< 0.01$  mm, Wirz et al., 2014). The inclinometer measurements mounted directly on the GPS mast allow correction of GPS positions for mast tilt (Wirz et al., 2014). SD in inclination ( $\theta$ ) are typically around  $0.4^\circ$ , and around  $2.5^\circ$  for the orientation ( $az$ ) of the mast tilt. It has been found that the correction for mast tilt is only appropriate where tilting is greater than the accuracy of the inclinometer measurements (see Supplement and Wirz et al., 2014).

GPS position data were collected continuously between summer 2011 and summer 2014. However, all stations have some significant data gaps complicating the data analysis and interpretation. During the first winter (2011/12) a large gap simultaneously visible for all positions lasting around 30 days is due to a power outage at the GPS reference location. In case of a data failure at this position the differential GPS position processing cannot be performed. Position R7a has a large data gap from 17 July 2012 to 23 April 2013 caused by a missing instrument at the respective position due to maintenance. For R6a and R6b the data series end in summer 2013. For this study we structure the total study period from 20 August 2011 to 19 August 2014 into three periods of a year each. The study years 2012, 2013 and 2014 lasting from 20 August of the previous year to 19 August of the said year e.g. study year 2012 lasts from 20 August 2011 to 19 August 2012.

## 2.4 Auxiliary data

GST measurements from the miniature temperature data loggers have an accuracy of  $\pm 0.5^\circ\text{C}$  (near  $0^\circ\text{C}$ , Gubler et al., 2011) and a temporal resolution of 3 h. For each GPS station, a daily mean GST was calculated by averaging across all measurements of the respective temperature data loggers deployed at the respective site. Applying the approach of Schmid et al. (2012), the duration of the winter snow cover and zero curtain period were derived from GST. The zero curtain period is defined as the duration of the zero curtain, the effect of latent heat in maintaining temperatures near  $0^\circ\text{C}$  over extended periods in freezing or thawing soils (e.g., Outcalt et al., 1990). Winter snow

cover and the zero curtain period was calculated for each individual station as well as jointly accross all GST data points in the study site (Wirz et al., 2015).

Air temperature and liquid precipitation measured at the local weather station are available with a temporal resolution of 2 min and an accuracy of  $\pm 0.3^\circ\text{C}$  for air temperature and  $\pm 5\%$  for liquid precipitation measurements. Air temperature was aggregated to a daily mean value. The measured sum of liquid precipitation was aggregated for daily mean and daily maximum.

Based on daily webcam images taken at noon, for each day it was subjectively classified if *new snow* (true/false), *strong melt* (true/false), a *wet front* (values, 1: clearly absent, 2: rather absent, 0: no statement possible, 3: rather visible, 4: clearly visible) or *water outflow* are visible at the active front of each rock glacier (see Fig. 8).

### 3 Methods

#### 3.1 Velocity estimations using SNRT

For the calculation of the magnitude of the horizontal velocity ( $v$ , in this paper referred to as velocity) and the direction of movement ( $azi_v$ ) the method SNRT (Signal-To-Noise Thresholding) was applied. Detailed information and a discussion of limitations and advantages of this method are given in Wirz et al. (2014). When using SNRT, temporal resolution (duration of applied smoothing window, here called *velocity period*) directly depends on the signal-to-noise ratio (SNR) of the position data and therefore varies with time.

For each velocity-period the SNR must be higher than a predefined threshold (SNR-t). A suitable SNR-t is found empirically (cf. Wirz et al., 2015), using a similar approach as Laube and Purves (2011). In this study, a threshold of 40 seems optimal, because (a) the influence of noise on estimated velocities is strongly reduced, and (b) the same SNR-t can be applied for rather slow ( $\leq 0.5\text{ m a}^{-1}$ ) and fast ( $\geq 4\text{ m a}^{-1}$ ) stations, facili-

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tating the comparison of individual stations (Wirz et al., 2015). Sensitivity of the timing of velocity changes to SNR-t is reported in Sect. 4.4.

Mean annual horizontal velocities of each study year ( $MAV_{12}$ ,  $MAV_{13}$ ,  $MAV_{14}$ ) are given as total horizontal displacements divided by time and were only calculated if within the first and last 10 days of the period at least one data point existed.  $MAV_{12-14}$  refers to the mean velocity over the entire measurement period. Inter-annual variability between the study years (2012, 2013, and 2014) was calculated with respect to the MAV of the previous year. The intra-annual variability in velocity of each GPS station is given as relative deviation to the  $MAV_{12-14}$ . The SNR of velocities in the vertical direction is much lower and therefore does not allow investigation of the intra-annual variability.

### 3.2 Detection of peaks in velocity data

Especially at two GPS stations (R2b, R7c) sudden strong peaks in velocities were observed. We here define a peak, as a velocity-period where (a) the velocity is distinctly higher, both compared to the velocity before and after the peak, and (b) the strength of the peak ( $diff_p$ ) must be greater than a threshold  $t_p$ .  $Diff_p$  is the percentage velocity ratio between the peak-velocity to the mean ( $\mu$ ) of the previous ( $v_{i-1}$ ) and following ( $v_{i+1}$ ) velocity periods ( $diff_p = \frac{v_i}{\mu(v_{i-1}, v_{i+1})}$ ). The detection of peaks is sensitive to (a) the SNR-t used to calculate velocities (here  $SNR - t = 40$ ), and (b) the threshold  $t_p$  (here  $t_p = 6$ ) used for the peak-detection (Fig. 7, Sect. 4.4).

### 3.3 Analysis of velocity peaks

To investigate the relationship between individual meteorological factors (see Sect. 2.4) and the occurrence of a peak in velocity we applied both qualitative and quantitative analyses. All analyses are performed with the software R using the packages MASS (Venables and Ripley, 2002) and pROC (Robin et al., 2011). As potential explanatory variables we used: cumulative sum and maximum of daily sum of liquid precipitation

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(Prec. and mPrec.), cumulative sum of positive degree days of air temperature ( $PDD_{air}$ ) and GST ( $PDD_{gst}$ ), number of days with visible fresh snow ( $n.snow$ ), and number of days during the zero curtain period ( $zc$ , Table 1). All variables were calculated once for the duration of the peak only and once for the days during and 7 days before peak.

Because the duration of the peaks varies, the cumulative sum is normalized by the duration of the peak (number of days).

To visualize potential relationships between individual explanatory variables and the occurrence of peaks we used spineplots (Friendly, 1994), showing the frequencies of the occurrence of velocity peaks as opposed to the absence of velocity peaks (later called no-peak-periods) on potential meteorological variables. The width of the individual bars relate to the 25 %-quantiles of the explanatory variable. Since a range of processes and meteorological variables may have been relevant for the occurrence of peaks during snowcover and snow-free conditions, we distinguished between periods with an insulating snow cover (snowcover period) and without (snow-free period). The snowcover period includes the days where an insulating snow cover can be derived from GST data (Sect. 2.4). In addition, logical values are applied to separate between periods during and outside the zero curtain period.

In order to quantify the importance of the individual variables we applied the Wilcoxon rank-sum test (Baur, 1972), with the alternative hypothesis that the distribution of explanatory variables differs for peak-periods and no-peak-periods. Based on this preliminary analysis, relevant explanatory variables could be preselected.

Logistic regressions are used to study the relationship between a set of explanatory variables and a binary response variable, such as avalanche release (Jomelli et al., 2007) or occurrence of debris flows (Xu et al., 2012), landslides (Bernknopf et al., 1988; Ohlmacher and Davis, 2003; Can et al., 2005), or rock glaciers (Brenning and Trombotto, 2006). In this study, occurrence of a peak is the binary variable and the logistic model has the form of

$$\text{logit}(x) = \ln \frac{\Pi(x)}{1 - \Pi(x)} = \beta^T x, \quad (1)$$

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where  $\Pi(x)$  is the conditional probability of the occurrence of a peak given a set of explanatory variables  $x$ , and  $\beta$  is a coefficient vector determining the contribution of each explanatory variable to a prediction (Hosmer et al., 2013). The odds of  $\Pi(x)$  are given by the ratio of  $\Pi(x)/(1 - \Pi(x))$ . If the variable  $x_i$  with coefficient  $\beta_i$  is increased by unit one, the odds of  $\Pi(x)$  change by a factor of  $e^{\beta_i}$ .

All periods of both stations (R2b and R7c) were included in the logistic regression models (number of periods used for logistic regression models:  $N = 276$ , with  $N_{\text{peaks}} = 37$ , and a median duration of the velocity periods of 6 days). As potential variables for the logistic regression, all variables with a significant  $P$  value from the Wilcoxon rank-sum test ( $p_w \leq 0.05$ ) were selected. In addition, interaction-terms with the indices for snowcover (snow.ind), for zero curtain (zc.ind) and for position (R2b and R7c) were included in the models to account for seasonal effects and differences between the individual rock glaciers. As precipitation is not normally distributed, we applied a log-transformation for Prec. and mPrec. To obtain the most appropriate models (later called final models), an iterative stepwise model selection by the Akaike-Information-Criteria was applied (AIC, Venables and Ripley, 2002). Final model performance was evaluated using the Area Under the Receiver-Operating Characteristics curve (AUROC, Hosmer et al., 2013).

## 4 Results and interpretation

### 4.1 Mean velocities and their inter-annual variability

The average mean annual horizontal velocities ( $MAV_{12-14}$ ) in the study site over the three study years ranged from 0.2 to  $6.5 \text{ m a}^{-1}$  (Table 2). Highest velocities were measured at the steep fronts of the rock glaciers Breithorn (R2b:  $6.5 \text{ m a}^{-1}$ ) and Dirru (R7c:  $4.9 \text{ m a}^{-1}$ ). The average vertical displacement ranges from 5 cm to more than 5 m per year, and were also highest for Rb2 and R7c. For R2b and R7c as well as R7a, the vertical displacement indicated a thinning of the rock glacier body (and maybe extending



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flow) as it was higher than the expected vertical change due to the horizontal displacement and the slope angle. For the other stations (R2a, R6a and R6b), the vertical displacement was less than the vertical change that would result based on the slope angle and the horizontal displacement, indicating compression (Table 2). However, uncertainties in vertical change related to slope angle were at all stations similar or even higher than the difference between the vertical change related to the slope and the measured vertical displacement and the values must be treated with care.

For the rock glaciers Dirru and Breithorn, the spatial differences further indicated extending flow: for the rock glacier Dirru, the position at the front (R7c) moved more than 4 times faster ( $4.9 \text{ m a}^{-1}$ ) than the upper station (R7a:  $1.2 \text{ m a}^{-1}$ ). Similarly, velocities of the lower station on rock glacier Breithorn were nearly 4 times higher ( $6.5 \text{ m a}^{-1}$ ) than the upper station (R2a:  $1.7 \text{ m a}^{-1}$ ). For rock glacier Steintälli, velocities of the upper lobe were 2.5 times higher (R6a:  $0.5 \text{ m a}^{-1}$ , R6b:  $0.2 \text{ m a}^{-1}$ ).

At all stations, mean annual velocities (MAV) increased over the entire observation period (2–42 %, Table 2). A continuous increase in velocity over three years is especially visible for R2a (Fig. 4). For R2b,  $\text{MAV}_{13}$  was 22 % higher than  $\text{MAV}_{12}$ , but  $\text{MAV}_{13}$  and  $\text{MAV}_{14}$  were similar (2 % for 2014). In contrast, for R7c MAV were similar in 2012 and 2013 (2 % for 2013), but MAV in 2014 were 42 % higher than in 2013. For R6a  $\text{MAV}_{13}$  were 15 %, and for R6a 33 % higher compared to  $\text{MAV}_{12}$ . Further, at all stations the minima in velocity increased from 2012 to 2014 (for R6a and R6b only data until summer 2013).

At the study site, MAAT was highest in the period 2012 ( $1.4^\circ\text{C}$ ) and coldest in 2013 ( $-0.3^\circ\text{C}$ , Table 2). Similarly the average mean annual ground temperatures (MAGST) over all iButtons, was highest in 2012 ( $0.20^\circ\text{C}$ ), and lowest in 2013 ( $0.04^\circ\text{C}$ ). Further, in Grächen at the Meteoswiss weather station (1550 m a.s.l.), the average temperature was highest in 2012 ( $6.9^\circ\text{C}$ ) and lowest in 2013 ( $5.7^\circ\text{C}$ ). Both air temperatures and GST in winter (mean in January and February) were lowest in 2012 and highest in 2014 (Fig. 3), both in the study site and in Grächen. The annual sum of precipitation at the study site was highest in the period 2014 (805 mm) and lowest in 2013 (470 mm, 2012:

545 mm). In Grächen the annual sum of precipitation was highest in 2013 (659 mm, +10 % compared to 2012 and 2013). However, at the Meteoswiss station in Zermatt (1638 m a.s.l.) highest precipitation was also observed in 2014. The snow cover duration derived from GST was longest during the period 2013 (226 days, median of GST measurements), and shortest in 2014 (195 days, 2012: 218 days). At individual stations, measured differences in MAGST between the three study years differed for the individual stations (Table 2).

## 4.2 Intra-annual variability: seasonal

At all stations, horizontal velocities have a quasi-sinusoidal form over each year, with a maximum in autumn (often around October, when neglecting the short velocity peaks at R2b and R7c) and a minimum in late winter/early spring (often around March, Figs. 3 and 4). For stations with data for all three years, the minimum in velocity occurred latest in 2013 and earliest in 2014. The amplitudes of the intra-annual variability range from less than 30 to more than 2000 %. Greatest amplitudes were observed at R7c ( $\geq 240\%$ ), especially in 2014 (2800 %). Also at R2b, the intra-annual variability was large ( $\geq 80\%$ ). For the other stations (R2a, R6a, R6b, R7a) the yearly amplitude in velocity was around 30 % (from  $-15$  to  $+15\%$ ). At individual stations the amplitudes were similar between the different years (Fig. 3).

The exact timing of acceleration and deceleration is often difficult to clearly determine, because either peaks in velocity occurred (R2b and R7c, see next section), and/or the duration of the velocity periods differ between the stations and sometimes is too long (e.g.,  $> 1$  months for R6b). Nevertheless, some observations can be made: acceleration in spring of different stations and for years started between March and May, frequently in April. The winter deceleration started between September and December, mostly in October. Differences in the start of winter deceleration between individual stations was larger ( $\sim 3$  months) compared to the differences in the start of spring acceleration ( $\sim 3$  weeks). For all rock glaciers, the deceleration started earlier at lower (R2b, R6b, R7c) than upper stations (R2a, R6a, R7a). Where data is available,

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the deceleration started latest at R2a (December). The acceleration in spring always started during the zero curtain period (Fig. 4). Further, the timing of acceleration frequently occurred nearly simultaneous for the individual stations located upon the same rock glacier (e.g. R7a and R7c in 2012 and 2014 (R7a has no data in 2013), Figs. 3 and 4). However, clear differences in the timing of acceleration and deceleration exist both between years and positions.

For the stations on R2 and R7, spring acceleration occurred more abruptly than the rather continuous and smooth deceleration in winter (Fig. 3). For R6a, and especially R6b, this is less clear, because of to the comparably long duration of the individual velocity periods (R6b: 27 d, R6b: 69 d). Nevertheless, also for R6a, a strong increase in velocity is visible during zero curtain in all study years with available data. Further, at four stations (R2b, R6a, R6b, R7a) the movement direction during the period of acceleration slightly differs from that during the period of deceleration. At all those stations, the movement direction pointed slightly more (12–15°) towards the North during the period of acceleration, respectively towards the South during the phase of deceleration.

Over the entire observation period, the yearly maxima in air temperature and GST (running mean over 60 days) was in all three study years rather similar and typically occurred in late August/September (Fig. 3). By contrast, minimum temperatures in winter increased over the three study years both for GST and air-temperature. Lowest air temperatures and GST were observed in February/March. The phase lag between temperature (air and GST) and velocity differ between the individual stations and years and is often difficult to determine (Fig. 3). It ranges from less than a month (R6a, minimum in 2012) to more than three months (R2a, maximum in 2013). As both, the depth where the main movement occurs and the thermal conditions of the rock glacier body are unknown, we did not performed any statistical analyses on the observed seasonal variability of the rock glacier velocities.

### 4.3 Intra-annual variability: velocity peaks

In addition to the seasonal variations in velocities, short peaks in velocity of a few days duration can be observed at some GPS stations. Applying the methods described in Sect. 3.3, velocity peaks were detected for the lower station on rock glacier Breithorn (R2b), and the two stations on rock glacier Dirru R7a and R7c (Figs. 4 and 5). However, at R7a only one peak was detected during the zero curtain period in 2013 (11.6.–23.6.13,  $\text{diff}_p = 8\%$ ). We therefore, limited analysis of peaks to stations R2b and R7c.

#### 4.3.1 Characteristics of velocity peaks

For R2b in total 17, and for R7c in total 20 peaks were detected (Tables 3 and A2). The velocity periods detected as peaks at the two stations occurred roughly around the same time of the year, e.g., in every year and at both stations one or more peaks were detected during the zero curtain period. Eight of those peaks, observed at R2b and R7c were synchronous, or at least overlapping. In addition, one peak at R7c directly started after a peak at R2b. Nevertheless, most of the individual peaks (R2b:  $N = 10$ , R7c:  $N = 13$ ) did not occur simultaneously at both stations, and sometimes strong peaks were detected at one station but not at the other station (e.g., 9.–11.5.12 at R2b, Fig. 5).

Peaks were detected between March and December, most frequently between May and October ( $N = 32$ ). For R7c, the number of peaks per month was highest for June ( $N = 5$ ) and July ( $N = 4$ ). For R2b, most peaks occurred in September ( $N = 4$ ) and May ( $N = 3$ ). The duration of the peaks for R2b ranged from 3 to 15 days (with a median of four days), respectively from one day to 20 days for R7c ( $\text{md} = 5$ ). The number of peaks per individual study year (2012, 2013, or 2014) varied between 5 and 7 for R2b, and 5 and 8 for R7c (Table 3). At both stations, most peaks occurred in 2014 (R2b:  $N = 7$ , R7c:  $N = 8$ ). At R7c, during each year, and for R2b in 2014, the number of peaks was higher during the snow-free than the snowcover or zero curtain period (Table 3), even when the number of peaks was normalized by the duration of the periods. At R2b, in

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2012 the number of peaks was highest during the zero curtain period. In 2013, at R2b the number of peaks was nearly identical for the snow-free and zero curtain period.

The strength of the peaks ( $\text{diff}_p$ ) was stronger at R7c (with a mean  $\mu_{\text{diff}_p} = 237\%$ , and a median  $\text{md}_{\text{diff}_p} = 47\%$ ) than at R2b ( $\mu_{\text{diff}_p} = 20\%$ ,  $\text{md}_{\text{diff}_p} = 11\%$ , Table A2). At R7c  $\text{diff}_p$  ranged from 7 to 2424 %, at R2b from 6 to 98 %. At R2b, the mean of  $\text{diff}_p$  was highest in 2012 ( $\mu_{\text{diff}_p} = 38\%$ ), and lowest in 2014 ( $\mu_{\text{diff}_p} = 11\%$ ). At R7c, the mean of  $\text{diff}_p$  was highest in 2014 (mean=484 %) and lowest in 2013 (mean = 68 %). For both stations, the strongest peaks per period occurred during the zero curtain period (Table 3). Only in 2014 at R7c, the strongest peaks happened in July during the snow-free period (8 and 21 July 2014). On average over all peaks, for R2b  $\text{diff}_p$  was stronger during the zero curtain ( $\mu_{\text{diff}_p} = 36\%$ ) than the snow cover ( $\mu_{\text{diff}_p} = 27\%$ ) or snow-free periods ( $\mu_{\text{diff}_p} = 11\%$ ). At R7c, generally peaks were stronger during the snow free ( $\mu_{\text{diff}_p} = 276\%$ ) than the zero curtain period ( $\mu_{\text{diff}_p} = 121\%$ , no peaks during the snow-cover period outside the zero curtain period).

The cumulative horizontal displacement during peaks was equal to 10 % (2.1 m, 99 days) of the total displacement for R2b and 25 % (3.6 m, 124 days) for R7c. For R2b, around 10 % (6.8°) of the total inclination occurred during peaks. For R7c, inclination was generally smaller, but such was not available for the whole period. At R2b, the displacement during the strongest peak ( $\text{diff}_p = 98\%$ ), which lasted for three days, was 9 cm. During this peak, the mast at R2b tilted by 2.5° and the elevation changed by 11 cm. However, the change in elevation corrected for the mast tilt was only 1 cm. At R7c, the displacement during the strongest peak ( $\text{diff}_p = 2424\%$ ), lasting for one day, was 49 cm and the change in elevation was 26 cm.

The deviation from the main movement direction ( $\text{diff}_{\text{azi}}$ ) was stronger during peak-periods (R2b:  $\mu_{\text{diff}_{\text{azi}}} = 17^\circ$ , R7c:  $\mu_{\text{diff}_{\text{azi}}} = 10^\circ$ ) than during no-peak-periods (R2b:  $\mu_{\text{diff}_{\text{azi}}} = 6^\circ$ , R7c:  $\mu_{\text{diff}_{\text{azi}}} = 4^\circ$ ), especially for R2b (Fig. 4). During the strongest peaks,  $\text{diff}_{\text{azi}}$  was 27° for R7c, and 123° for R2b (towards its orographic right margin). The strong  $\text{diff}_{\text{azi}}$  during the strongest peak points to a rotation of the station (around

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Z axis that could not be detected with the measurement setup). However, excluding the strongest peak at R2b, the mean of  $\text{diff}_{\text{azi}}$  of all peak-periods ( $\mu_{\text{diff}_{\text{azi}}} = 3^\circ$ ) becomes even smaller than for all no-peak-periods ( $\mu_{\text{diff}_{\text{azi}}} = 6^\circ$ ). For R7c, excluding the strongest peak has nearly no influence of the mean of  $\text{diff}_{\text{azi}}$  of peaks-periods ( $\mu_{\text{diff}_{\text{azi}}} = 10^\circ$ ).

### 4.3.2 Relation to meteorological factors

During the snow free periods, eight peaks are detected for R2b and 15 for R7c ( $N = 23$ , Table 3). For most of those peaks strong liquid precipitation ( $\geq 10$  mm) was measured during the peak ( $N = 16$ ) and/or few days before the peak ( $N = 2$ , Fig. 5, Table A2). For most ( $N = 6$ ) peaks in summer where liquid precipitation was below 10 mm, new snow that melts again within few days was observed, often ( $N = 4$ ) in combination with a rain on snow event (ROS). Only for one peak (at R7c, 27 June–1 July 2014) precipitation was below 10 mm and no new snow was observed. During this peak few remaining snow patches from winter snow cover were visible on webcam images and the cumulative sum of precipitation was 9 mm, indicating ROS. During several days ( $N = 6$ ) where the daily sum of precipitation was high ( $\geq 10$  mm) no peak was observed (Fig. 5).

The positive relationship between the occurrence of a peak during the snow-free period and the maximum of the daily sum of precipitation during the peak is also visible in spineplots (e.g., Fig. 6 and Figs. S2 and S3 in the Supplement). However, when precipitation was exceptionally high (maximum daily sum  $\geq 40$  mm), a peak was not always detected (Fig. 5). In addition, for both stations the number of peaks is higher when new snow was observed during or seven days before the peak (e.g., Fig. 6), but few no-peak-periods occurred when new snow was detected.

During the snowcover period ( $N = 14$ ), except for two peaks at R2b, all peaks ( $N = 12$ ) were during the zero curtain period, in combination with a ROS (Fig. 5 and Table A2). During two peaks no meteo data are available, but during those peaks new snow and strong melt was visible on webcam images. The peaks outside the zero curtain period can be related to new snow and strong melt (December 2011), as well as

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rain on snow (December 2012, Fig. 5 and Table A2). For both stations, during the snow cover period a positive relationship between number of days during zero curtain or increasing  $PDD_{air}$  during the peak and number of peaks exists (e.g., Figs. S2 and S3). For R7b, in addition, the number of peaks increases with mean and maximum sum of precipitation during the peak.

Based on those observations and the  $P$  values of the Wilcoxon rank-sum test (Table S1 in the Supplement) the potential variables for the full logistic regression models were: mean and maximum sum of precipitation,  $PDD_{gst}$  and  $PDD_{air}$ , during, as well as 7 days before, the peak, and the indices for snow cover (snow.ind) and zero curtain (zc.ind).

The AUROC values of the final-models ( $N = 16$ , e.g. Table 4) ranged from 0.76 to 0.85. Hence, according to Hosmer et al. (2013), these models were fair to good. Although, different variables for precipitation and temperature were included in the final models, the estimates for precipitation and temperature were similar. The highest AUROC was obtained if sum of liquid precipitation and  $PDD_{gst}$  during the peak were included in the full-model (Table 4). An overview of all final logistic regression models, the included variables and the AUROC values is given in Table S2.

All the final models included precipitation, and its interaction-term with snowcover. Additionally, some contained the interaction-term of precipitation with position ( $N = 13$ ), with temperature ( $N = 7$ ), and/or with zero curtain ( $N = 6$ ). In nearly all the models ( $N = 15$ ) precipitation was significant. Temperature was included in eleven of the final models, but was only significant in three.

The coefficients of the final models indicate the following (values refers to the final model with highest AUROC, Table 4): chances for the occurrence of a peak are generally higher during the snow-free period than during winter conditions and higher for R7c than for R2b (a reduction of the odds for R2b of approximately 0.5). Zero curtain has the strongest influence on odds; during zero curtain the odds for the occurrence of a peak increase by more than 14 times, but uncertainties are large (Table 4). The estimates for precipitation were mostly higher for the mean than the maximum sum of

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precipitation, and generally higher if only the days during the peak were included. In all final models the influence of precipitation on the odds are higher during the snow-free than the snowcover period and stronger for R7c than for R2b. For example, during the snow-free period an increase of  $\log(\text{Prec.0})$  by one unit leads to an increase in the odds by a factor of 4 for R7c, and a factor of 2 for R2b. A change in temperature (by one degree) generally has a smaller influence on odds than a change in precipitation by one unit.

### 4.4 Sensitivity tests

Applying different SNR-t values has a negligible influence on the observed seasonal variability for all stations (e.g., Fig. 7b). The detection of peaks, however, is sensitive to the applied thresholds. The higher the SNR-t, the less peaks are detected and the start of a peak is often delayed (Fig. 7a and b). Hence, for SNR-t a balance between the reliability of a peak and the detection of all peaks needs to be considered.

For small SNR-t ( $< 20$ ), velocities are influenced by noise and hence, velocity peaks are potentially caused by noise in the GPS positions (Wirz et al., 2014). For higher SNR-t ( $\geq 30$ ), variability is strongly reduced, velocities become more stable, and differences between the variability of estimated velocities (and detected peaks) for different SNR-t become smaller. In addition, the number of peaks during high winter (December–March) is strongly reduced. However, with a SNR-t of 40 peaks were almost solely detected for stations with high velocities (R2b and R7c). Further, the number of detected peaks also depends on the applied threshold  $t_p$  (Fig. 7c). The influence of  $t_p$  is larger for R2b than for R7c. For R7c, for  $t_p \geq 3\%$  the number of peaks is almost stable. For R2b, with  $t_p \geq 6\%$  the number of peaks become quite stable and detected peaks correspond well with manually identified peaks.

We studied the sensitivity of our statistical analysis of peaks to a change in SNR-t (20, 40) and  $t_p$  (6, 10) and found that a change in the SNR-t and  $t_p$  has little influence (cf. Tables S3, S4, and S6): for example, independent of the applied thresholds, the estimates for precipitation, temperature and zero curtain are similar in all in all final

models and the highest AUROC (“best” model) was always obtained if sum of precipitation and PDD<sub>gst</sub> during the peak were included.

## 5 Discussion

This section is structured according to the research questions formulated at the beginning of this paper. In Sect. 5.1, we discuss how the observed main patterns on the short-term variability of this study compare with the observations in previous studies (summarized in Table A1). In Sect. 5.2 potential controlling factors and related processes causing the observed short-term variability are discussed. In Sect. 5.2.4, we discuss the main advantages and limitations of our approach.

### 5.1 Short-term variability of velocities in the context of previous research

*The observed intra-annual patterns of the short-term variability on the rock glaciers within this study area generally correspond well with observations in earlier studies.*

This paper further supports the results of Wirz et al. (2015) with an additional year’s worth of data. The observed intra-annual patterns on the rock glaciers within this study area are similar to observations made in previous studies on the intra-annual variability (Table A1): the seasonal cycle and the timing of minima and maxima in velocity observed in this study agrees well with previous observations on rock glaciers (Table A1, Haeberli, 1985; Roer, 2005; Kääb et al., 2005; Perruchoud and Delaloye, 2007; Buchli et al., 2013), although differences between individual rock glaciers and from year to year have been reported (Delaloye et al., 2010). Similarly, as described by Haeberli (1985), the maximum in velocity occurred earlier at the lower station than the upper station on the same rock glacier (Fig. 3).

Compared to most of the earlier studies, the higher temporal resolution of our measurements (for most of the stations) allows us to detect more details in the intra-annual variability of rock glacier velocities, such as the timing of seasonal acceleration, an

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asymmetric seasonal cycle and velocity peaks. Already in previous studies, a smoother deceleration in winter than acceleration in spring was observed (Table A1, e.g., Perruchoud and Delaloye, 2007). However, as for the stations on the rock glacier Steintälli, such an asymmetric annual cycle was not always detected in previous studies (e.g. on Muragl rock glacier, Arenson et al., 2002; Kääb, 2005; Krainer and He, 2006). Both the rock glacier Muragl and Steintälli have velocities of less than  $0.5 \text{ m a}^{-1}$ , and hence, the lacking of an asymmetric annual cycle could also result from the coarser temporal resolution of the velocities ( $\sim$  monthly, Sect. 4.4).

Previously, short abrupt velocity peaks in rock glacier velocities were only detected on one rapidly moving rock glacier in a nearby valley during snowmelt (Furggwanhorn rock glacier with  $\text{MAV} > 3 \text{ m a}^{-1}$ , Buchli et al., 2013). However, in most of the previous studies, temporal resolution was too low to be able to detect such short-lived velocity peaks. The coarser temporal resolution of the velocity estimations (median duration of  $\geq 15 \text{ d}$ , Sect. 5.2.4) might also explain why for rock glacier Steintälli (R6a, R6b) and at the upper stations of the rock glacier Breithorn (R2a) and Dirru (R7a) almost no such peaks, lasting only few days, were detected.

## 5.2 Effects of meteorological factors and hypotheses on underlying processes

The aim of the following is to discuss plausible factors and potential underlying processes that might control the observed patterns of the short-term (inter- and intra-annual) variability of rock glacier movements. Both velocities and meteorological factors are measured at the surface, however, the actual movement and the related processes occur at depth, and therefore an inference has to be made from point measurements at the surface to depth and across the entire landform.

### 5.2.1 Seasonal cycle

*The findings of this study suggest that rock glaciers have a seasonal cycle in velocities, where seasonal acceleration seems to be strongly influenced by meltwater and the amount of seasonal deceleration by winter temperatures.*

5 The seasonal decrease in velocity was typically smooth and occurred with a phase lag of few weeks to months to decreasing air temperature and GST (Fig. 3). In winter, decreasing air temperatures lead through the process of heat conduction to a phase-lagged decrease of the ground temperatures, which may be influenced by a snow cover, but very seldom by water infiltration. Hence, the smooth deceleration in winter may be a result of a decrease in water content within a rock glacier (and shear horizon in particular) as a result of strongly reduced water input (percolation) during winter conditions (nearly no liquid precipitation and snowmelt leading to drainage, Coe et al., 2003) and/or influenced by slow refreezing of pore water as a result of heat loss (e.g., Ikeda et al., 2008). The observation that both observed minimum temperatures in winter and minimum velocities in winter increased over the three study years, suggest that winter temperatures influence deceleration of rock glacier movements in winter, as previously proposed by various authors (Ikeda et al., 2008; Kääb et al., 2007; Delaloye et al., 2010). Higher temperatures in winter, lead to a reduced ground cooling and, therefore, to an increase in the strain rates of the ice in the frozen matrix (e.g., Yamamoto, 2013), and to a higher amount of the unfrozen water content (especially if temperatures were close to 0 °C, Anderson et al., 1973; Arenson et al., 2002), both facilitating slope movement. Commonly, higher GST in winter are associated with a thicker insulating snow cover (e.g., Ikeda et al., 2008). This, however, is unlikely for this study (at the Meteoswiss station in Grächen the thickest winter snow cover (mean in January and February) occurred in 2012).

By contrast, to the smooth deceleration in winter, an abrupt and strong acceleration in spring was observed at most stations. At all stations acceleration commenced during snowmelt periods (zero curtain), frequently at its beginning. These observations

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5.2.2 Short velocity peaks

Based on the observations of this study we hypothesize that peaks in velocities were mainly caused by strong water infiltration from heavy precipitation or strong snowmelt during or few days before the peak.

Velocity peaks detected at R2b and R7c, all occurred outside cold winter conditions and during or shortly after (few days) high water input, either from heavy precipitation or snowmelt (indicated by ROS during zero curtain period, cf. Marks et al., 2001), and sometimes from late summer snowfall that melts again within few days (Fig. 5). Both the qualitative and the statistical analyses have shown that the influence of temperature is weaker and indicate that likely no peak was solely caused by high temperatures without associated water input.

Water infiltration from heavy precipitation or snow meltwater may lead to an increase of the pore water pressure and hence a reduction of the shear resistance (cf. Terzaghi, 1943), thus trigger increased velocities. At both stations, maximum velocities at R2b and R7b within a year were mostly measured during peaks in the zero curtain period in combination with ROS. Similarly, the two observed velocity peaks during the snowmelt period at the Furggwanhorn rock glacier are supposed to be caused by snow meltwater, that infiltrating through the active layer and running off the permafrost body, thus, reducing here the shear resistance (Buchli et al., 2013). The short duration of the peaks further suggests that the infiltrated water runs off within a short time. Indeed, the few existing studies on the hydrology of rock glaciers all have shown that water is transmitted through the rock glacier within few hours (Krainer and Mostler, 2002; Ikeda et al., 2008; Buchli et al., 2013). They further observed that water flows in direct contact with the ice (Krainer et al., 2007), which might indicate that ground ice act as barrier of flow. Further, the observed short time-lag between the water input (e.g., precipitation) and the start of the velocity peak further indicates that the infiltrated water reached the shear horizon(s) within a short time and/or that the corresponding shear horizon lies at rather shallow depths (e.g., active layer base Buchli et al., 2013). Indeed, the velocity

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peaks at the Furggwanghorn rock glacier were caused by a displacement at the active layer base (at 4 m depths, Buchli et al., 2013). However, as in this study only measurements at the surface are available it is unknown where the measured movement actually took place and if the infiltrated water reached the corresponding shear horizon (Fig. 1).

Only approximately half of the peaks occurred simultaneously at the two stations, more frequently during the snow-free period. In addition, velocity peaks were not always detected after/during strong precipitation events or rain on snow events during the zero curtain period and no clear reasons were found why in those cases no velocity peak occurred. A potential explanation for those observations, especially during the snowmelt period, might be that the amount of water-infiltration caused by snowmelt can vary significantly even within a catchment (Grünewald et al., 2010). The timing and intensity of heavy rain in summer can also vary significantly even within a small catchment (e.g., Goodrich et al., 1995). Indeed, the measured precipitation during single rain fall events in summer 2014 sometimes varied significantly between the two weather stations within the study site. Those observations, however, also indicate that the exact circumstances causing a velocity peak are still largely unknown.

Speed-up events of short duration are a well known phenomenon for glaciers and are generally assumed to result due to a high water input into a poorly connected drainage system and to terminate as soon as the drainage system becomes more channelized and more efficient (Kamb, 1987; Nienow et al., 1998). Two observations, however, indicate that at least part of the drainage system was already channelized before the velocities started to increase: (a) the location of the water outflow visible at the front of rock glacier Dirru during periods of strong melt (e.g., Fig. 8) remained more or less constant over the three years, indicating that at least a part of the drainage system of R2 and R7 likely remained rather constant. (b) The spring at the front of Dirru always became visible before (or at the same time) velocities started to accelerate.

Potentially, high velocities in combination with steep topography, might lead to a positive feedback mechanism: high velocities of rock glacier tongues, in combination with



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the steep topography, possibly lead to a thinning of those rock glacier tongues, as was indicated by the observations of this study (Sect. 4.1). High velocities are often associated with open fissures and depressions, as it was observed in this study (Fig. 8) as well as on other fast-moving rock glaciers (e.g., Roer et al., 2008; Delaloye et al., 2013; Buchli et al., 2013). In addition, high velocities could lead to more open pore spaces (dilatancy effect) and, hence, to a higher permeability of the ground that favoring fast water infiltration. All those effects likely enhance the exposure of the shear horizon(s) to changes in water infiltration or temperature and therefore might lead to increasing velocities.

### 5.2.3 Inter-annual variability

The observed increase in mean annual velocities over the three years is in good agreement with the observed average increase in velocities of +32 % from summer 2012 to summer 2014 observed at eight rock glaciers in the Valais and Bernese Alps made by the Swiss permafrost monitoring network (PERMOS, 2015). In previous studies, frequently a positive correlation between annual velocities of rock glaciers and MAGST was observed (e.g., Hoelzle et al., 1998; Delaloye et al., 2010; PERMOS, 2013), but with a phase lag of between 1 year and several months (Delaloye et al., 2010). And both for rock glaciers and deep-seated landslides, higher velocities have been measured in years with a thicker snow cover (e.g., Ikeda et al., 2008; Crosta and Agliardi, 2003). In this study, the temporal time period is too short (and variations in MAGST too low) to draw conclusions on any such link. However, our results indicate a strong influence of water infiltration. Furthermore, winter temperatures seem to influence minimal velocities. The observations regarding intra-annual variability indicate a complex interplay of factors, acting on different time scales (few days–season).

5.2.4 Advantages and limitations of our approach

The observed intra-annual variability strongly depends on the temporal resolution of the velocity estimations. In comparison to most previous studies, our data have a much higher temporal resolution (Table A1, e.g., Haeberli, 1985; Kääb et al., 2003; Perruchoud and Delaloye, 2007; Liu et al., 2013). Furthermore, in comparison to the few earlier studies with similar high temporal resolution (daily), our measurements have (a) a much longer temporal coverage, and (b) with three neighboring rock glaciers a better spatial coverage (earlier studies with high temporal resolution only included 1–3 point measurements on a single rock glacier, Roer, 2005; Krainer and He, 2006; Buchli et al., 2013, Table A1).

A key advantage of the method SNRT is that the smoothing windows directly depend on the SNR of the data (Wirz et al., 2014). This, however, implies that temporal resolution of the velocity estimations may differ between individual stations. Where velocities are lower, the velocity periods need to be larger to get an SNR above SNR-t. For the relatively slow stations R6a and R6b, with average duration of one, respectively two months for R6b, the temporal resolutions of velocities are similar to most of the previous studies on intra-annual variability of rock glaciers (e.g., Perruchoud and Delaloye, 2007; Liu et al., 2013). However, for the other stations, velocity estimations presented in this study have a much higher temporal resolution (few days–two weeks) compared to such previous studies. The temporal resolution of the position measurements is similar to those from Buchli et al. (2013) and Krainer and He (2006), but the temporal coverage in those studies was less than a year and thus periods with similar seasonal conditions occurred only once.

A main limitation of our data is that we only have few point measurements on individual landforms at the surface, that (a) are not necessarily representative for the entire landform, or parts of it (e.g. rock glacier tongue), and (b) refer to the cumulative displacement potentially occurring at different depths (Fig. 1). However, surface velocity measurements with a high spatial resolution have shown that the velocity field is rather

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homogenous (at least along the central flow line, e.g., Kääb et al., 2003). Furthermore, remote sensing data showed that movements extend across the whole active lobe of Dirru (R7a and R7c, Strozzi et al., 2009a) and Breithorn (R2a and R2b Strozzi et al., 2009b). In addition, surface velocity measurements form a good approximation of the deep movement (Lambiel and Delaloye, 2004), as the main movement within a rock glacier is concentrated within a thin shear horizon (e.g., Arenson et al., 2002), although the movement may occur at different depths (Fig. 1, cf. Roer et al., 2008): The observed displacement at the surface can result due to (1) a displacement within one (Arenson et al., 2002) (or (3) several shear horizons Delaloye et al., 2013), (2) internal deformation above the shear horizon (however this is mostly small, Arenson et al., 2002), (4) a displacement of the active layer (Buchli et al., 2013), (5) a sliding of the front similar to a rotational slide (Roer et al., 2008), and/or (6) a displacement or rotation of a single boulder (Wirz et al., 2014).

## 6 Conclusions and further work

Within this study, continuous GPS measurements from summer 2011 to summer 2014, on three rock glaciers with distinct morphology, have been analyzed in relation to meteorological factors, such as GST, air-temperature, precipitation, and snow(melt). The presented dataset is unique regarding the high temporal resolution of the measurements (daily) in combination with the comparably long temporal (2–3 years) and spatial coverage (6 stations on three independent rock glaciers). The high temporal resolution (daily) of the data allows us to investigate the influence of meteorological factors, and their changes, on the short-term variability of rock glacier movement. We performed detailed qualitative and statistical analyses on the intra-annual variability of rock glacier movement, with a clear focus on the short-term peaks, and its relation to meteorological factors. The main findings of this study are:

- The seasonal variability of the rock glacier movement is strongly influenced by snow meltwater infiltration and winter temperatures, as indicated by the obser-

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vation that both velocities (lowest velocities in winter and MAV) and winter-temperatures increased over the observation period, and that the spring acceleration is mostly rapid and abrupt and always started during the snowmelt period.

- At two steep fast-moving rock glacier tongues in addition to the seasonal cycle, short velocity peaks occurred immediately after strong water input from snowmelt (in combination with ROS) and heavy precipitation. This rapid and high magnitude response in rock glacier movement suggests high water input events with rapid infiltration into the rock glacier body as a forcing mechanism.

Our measurements, and the statistical analyses, revealed that both large similarities, but also clear differences in the reaction to changes in environmental factors and the resulting short-term variability exist, both between different rock glaciers but also different parts (e.g. tongue vs. middle) of the same landform.

The high resolution and spatial proximity of GPS and meteorological measurements allowed us to study and demonstrate the influence of meteorological factors on the short-term variability of the movements for three different rock glaciers. However, it is likely that the surface movement on rock glaciers derives from movements occurring at different depths. To identify the depth of the movement, subsurface measurements would be required.

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**Table 1.** Overview of used potential explanatory variables. As potential important time we used during the peak, as well including the days during the peak and 7 days before the peak. For precipitation for the logistic regression models a log-transformation was applied (log).

Name	Description	Used data	log
Prec	Mean daily rain-sum	weather station in the study site	yes
mPrec	Maximum daily rain-sum	weather station in the study site	yes
PDD <sub>air</sub>	Mean sum of Positive Degree Days derived from daily mean air-temperature	weather station in the study site	no
PDD <sub>gst</sub>	Mean sum of Positive Degree Days derived from GST	GST of iButtons next to the GPS	no
n.snow	Mean number of days with fresh snow	webcam images	no
zc	Mean number of days during zero curtain	derived from GST of all iButtons	no
with adjunct	time period	example	
0	days during peak-period	Prec.0	
7	days during peak-period as well as 7 days before	Prec.7	



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**Table 2.** Characteristics of individual GPS stations.  $N$ : number of daily GPS fixes obtained; from/to: measurement period;  $\text{disp}_{\text{tot}}$ : total displacement;  $\text{disp-ele}_{\text{tot}}$ : total vertical displacement;  $\text{disp-ele}_{\alpha}$ : vertical displacement related to slope angle;  $\text{MAV}_{12-14}$ : mean velocity for the entire measurement period;  $\text{MAV}_{12}/\text{MAV}_{13}/\text{MAV}_{14}$ : mean annual velocities; As the uncertainties in the estimation of the slope angle, relevant for the correction of the vertical displacement, is quite uncertain, we added for  $\text{disp-ele}_{\alpha}$  in parentheses, the vertical change related to an increase of the slope by  $5^{\circ}$ .

pos	$N$	from	to	$\text{disp}_{\text{tot}}$ [m]	$\sigma_{\text{disp}}$ [mm]	$\text{disp-ele}_{\text{tot}}$ [m]	$\text{disp-ele}_{\alpha}$ [m]	$\text{MAV}_{12-14}$ [ $\text{m a}^{-1}$ ]	$\text{MAV}_{12}$ [ $\text{m a}^{-1}$ ]	$\text{MAV}_{13}$ [ $\text{m a}^{-1}$ ]	$\text{MAV}_{14}$ [ $\text{m a}^{-1}$ ]	$\text{MAGST}_{12}$ [ $^{\circ}\text{C}$ ]	$\text{MAGST}_{13}$ [ $^{\circ}\text{C}$ ]	$\text{MAGST}_{14}$ [ $^{\circ}\text{C}$ ]
R2a	846	25 Feb 2012	19 Aug 2014	4.29 <sup>1</sup>	0.006	1.59 <sup>1</sup>	2.0 <sup>1</sup> (0.5)	1.7 <sup>1</sup>	1.4 <sup>2</sup>	1.6	2.0	NA	0.93	0.59
R2b-f	981	20 Aug 2011	19 Aug 2014	20.32	0.01	14.97	13.7 (2.7)	6.8	5.9	7.1	7.3	1.38	1.09	1.67
R6a	601	20 Aug 2011	19 Aug 2013	1.02	0.006	0.16	0.4 (0.1)	0.5	0.4	0.6	NA	0.26	0.31	NA
R6b	644	20 Aug 2011	19 Aug 2013	0.41	0.005	0.10	0.1 (0.04)	0.2	0.2	0.2	NA	0.53	0.37	NA
R7a	700	20 Aug 2011	19 Aug 2014	3.50 <sup>3</sup>	0.005	1.20 <sup>3</sup>	1.1 (0.3)	1.2	1.4 <sup>4</sup>	NA	1.7	0.31	−0.45	NA
R7c	784	20 Aug 2011	19 Aug 2014	14.59	0.006	9.62	9.5 (1.9)	4.9	4.2	4.3	6.1	0.38	0.15	0.38

<sup>1</sup> Refers to measurements from 23 Feb 2012 to 19 Aug 2014.

<sup>2</sup> Refers to measurements from 23 Feb 2012 to 19 Aug 2012.

<sup>3</sup> Has data gap from 18 Jul 2012 to 22 Apr 2013.

<sup>4</sup> Refers to measurements from 20 Aug 2011 to 17 Jul 2012.

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**Table 3.** Peaks observed at R2b and R7a during the three different years of observation. For each year the duration (days) of the snow-free, the snow cover, and the zero curtain period is given. The first number in brackets indicates the number of peaks during winter snow cover (including the zero curtain period), the second number in the brackets refers to the number of peaks during the zero curtain period. Both, winter snow cover and zero curtain period are derived from GST measurements (Sect. 2.4).

study year	snow-free	snow	zc	Peaks R7c	Peaks R2b
2012	104	262	83	5 (1, 1)	5 (4, 3)
2013	95	270	96	7 (3, 3)	5 (3, 2)
2014	150	215	79	8 (1, 1)	7 (2, 1)
total				20 (5,5)	17 (9,6)

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**Table 4.** Model coefficients (and standard errors in parentheses) of the the final model with highest AUROC values (final model 1) and the final model with highest AUROC where temperature was not included (final model 2). In addition, the corresponding AUROC and AIC values are given.

	final model 1	final model 2
(Intercept)	−0.61 (0.64)	−1.54 (0.44) <sup>***</sup>
log(Prec.0)	1.42 (0.40) <sup>***</sup>	1.04 (0.28) <sup>***</sup>
PDD <sub>gst</sub> .0	−0.17 (0.09) <sup>*</sup>	–
zc.indTRUE	2.57 (1.33).	3.65 (1.52) <sup>*</sup>
snow.indTRUE	−2.81 (1.50).	−3.40 (1.63) <sup>*</sup>
pos55	−0.75 (0.49)	−0.87 (0.48).
log(Prec.0):PDD <sub>gst</sub> .0	−0.047 (0.04)	–
log(Prec.0):snow.indTRUE	−0.93 (0.33) <sup>**</sup>	−0.71 (0.24) <sup>**</sup>
log(Prec.0):pos55	−0.56 (0.27) <sup>*</sup>	−0.50 (0.24) <sup>*</sup>
AUROC	0.85	0.83
AIC	152.1	156.6

Significance of Wald test: <sup>\*</sup> < 0.05, <sup>\*\*</sup> < 0.01, <sup>\*\*\*</sup> < 0.001.

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**Table A1.** Overview of previous studies on the intra-annual variability of rock glacier movement found in literature. For each study (if available) the following information are listed: name and location of investigated rock glacier(s) (Location), the number of measurement points ( $N$ ), the surveying technology (Technology), the observation period (Period), and the temporal resolution (Resolution). In addition for each study it is indicated if the following observations have been made (yes: was observed, no: was not observed, ?: no statement): a seasonal cycle of the movement (Seasonal cycle), a smoother seasonal deceleration than acceleration (Smoother deceleration), the seasonal acceleration started during the snowmelt period (Acceleration during snowmelt).

Location	$N$	Technology	Period	Resolution	Seasonal cycle	Smoother deceleration	Acceleration during snowmelt	Reference
Murtel/Muragl (Grison, Switzerland)	45/14	Photogrammetry	1971–1973		yes	?	?	Barsch and Hell (1975) Wagner (1994)
Gruben (Valais, Switzerland)	8	Electro-optical distance measurement	Aug 1979–Aug 1982	~ 3 months	yes	?	?	Haeberli (1985)
Muragl (Grison, Switzerland)	20	Total station	1998–2001	~ 4 months	yes	no	no	Kääb et al. (2003) Kääb et al. (2005)
Reichenkar (Stubai Alps, Austria)	3	GPS	Jul–Sep 2003 and (Jun–Oct 2002)	10 s (87 d)	no	no	no	Krainer and He (2006)
Oelgrube (Stubai Alps, Austria)	21	GPS	Jul–Sep 2003	55 days	yes	?	?	Krainer and He (2006) Hausmann et al. (2007)
Tsarmine (Valais, Switzerland)		GPS	Oct 2004–Aug 2005	≥ 8 months	yes	?	?	Lambiel and Delaloye (2004) Lambiel et al. (2005)
Huhh1 in Hungerlitalli (Valais, Switzerland)	25	Terrestrial geodetic survey	Jul–Aug 2003	36 days	yes	?	?	Roer (2005)
Furggentaelti (Bernies Alps, Switzerland)	32	Tachymetry	autumn 1998–1999 (one year)	monthly	yes	yes	yes	Mihajlovic et al. (2003) Krummenacher et al. (2008)
Becs-de-Bosson (Valais, Switzerland)	61 <sup>3</sup>	GPS	2004–2006	30–60 days	yes	yes	yes	Perruchoud and Delaloye (2007) Delaloye et al. (2010)
Furggwanghorn (Valais, Switzerland)	1	Borehole inclinometer	Oct 2010–May 2011	daily	yes	yes	yes	Buchli et al. (2013)
Mount Gibbs (Sierra Nevada, USA)	1	InSAR	Apr 2007–May 2008	48–138 days	yes	?	?	Liu et al. (2013)

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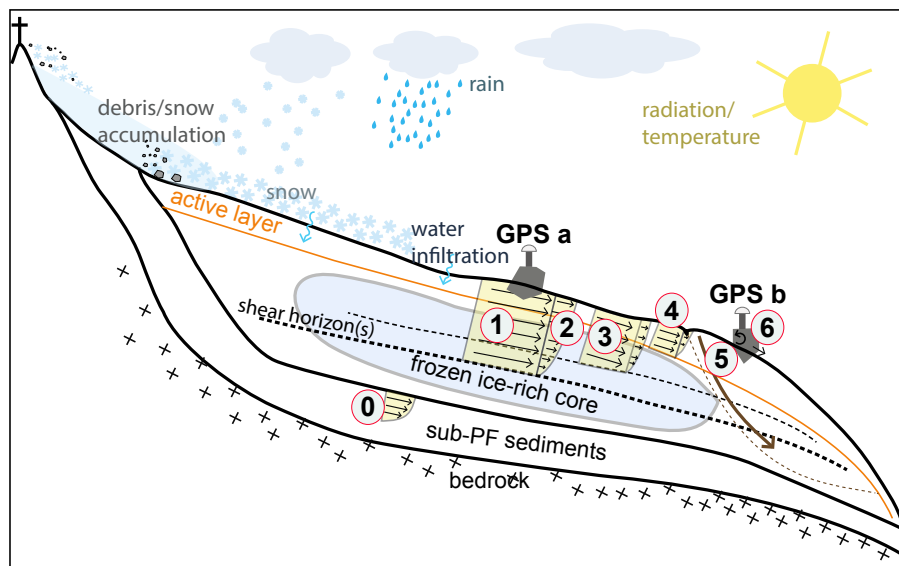


**Table A2.** Detected peaks. Main characteristics, including  $\text{diff}_p$ , during the period of winter snow cover (snow), during zero curtain (zc) are given. In addition, supposed main triggers are given: f.snow: fresh snow that melts again within few days, rain.p: intense ( $> 10$  mm) liquid precipitation during the peak-period, rain.bp: intense liquid precipitation before the peak (within  $\leq 7$  d before the start of the peak-period), high.T: high temperature in summer, melt: strong snowmelt in winter/spring, ROS: rain on snow event.

pos	from	to	dur	vel	$\text{diff}_p$	snow	zc	f.snow	rain.p	rain.bp	high.T	melt	ROS
R7c	10 Sep 2011	23 Sep 2011	14	0.02	10	F	F	x	x				x
R2b	10 Sep 2011	23 Sep 2011	14	0.02	11	F	F	x	x				x
R7c	5 Oct 2011	11 Oct 2011	7	0.01	7	F	F	x	x				
R2b	12 Dec 2011	18 Dec 2011	7	0.02	9	T	F	x				x	(x)
R2b	13 Apr 2012	19 Apr 2012	7	0.01	65	T	T	x				x	x
R2b	9 May 2012	11 May 2012	3	0.03	98	T	T					x	(x)
R7c	3 Jun 2012	5 Jun 2012	3	0.08	314	T	T					x	(x)
R2b	13 Jun 2012	18 Jun 2012	6	0.02	7	T	T					x	(x)
R7c	23 Jun 2012	12 Jul 2012	20	0.02	37	F	F		x		x		
R7c	3 Aug 2012	9 Aug 2012	7	0.01	21	F	F		x				
R7c	30 Aug 2012	4 Sep 2012	6	0.02	37	F	F	x	x				
R2b	1 Sep 2012	4 Sep 2012	4	0.02	11	F	F	x	x				
R7c	6 Oct 2012	10 Oct 2012	5	0.02	46	F	F		x	x			
R2b	26 Dec 2012	30 Dec 2012	5	0.02	7	T	F					x	x
R7c	16 Apr 2013	22 Apr 2013	7	0.01	52	T	T	x				x	
R2b	9 May 2013	12 May 2013	4	0.03	30	T	T					x	x
R7c	10 May 2013	14 May 2013	5	0.02	50	T	T					x	x
R2b	15 Jun 2013	18 Jun 2013	4	0.03	6	T	T					x	(x)
R7c	19 Jun 2013	21 Jun 2013	3	0.04	155	T	T					x	x
R7c	26 Jul 2013	30 Jul 2013	5	0.02	49	F	F		x				
R7c	8 Aug 2013	11 Aug 2013	4	0.02	90	F	F		x	x			
R2b	8 Aug 2013	11 Aug 2013	4	0.03	14	F	F		x				
R2b	7 Sep 2013	11 Sep 2013	5	0.03	17	F	F		x				
R7c	14 Sep 2013	18 Sep 2013	5	0.02	46	F	F	x					x
R2b	15 Sep 2013	18 Sep 2013	4	0.03	10	F	F	x					x
R7c	22 Oct 2013	25 Oct 2013	4	0.03	125	F	F	(x)					x
R2b	22 Oct 2013	25 Oct 2013	4	0.03	11	F	F	(x)					x
R2b	15 Mar 2014	29 Mar 2014	15	0.01	12	T	F	x				x	
R2b	20 May 2014	24 May 2014	5	0.02	12	T	T					x	x
R7c	24 May 2014	28 May 2014	5	0.03	33	T	T					x	x
R7c	17 Jun 2014	18 Jun 2014	2	0.06	102	F	F		x				x
R7c	27 Jun 2014	1 Jul 2014	5	0.03	22	F	F		(x)				x
R7c	8 Jul 2014	8 Jul 2014	1	0.49	2424	F	F	x					
R7c	21 Jul 2014	21 Jul 2014	1	0.27	1075	F	F	x					
R2b	27 Jul 2014	30 Jul 2014	4	0.03	7	F	F		x	(x)			
R7c	28 Jul 2014	11 Aug 2014	15	0.03	41	F	F		x	x			
R2b	11 Aug 2014	14 Aug 2014	4	0.03	8	F	F		x				

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**Figure 1.** Schematic profile of a rock glacier. The observed movement at the surface might result from movement at different depths of the rock glacier (cf. Roer et al., 2008): (0) Deformation of sub-permafrost sediments (cf. Roer et al., 2008), (1) displacement within main shear horizon (e.g., Arenson et al., 2002), (2) (little) internal deformation above shear horizon (e.g., Arenson et al., 2002), (3) displacement within additional shear horizon(s) (e.g., Delaloye et al., 2013), (4) displacement at base/within AL (e.g., Buchli et al., 2013), (5) displacement due to rotational slide (e.g., Roer et al., 2008), and/or (6) displacement/rotation of boulder at surface (Lambiel and Delaloye, 2004). Dashed lines within the rock glacier body indicate potential shear horizons.

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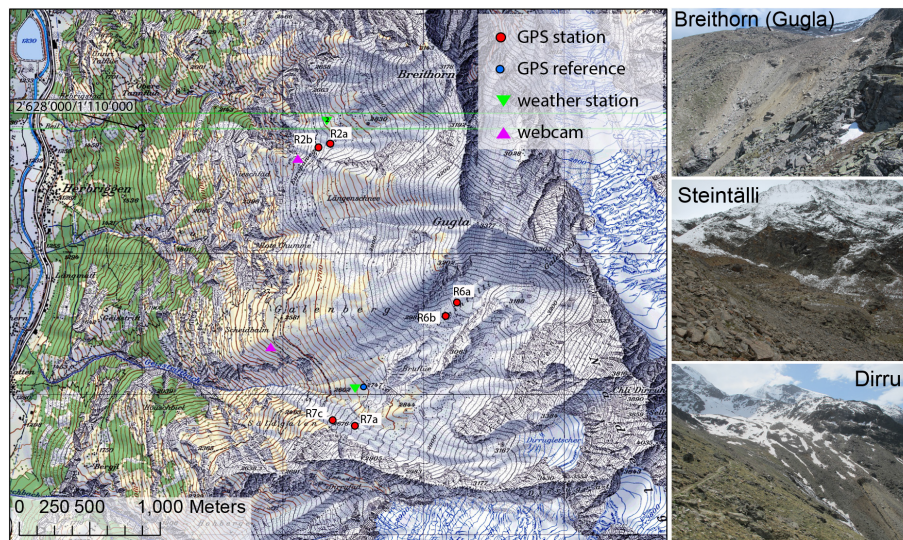
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**Figure 2.** Overview of study site and main instrumentation. Note, that the weather station next to the rock glacier Breithorn only has data since summer 2013. Right: field impressions of rock glacier Breithorn (R2), Steintälli (R6) and Dirru (R7). Background: topographic map LK25 from the year 2013 reproduced by permission of Swisstopo BA15027.

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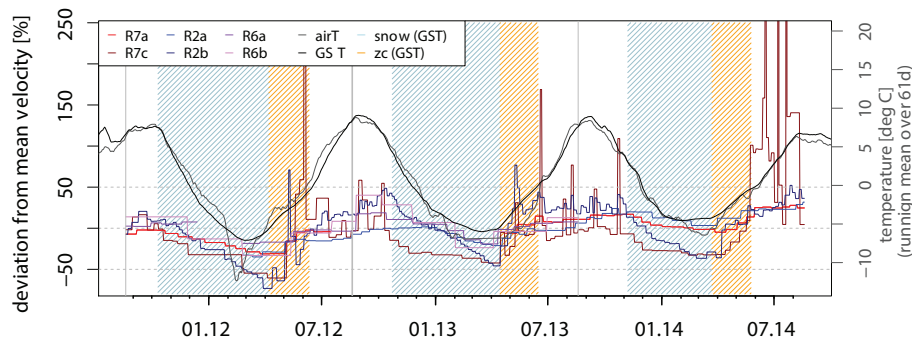
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**Figure 3.** Intra-annual variability of horizontal velocities. Left y axis: intra-annual variability, expressed as deviation from  $MAV_{12-14}$ . Right y axis: filtered air temperature and GST (running mean over 61 days). The period of an insulating snow cover (light blue) and zero curtain (orange) is shadowed. Vertical grey lines separate the three different years of observation (2012, 2013, 2014). Small figure shows the absolute velocities.

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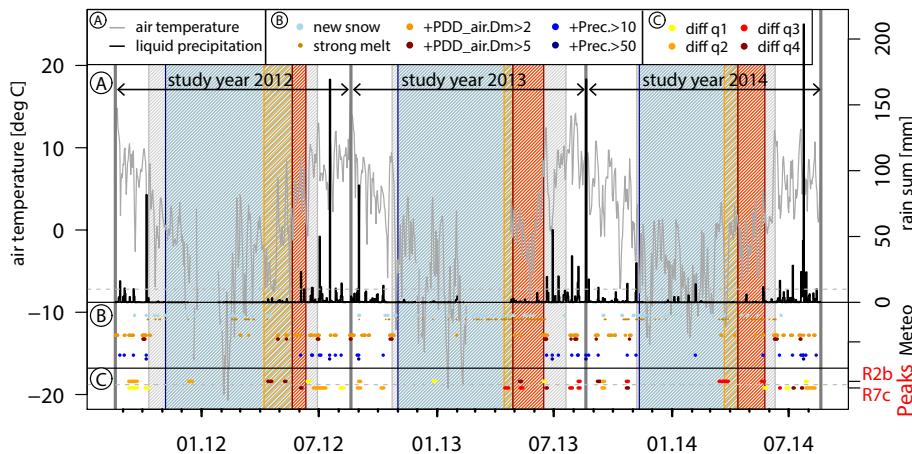
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**Figure 5.** Comparison of periods velocity peaks at R2b and R7c to meteorological factors. **(A)** Air temperature and liquid precipitation, both measured at the weather station within the study. Vertical grey lines indicate the three different study years (2012, 2013, and 2014). **(B)** In the middle of the plots, exceptional values of meteorological factors are given: fresh snow: on this day fresh snow was clearly visible on webcam images, strong melt: on this day strong melt was clearly visible on webcam images,  $+PDD_{air} \cdot Dm \geq 2$ : the difference of  $PDD_{air}$  on that day compared to the monthly mean of  $PDD_{air}$  was above  $2^{\circ}\text{C}$ ,  $+PDD_{air} \cdot Dm \geq 5$ : the difference of  $PDD_{air}$  on that day compared to the monthly mean of  $PDD_{air}$  was above  $5^{\circ}\text{C}$ ,  $+Prec \geq 10$ : the daily sum of liquid precipitation was 10 mm or more,  $+Prec \geq 50$ : the daily sum of liquid precipitation was 50 mm or more. **(C)** Occurrence of velocity peaks for R2b (upper bars) and R7c (lower bars). The colors of the peak-periods refers to the strength of the peaks (given as the 25-, 50-, and 75%-quantile of  $diff_p$ ).

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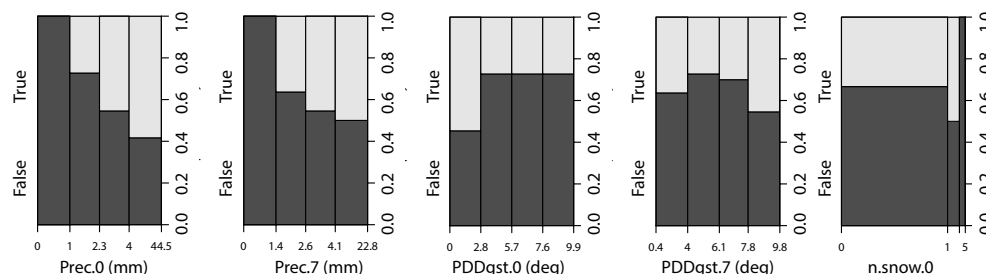
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**Figure 6.** Spineplots for periods during the snow-free period of R7c for selected variables (cf. Table 1). Frequencies of the occurrence of a peak (lightgrey) as opposed to the absence (darkgrey) of a peak conditional on potential explanatory variables. Bar widths refer to the 25%-quantiles of the explanatory variables, except for new snow (n.snow). Note: spineplots for all potential explanatory variables of both positions (R2b and R7c) during the snowcover and snow-free period can be found in the Supplement to this paper (Figs. S2 and S3).

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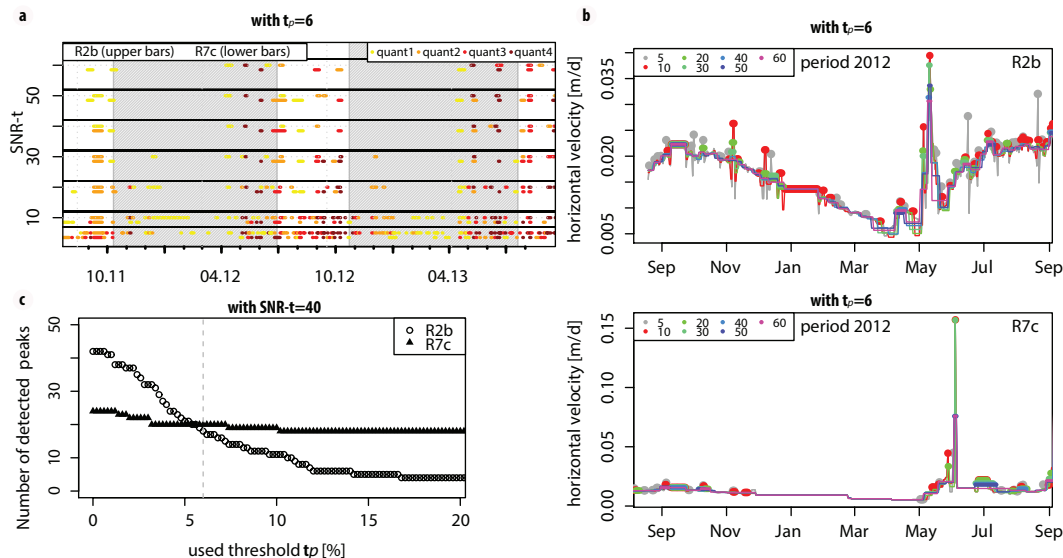
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**Figure 7.** Detected peaks depend on the chosen SNR-threshold (SNR-t) for velocity estimations and threshold ( $t_p$ ) for peak detection. **(a)** Sensitivity of detected peaks for different SNR-t ( $t_p = 6\%$ ) for R2b and R7c. The colors refer to the strength of the peak ( $\text{diff}_p$ , the 25-, 50-, and 75%-quantile of  $\text{diff}_p$ ). The period with an insulating winter snow cover is shadowed in light grey. **(b)** Estimated horizontal velocities and detected peaks (points) applying different SNR-t for R2b (upper) and R7c (lower). **(c)** Sensitivity of the detected peaks for thresholds  $t_p$  for R2b (points) and R7c (triangles). The x axis refers to different values applied for  $t_p$ . In this study, we apply  $t_p = 6$ , and SNR-t = 40.

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**Figure 8.** Visible cracks (left, from September 2011) and depressions (middle, from June 2013) at the front of the rock glacier Breithorn, and visible water outflow (right) at at front of rock glacier Dirru (from June 2013).

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