Interactive comment on "Short-term velocity variations of three rock glaciers and their relationship with meteorological conditions" by V. Wirz et al.

Dear Editor and referees,

Firstly, as authors we would like to thank all three referees for their constructive comments and suggestions. We have set out to respond fully to both the content and spirit of each comment in full, and hope that the edited manuscript reflects these changes.

All three referees mentioned at the beginning of their review, that the data and methods presented in this study are novel and contribute to the current understanding of intra-annual velocity variations of rock glaciers. However, as main weaknesses the referees mentioned the following points: a) the focus of this paper (especially in the discussion section) is sometimes vague and the links between statistical analysis and the discussion processes should be strengthened, b) the processes mentioned in the discussion should be better introduced, c) the representativeness of the point measurements are insufficiently explained, d) part of the manuscript (mainly instrumentation section) are similar to the previous publication Wirz et al., 2015, and e) the geomorphological characteristics of the rock glaciers are insufficiently introduced.

In our new version we have substantially rewritten and restructured the manuscript to address these points, paying special care to making the focus of the paper clearer. The following list presents the main changes we have made as a global summary – we list our detailed responses and changes made to each referee individually later in this document.

- We have restructured and rewritten the discussion section to make the focus of this paper (newly gained insights on short-term variability) clearer and to better link statistical analyses with discussed processes.
- We have rewritten the abstract to make the focus of this paper (short-term variations/ relation of velocity peaks to meteorological factors) clearer.
- We have rewritten (and shortened) the introduction to better set out the aims of the paper and to more clearly introduce current knowledge on rock glacier movement (mechanical) and the involved processes and related reaction/response times.
- We have shortened the results- and discussion- section on inter-annual variability (as here the data basis is limited with 3 years) to further strengthen the focus of our paper on intra-annual variability.
- We better introduced and explained the representativeness of our point measurements, by showing areas with rather homogenous velocity fields (as found in previous studies with higher spatial resolution of the measurements) in Fig. 2 and better introduced the selection of measurement locations.
- Removed the section instrumentation of the study site and included main information in the sections "GPS and inclinometer data" and "auxiliary data", to avoid repetition from previous publications (e.g. Wirz et al., 2015).
- We rewrote the sections "data" and "methods": We made one section "data and methods" (section 3 in the new manuscript), and removed redundant parts from previous papers.
- We added a new Table (Table 2 in the new manuscript), updated Figure 2, to provide more information on the main characteristics of the rock glaciers regarding topography, geomorphology and kinematics (mean annual velocities od rock glacier lobes).
- We calculated the snow cover and zero curtain periods based on local iButtons only and updated logistic regression models and all results and related sections in the manuscript.
- We included one additional year of GST data for R7a and one additional year of GPS and GST data for R6a and R6b, because this data are now available. We now have three years of data (GST and GPS) for all stations.
- We changed the Fig. 1–6 and 10 according to the referees' comments (see details below) to make easier to be read.

In the following, we describe in detail how we have responded to each individual comment:

Authors' responds to comments of Referee 1

R#1 GENERAL COMMENTS

1) The authors insufficiently explain a) the representativeness of their point-derived data for rock glacier measurements, and b) the influence of the spatial resolution on the derivation of velocity peaks.
2) The mechanical movement and influencing properties are poorly introduced, thus, the analysis and draw of conclusion for 4) inter-annual, 5) seasonal intra-annual and 6) short-term velocity peaks show deficits and could be significantly improved (see specific comments 1-6).

AC: See comments on general changes on the manuscript above, and our detailed response below. We deal with these points comprehensively in the rewritten manuscript.

R#1 SPECIFIC COMMENTS

R1 C1: How representative are point surface measurements?

To identify rock glacier movement two GPS sensors are installed on large boulders located in the upper area of the rock glacier or on the rock glacier tongue. The authors assume a priori that these boulders are carried along with the displacement and their velocity is representative for the whole upper or lower rock glacier part (1). Rock glaciers consist of different lobes, ridges and furrows which implicates that parts of the rock glacier move with different velocities. Delaloye and colleagues are monitoring the Dirru rock glacier since 2007 with manual GPS and InSAR and identified areas that move with different velocities (Delaloye et al. 2008b, Fig.7 and 2013, Fig. 2). Thus, the selection of the GPS location is crucial for the representativeness of the movement data. However, the authors provide no or insufficient information about geomorphic features of the rock glacier such as lobes, ridges and furrows (2). Furthermore, they do not explain how they selected their measurement device location and on which geomorphic properties this selection is based (3). To compare automatic GPS-derived movement with movement from InSAR, manual GPS (Delaloye et al. 2008a, Strozzi et al. 2009a) or photogrammetric data in the future could resolve the representativeness of point surface measurements (4).

A-R1C1:

(1) Small differences in 3D-velocities at the surface of single rock glaciers have been observed in various studies based on high-resolution photogrammetry (e.g., Kääb et al., 2003). For example, higher velocities were typically measured along the central flow line (than towards the margins), or on top of micro-topographic ridges (e.g., Kääb et al., 2003). Nevertheless, it is known from those measurements with high spatial resolution and coverage that the surface velocity field of rock glaciers in general is highly coherent even at the scale of individual rocks, that differences in velocities on top of the ridges compared to furrows are very small (the transverse ridges and furrows on the rock glaciers are advected downstream with a velocity that equals the overall movement of the rock glacier body (Kääb and Weber, 2004), and that the observed surface displacement is not only the sum of individually displacing or sliding particles (Kääb et al., 2003; ; Kääb and Weber, 2004). In addition, GPS stations were placed in the field such that they are as representative as possible for the displacement of the entire lobe (upon which they are placed, see Wirz et al., 2014). Therefore, we argue that small differences in surface speed (that might occur between ridges and furrows) are for the purpose of this study not relevant and do not have an influence on the results of this study.

Delaloye et al., 2008 observed that for the rock glacier Dirru areas with different velocities exist. However, they mainly identified a fast moving lower zone and an upper slower moving zone. Their measurements also clearly reveal that spatial differences occur over larger areas and not between different boulders. Also the RADAR interferometry measurements by Strozzi et al. (2009a) and Barboux et al. (2013), as well as the GPS measurements by Delaloye et al. (2013), all reveal that the rock glaciers Dirru and Breithorn have rather homogenous velocity fields, with lower velocities in the upper flatter part and higher velocities in the lower steep part. Unfortunately no previous measurements with higher spatial coverage exist for rock glacier Steintälli.

Therefore, we think that although small differences in surface velocities might exist between individual measurement points upon the same rock glacier, our single point measurements are relevant and provide new insights on the short-term variability of rock glacier.

(2) In order to better describe the topographic, morphologic, and kinematic situation of the rock glaciers (and the locations of the GPS stations) we added in Fig. 2 the outlines of areas on the rock glacier with velocity estimates from expert knowledge and published observations (Delaloye et al., 2008b; Strozzi et al., 2009a, b; Delaloye et al., 2010, 2013; Wirz et al., 2015) and added a new Table (Table 2 in the new manuscript) with an overview/summary regarding the topographic, morphologic and kinematic situation of the three rock glaciers investigated. In addition, we mentioned in the manuscript (already in the submitted version) in the description of the study site (description of each individual rock glacier) that differences in velocity exist between upper and lower part of Dirru and referred to the measurements of Delaloye et al., 2013 and Strozzi et al., 2009.

(3) The selection of field sites has been described in previous publications (Wirz et al., 2013 and 2015). We here mainly refer to these publications and added a short description of the selection of measurement locations.

To address R1 C1 we changed our manuscript as following:

- P461, L25 (we added the following sentences): "In areas of compressive flow, surface structures such as transverse ridges and furrows are typical. However, related variations in flow speed are very small (Kääb et al., 2003; Kääb and Weber, 2004) and these surface structures are advected downstream with the speed of the rock glacier body (Kääb and Weber, 2004)."
- P466, L5 (we added the sentence): "The GPS stations are installed on large well-grounded boulders, in such a way that the displacement is as representative as possible for this rock glacier lobe (e.g. in the middle of the rock glacier lobe, not at its margins; further details on the strategy for the selection of GPS locations is given in Wirz et al., 2013)."
- P467, L14 (we added the sentence): "Further details on the description of the individual rock glaciers as well as a detailed description of the field instrumentation can be found in Wirz et al. (2015)."
- Added in Fig. 2 the outlines of areas with velocity estimates based on previous observations and expert knowledge.
- Added new table with overview of topographic, morphologic and kinematic situation. And added the following sentence to the manuscript: "Table 2 gives an overview of the main topographic, geomorphologic and kinematic situation of each rock glacier."
- We added in Fig. 2 the outlines of areas on the rock glacier with velocity estimates from expert knowledge and published observations (Delaloye et al., 2008b; Strozzi et al., 2009a, b; Delaloye et al., 2010, 2013; Wirz et al., 2015).

R1 C 2: Spatial resolution of GPS-measurements

According to Wirz et al. (2013:387), the spatial resolution of 30s-sampling is in the range of cm. If this is correct, the observed peaks lay in the range uncertainty of the GPS instrument. Please address resolution and accuracy of the GPS and implications for velocity peak derivation.

A-R1C2:

The accuracy of the single GPS measurements (with 30s-resolution) lie in the range of cm, but the accuracy of daily GPS solutions (applying single-frequency differential carrier-phase technique), is supposed to be in the range of few mm (as no reference values exists it was estimated at the reference station, see Wirz et al., 2014 for further details). Furthermore, peaks are derived from velocity estimates (using MCS to include uncertainty of GPS solutions), which included a smoothing window depending on the signal-to noise ratio. Applying a threshold of 40 (SNR-t=40, to separate signal from the noise and defining the size of the smoothing window) results in a signal (of the velocity) that was at least 40 times higher than its uncertainty. In addition, velocity peaks (velocity periods detected as peaks), have a velocity that is at least 6 times higher than the average velocity of the previous and following velocity period. Applying this approach to define a velocity peak and using SNRT, velocity differences defining a peak are clearly higher than the related uncertainties:

Minimal velocities of the periods that were detected as peaks are 9mm/d for station R2b, respectively 13mm/d for station R7c, and, thus, clearly higher than the average standard deviation of the velocity estimates (around 0.4 mm/d). Hence, detected peaks are clearly outside the range of the uncertainty.

In section 5.2 (in the new manuscript), we clearly mention that lacking peaks are potentially the result of the coarser temporal resolution of the velocity estimates.

R1 C 3: Mechanical movement and response time

Rock glaciers can deform or creep (Haeberli et al. 2006) as a result of pore pressure in the active layer or as a result of permafrost warming in the shear horizon. The authors provide a figure (Fig. 1) to enable an overview about theses deformation or creep processes. The authors assume that "the movement observed at the rock glacier surface might be the result from movements occurring at different depth" (page 461:28ff). However, this figure stands alone without any explanation. Deformation or creep processes have different response times. Thawing of ice depends on conductive and non-conductive heat transport processes, thus, response time depends on the velocity of theses heat transport processes. Pore pressure increase results from water input, permeability and pore geometry. Response time and reaction time should differ from pure heat transport processes. I recommend the comprehensive study by Bull (2009) "Geomorphic Responses to Climatic Change" for an overview of response, reaction and relaxation time and to address this systematic view in the introduction. Response time is crucial for the understanding of short-term peaks.

A-R1C3:
We have rewritten the introduction section of the manuscript to better introduce rock glacier movement (including also some additional literature), related processes and response time (see general comments at the beginning of the author comments), but we did not found Bull (2009) very helpful for this study. In addition, we tried to better integrate Fig. 1 in the introduction section (4th paragraph of section 1 in new manuscript)
However, most (nearly all) of the existing studies on rock glacier kinematics/dynamics are based on a qualitative interpretation of measurements regarding changes at the surface (the rock glacier geometry). Furthermore, studies on the intra-annual variability are limited with only limited time- (and/or spatial) coverage. Thus, the current knowledge on reaction and response time and related processes causing the observed temporal variability is still limited and speculative. Only few studies (Buchli et al., 2013) had direct observation of displacement and temperature with high temporal resolution. However, they did not found a direct correlation between velocities and temperature (which stayed more or less constant at 0°C). Regarding water content, to our knowledge no direct observations at depth (below the active layer, AL) exist.
Further, we do not fully agree with the statement by R#1 "Rock glaciers can deform or creep (Haeberli et al. 2006) as a result of pore pressure in the active layer or as a result of permafrost warming in the shear horizon." - we would argue that the process of creep can also include deformation. In addition, to our knowledge it is not clear that rock glacier movement does not include sliding (e.g., at the AL base or in cases of a total collapse (e.g., Krysiecki et al., 2008). Furthermore, water can also infiltrate down into the rock glacier body (below AL), as rock glaciers are permeable (Arenson et al., 2002). Thus, pore water pressure likely plays a role below the AL. On the other hand, if the movement occurs within the AL, its temperature (at least in winter when it is frozen) might have an influence on its movement (deformation). Through rewriting the introduction we tried to clarify these points in the introduction as well.

R1 C 4: Why do the rock glaciers show high inter-annual velocities?

The inter-annual variability is not the focus of this paper, however, the deviation of Mean Annual Velocities (MAV) is used to identify peaks (1). The Dirru and Breithorn rock glacier show high annual velocities (4.9 and 6.8 m/a) which are significantly higher than "typically" displacements mentioned by Haeberli et al. 2006 (page 461:20f.). Unfortunately, there is no detailed explanation why the investigated rock glaciers move so fast (2). An explanation could enhance the understanding of short-term peaks that are defined as deviation from the mean. Furthermore, the calculation of Mean Annual Velocities (MAV) of R2a should be taken with care, thus, the periods differ in length (3). It excludes possible movement acceleration in autumn 2011 and could underestimate the MAV in 2011/2012. The current period naming is confusing and periods should be renamed to 2011/12, 2012/13 and 2013/14 (4). Not all variables (σdisp) of Table 2 are explained in the text (5).

A-R1C4:
(1) As explained in the Methods (section 3.4 in the new manuscript) the detection of velocity peaks is not based on the MAV, but in relation to the previous and following velocity period. The average velocity over the entire observation period (summer 2011 to summer 2014, $MAV_{12\text{-}14}$) is used to compare the intra-annual variability of the different GPS stations, because they differ in the absolute velocity.

(2) A discussion of the high velocities at R2b and R7C is not the focus of this paper and other measurements (longer time series) would be required to investigate the reason for the high velocities observed. However, we did mention in section 2.1 potential causes for the strong acceleration of the tongues of Dirru and Breithorn and referred to the study of Delaloye et al., 2013 (e.g., both tongues are steep and end in a steep valley (no retention). Although, the exact reasons for the high velocities observed at the tongues of Dirru and Breithorn are still not clear (e.g., Delaloye et al., 2013).

(3) Yes, MAV for R2a in first year should be treated with care as measurements did only start in February. We mentioned this in the manuscript (as footnote in Table 2). In MAV12 at R2a not only the acceleration phase in autumn is not covered but also the period with minimal velocities. Thus it not necessarily underestimates the "true" MAV. To make it more clear we added the following sentence in the caption of Table 2: "Note, that for R2a only GPS measurements since 23.02.2012 exist, and, thus, results of MAV12_14 and especially for MAV12

(4) We changed period naming as suggested by R#1 (e.g., 2011/12) throughout the manuscript.

(5) We explained σ_{disp} in the table caption of Table 4 (numbering refers to new manuscript). σ_{disp} is the standard deviation of the total displacement, obtained applying 2000MCS

R1 C 5: The intra-annual variability of rock glacier movement

The intra-annual variability is compared to air temperature derived from the meteo station and GST, zero-curtain and snow-cover period derived from all iButtons. The movement obtained at one point of the rock glacier is compared to statistical calculated ground temperature, snow cover and zero-curtain conditions of the whole catchment. Air temperature maybe shows no large differences on short distances. However, GST and snow cover can vary significantly on short distances (Gubler et al. 2011) due to surface properties. Snow can be redistributed due to avalanches and wind and accumulate with higher depths in depressions and lower depths on ridges. This results in different snow height with different potential of insulation and snow water equivalent. The authors conclude snow cover and snowmelt as an important factor of seasonal rock glacier movements. Unfortunately, literature on snow cover distribution, influence of snow cover on permafrost such as Keller (1994), Hanson and Hoelzle (2004) or Luetschg et al. (2008) is absent in the manuscript. Thus, snowmelt is reduced to pore pressure increase and rapid warming. Thermal influences of snowmelt, response time due to heat transport and mechanical influences of snow cover and snowmelt are insufficiently introduced and discussed.

A-R1C5:

- In order to account for the large spatial variability (that exist even within short distances) of GST (and snow) as found by Gubler at al. (2011), we used five iButtons next to each GPS station to describe GST (and duration of insulating snowcover and zero curtain) at each GPS station.
- For the qualitative analysis of the seasonal cycle we compared velocities to GST, snow cover and zero curtain next to the GPS station and to the average in the catchment. We agree, however, that for the analysis of the peaks, it is better to calculate local snow cover and zero curtain (see also general comments). Zero curtain at one GPS station is now defined as period during one at least based on one iButton a zero curtain was detected. Similarly, the snow cover duration at one GPS station starts with the first day an insulating snow cover was detected at one iButtons next to the GPS station and ends whit the last day where an insulating snow cover was detected for one iButtons next to the GPS station. We changed the corresponding values in section 4.4.2, 4.3.2 and Table 5.

  However, we still also show the zero curtain and snow cover distribution in the study site in Fig. 4 (Fig. 4–6 in the new manuscript), because as it is likely that snowmelt above the GPS station has also an influence on the movement (observed at the GPS station).
- We think that additional literature on the influence of snowcover on permafrost temperature is not relevant for the understanding of our manuscript paper and would be beyond the focus of this paper.

R1 C6: Short-term velocity peaks

Short-term velocity peaks are identified of two rock glacier lobes and statistically related to meteorological factors. Why only two locations are analysed remains unexplained (1). The velocity peaks are correlated to liquid precipitation of the meteo station, GST from iButtons next to the GPS and zero curtain of all iButtons. The latter use of all iButtons makes no sense (2). Not all snowmelt of the catchment area will drain through the rock glacier and affect rock glacier movement. Most observed velocity peaks are in the range of centimeters and lay in or close to the measurement uncertainty of the GPS instrument (3). However, the spatial resolution of the GPS is not discussed in the manuscript. A strong correlation between precipitation and velocity peaks is observed which is interesting and should be emphasized in the paper (4). However, the calculation of meteorological parameters for the peak and 7 days before the peak assumes a fast reaction time of the rock glacier to meteorological influences such as precipitation (5). This excludes a priori movement processes with longer reaction time such as rock glacier creep due to active-layer thawing. Peaks that are triggered by rainfall all occur in summer to autumn after an active-layer has developed or is developing. A path-dependence of precipitation influence could be possible which means that a sufficient active-layer needs to be present. However, path-dependency and active-layer development is not included in this manuscript (6). From my opinion, underground information derived from boreholes, temperature modeling or geophysical measurements are necessary to understand how the rock glacier is influenced by meteorological factors. Unfortunately, the authors use a black box approach measuring meteorological influences and kinematic response without having any information on the internal structure of the rock glaciers or movement relevant properties such as active-layer depth, ice content or shear horizon depth. As a consequence, all attempts to explain the sources of kinematic behavior remain speculative.

A-R1C6:
(1) The analysis of the peak detection was applied to all stations, but only at three stations peaks were detected. At the beginning of section 4.3 we mentioned that peaks were only detected at three stations (R2b, R7c, and R7a), that at R7a only one peak was detected, and that we therefore limit the analysis to R2b and R7c.

(2) As proposed in R1C6, we now calculate also zero curtain and duration of an insulating snow cover based on the local GST measurements next to each GPS station (see A-R1C5).

(3) See A-R1C2. Furthermore, most peaks last for few days thus displacement in total is few cm and thus clearly higher than the uncertainty (few mm, sub-cm).

(4) See general comments: We rewrote the discussion section to further emphasize the correlation between occurrence of a peak and water-input.

(5) We did this analysis also for longer time periods (investigated it also with Wilcoxon rank-sum test and Spineplots), but correlations for variables including longer time periods were poorer and the model has too many dimensions (too many variables in comparison to the number of observations). Further, we think that the short duration of the peaks rather point to a short-lasting processes (short response time, and thus likely also a rather short reaction time). We therefore decided to limit our analysis to rather short periods.

(6) We agree that based on our observations (at the surface and not within the rock glacier where the actual movement takes place) we can only built hypotheses on the occurring processes. However, borehole measurements are expensive and pore water pressure in the ground difficult to measure. By analyzing 6 GPS stations distributed on 3 landforms and having meteorological measurements at the study site, we have an improved data basis compared to most of the previous studies on intra-annual variability of rock glaciers. But of course, only measurements of the internal characteristics of the rock glacier (ice content, pore water pressure, temperature) and velocity at depth would allow to directly investigate controlling factors and related processes.
We clarified these points in the discussion section (mainly 5.1 and 5.3 in the new manuscript).

R#1 TECHNICAL COMMENTS

R1-TC1: Page 460 ff: The introduction is comprehensive, however, the required background for the discussion of the observed mechanism is insufficiently introduced. As a consequence, the introduction should be reduced to approximately two pages and should sharpen the system understanding (landform, material, process and response time), mechanical basis of rock glacier movement, thermal influences on rock glaciers and snow cover interaction with permafrost. The appendix table A1 should be included into the text to give an overview about existing previous studies that the authors want to confirm (Hypothesis 1). The mechanical basis of rock glacier movement can be illustrated with Fig. 1, however, a more detailed description of the processes associated with movement is required. Potential meteorological factors influencing rock glacier movement should be introduced (Hypothesis 2).

A-R1TC1: We shortened, restructured and rewrote the introduction section according to the given suggestions and included the appendix table A1 in the manuscript.

R1-TC2: Page 465: The three rock glaciers are insufficiently introduced. The site description should be extended with special focus on movement-relevant properties. I would advise a table which summarizes topographic, geomorphometric and kinematic properties of upper and lower parts of the rock glaciers. Inter-annual velocity can be included in this section to illustrate differences of kinematic behavior.

A- R1TC2: We added such a table. See A-R1C1.

R1-TC3: Page 467 ff: The instrumentation section (2.2, 2.3, 2.4) is very similar to the corresponding sections in Wirz et al. (2015). The section should be reduced to one method section which shortly summarizes the set up. The instrumentation is published in 3 previous papers which can be cited. Only instrumentation which is used in this paper should be addressed with special focus on the spatial resolution of the GPS. Non- working meteo stations can be excluded. The method section (3.) can be slightly shortened and merged with the instrumentation section.

A- R1TC3: We removed the section 2.2 and shortened the sections 2.3 and 2.4. Further, we made one section (data&methods, section 3 in the new manuscript) and removed redundant parts from previous publications.

R1-TC4: Page 502: Table 2, all included variables should be explained in the text. Please change the confusing period naming to 2011/12, 2012/13, and 2013/14.

A- R1TC4: We agree and changed Table 2, its caption and the period naming as proposed by R#1.

R1-TC5: Page 504: Please include a column in Table 4 which explains the variables of the models. The table should be self-explainable without searching for the abbreviations in the text.

A- R1TC5: All variables are explained in Table 1 (Table 3 in new manuscript)**.** Therefore, we do not think an additional column in Table 4 is necessary. However we refer in the caption of table 4 to Table 1 (explanation of potential variables). We added the following sentences to the caption of Table 4: "An overview of all variables and its meaning is given in Table 3. In addition an index with the GPS position (R2b or R7c) is applied for potential differences between the two rock glaciers."

R1-TC6: Page 509: Zero-curtain is not visible, thus, it is derived from all iButtons. If you use only local IButtons and split the image into 6 subfigures zero-curtain will be visible. The correlation between occurrence of zero-curtain and acceleration of rock glacier movement will be highlighted. Please rename the periods.

A- R1TC6: The (main) aim of Fig. 3 is to give/allow a comparison of the intra-annual variability of all GPS stations. We therefore think Fig. 3 would not benefit from 6 sub-figures. The correlation between the acceleration in spring and zero curtain is visible in Fig. 5. To make this figure better readable (see also R2-TC, and R3C20) we removed the shadowing for snow cover, zero curtain, and GST and changed the colours for the individual stations.

R1-TC7: Page 510: This figure is confusing and overloaded with information. If direction of movement is constant it is not necessary to visualize it. Snow cover and zero-curtain show different ranges due to the use off all iButton data or only iButton data next to the GPS. This different use is confusing. Exclude the iButton numbers in the figure to enhance the clarity of the figure. Try to reduce the information to highlight the data which supports your argument.

A- R1TC7: To increase readability we excluded the iButton numbers, removed the direction of movement, and split this figure up into three figures (Fig. 4–6 in the new manuscript).

Author's responds to comments of Referee 2

R#2 SPECIFIC COMMENTS

R2 C1: Parts of the paper are redundant to Wirz et al. 2015 (e.g. instrumentation section). Redundant parts should be trimmed and cited. While it is understandable that the results of measurement campaigns are divided into more than one publication, it can also be confusing for the reader/scientific community.

A-R2C1: See also R1-TC3 and general comments at beginning of authors' comments. We remove the redundant parts and refer in the new manuscript to previous publications (for example we removed the instrumentation section). We rewrote and restructured the new manuscript to strengthen the focus of this paper and make differences to previous publication clearer.

R2 C2: In Figure 1 the potential causes for creep velocity variations are portrayed schematically. The reasoning started within this figure could be extended in more detail and structure to the discussion section. The potential consequences of water infiltration at different times of the year on the rock- and ice-mechanical properties could be discussed in a more structured way (interesting aspects such as the (ir)relevance of active layer formation for observed velocity variations and different lag times could be addressed in more detail).

A-R2C2: We rewrote the discussion and introduction section and better integrated Fig. 1 in the manuscript (4th paragraph in Introduction in the new manuscript). See also general comments at beginning of authors' comments and R1C3. As we have no information on the movement at depth, we however, do not think that structuring the discussion section according to Fig. 1 would improve our manuscript.

R2 C3: While the authors acknowledge that care has to be taken when point measurements are extrapolated, they (repeatedly) assume that a rock glacier's velocity field is 'homogenous' (490:1). However, the irregular surface (ridges, depressions etc.) shows that there have to be significant variations in creep velocities over longer time scales.

A-R2C3: See R1-TC3.

R2 C4: It would be interesting for the reader to get more information on the properties of the investigated rock glaciers. Maybe it would also be possible to characterize the rock glaciers based on ALS data instead of a 25m DEM.

A-R2C4: We added a new Table (Table 2 in the new manuscript) to provide additional information on the topography, morphology and kinematics for the three rock glaciers investigated and included better readable photos of each individual rock glacier in Fig. 2. See also R1C1.

We do not have access to ALS data that cover the entire area. We used a DHM of 25m resolution, because for the rock glacier movement the topography of the bedrock (approximated by the average slope in an area of 25 m) is more relevant than the small topographic structures (e.g., lobes and depressions at rock glacier surface that would be visible in ALS data).

Furthermore, we refer in the new manuscript to Wirz et al., 2015, where additional details (including a Table in the supplementary material that summarizes main geomorphological characteristics) are given.

R2 C5: In some sections language could be more fluent and precise (e.g. 5.2.2, 5.2.3, 5.2.4)

A-R2C5: We rewrote the discussion section and polished the English.

R#2 TECHNICAL COMMENTS

R2- TC: please refer to attached document.

A-R2TC: We found the comments in the annotated version helpful and changed our manuscript according to the proposed changes.

Author's responds to comments of Referee 3

General

The data on surface velocities presented in this paper is quite valuable because short- term variation in rock-glacier movement has been still rarely monitored, especially through a season with snow cover. In addition, the statistical approach is new for discussing meteorological conditions which potentially drive episodic acceleration and deceleration (short velocity peaks) of rock glaciers.

However, the focus of this paper is vague. Although six different points and three different years showed various magnitudes and patterns of the motions, the authors only found meteorological conditions driving rapid spring-summer acceleration (including short velocity peaks) and gradual winter deceleration. Thus, the findings of this study in the abstract is mostly identical to that of Ikeda et al. (2008), which also (already) showed continuous records of deformation with high temporal resolution over five years of a fast-moving rock glacier. The authors stressed that the three-year records with high temporal resolution are unique in themselves among the studies on rock glacier deformation. Such originality is questionable, because the methodological difference between this study and Ikeda et al. (2008) seems to be not critical to obtain the main conclusions. Furthermore, the latter study discussed rheology of the frozen sediment, horizontal varieties of the annual surface movements, and internal structure and temperatures, all of which are not considered in this study.

The instrumentation of this study for obtaining velocities and temperatures on the surface is more sophisticated than that of Ikeda et al. (2008). Thus, it could be possible to show different focus leading to some conclusions different from the previous studies including Wirz et al. (2015) as well as Ikeda et al. (2008). If the authors cannot deeply discuss the factors responsible for the spatial differences in velocity of the six points and for the inter-annual differences in the three years as the submitted manuscript, in my opinion, one solution would be to make a paper mostly focusing on the short velocity peaks at the two points using statistical approaches. In the submitted manuscript, there is only weak links between the results from statistical analyses and processes discussed subsequently. Thus, overall construction would be better to be revised.

AC: See our general comments at the beginning of the author comments: we rewrote and restructured our manuscript to better focus on the short-term velocity peaks and their relation to meteorological factors, using statistical analysis).

MINOR REMARKS R#3

R3-C1: (p. 462, ll. 22-25): "Measurements made in a borehole at the Furggwanghorn rock glacier ... 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)." Add information on the inclinometer measurement done by Ikeda et al. (2008).

A-R3C1: We included the study of Ikeda et al., 2008 in this sentence. And changed our manuscript as following: "The time series of borehole deformation measurements at the Furggwanghorn rock glacier (CH-Valais, Oct. 2010–May 2011, Buchli et al., 2013) and at the Büz North rock glacier (CH-Grison, 2000-2005, Ikeda et al., 2008) form the longest published data of displacement measurements with (sub)daily resolution, known to the authors (Table 1). "

R3-C2: (p. 463, ll. 22-23): "An overview of previous studies on intra-annual variability of rock glacier movements is given in Table A1." Add information of Muragl rock glacier (Arenson et al., 2002) and Büz rock glacier (Ikeda et al., 2008) in Table A1.

A-R3C2: We included the studies of Arenson, 2002 and Ikeda et al., 2008 in this table.

R3-C3: (p. 466, l. 22): What is DEM2? Do not use domestic abbreviations for worldwide readers.

A-R3C3: DEM2 refers to a digital elevation model with 2 m resolution. We changed DEM2 to "digital elevation model with a cell size of 2 m”.

R3-C4: (p. 468, ll. 13-14): "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." Delete this sentence.

A-R3C4: We deleted this sentence. In addition, we did no longer include this weather station in Fig. 2.

R3-C5: (p. 470, l. 12): Revise the chapter title, because the previous chapter also includes some methods.

A-R3C4: See general comments and A- R1TC3. We restructured the paper to a section “Study site” and another section “Data and methods”.

R3-C6: (p. 471, ll. 13-14): The first sentence needs a reference.

A-R3C6: We included a reference and changed the manuscript:” Especially at two GPS stations (R2b, R7c) sudden strong peaks in velocities were observed (Wirz et al., 2015).”

R3-C7: (p. 472, l. 16):What is “logical values”?

A-R3C7: We meant binary values (0/1, respectively yes/no). We changed logical values to binary values.

R3-C8: (pp. 477-478): The number of velocity peaks is focused first and the strength of velocity peaks second in this paper. Reconsider which is more responsible for the total deformation, and if the strength is more critical, change the order of descriptions.

A-R3C8: The total displacement “caused” by peaks depends on the strength and duration of the peaks. The focus of this paper lies on the occurrence of peaks (under what circumstances peaks are formed). We therefore started with the number of peaks and their occurrence first.

R3-C9: (p. 478, l. 18): "but such was not available for the whole period" It is difficult to understand this part.

A-R3C9: We changed this sentence as following: “ For R7c, inclination was generally smaller, but inclinometer measurements at R7c were not available for the whole period.“

R3-C10: (pp. 479-480): Why was only the occurrence of the peaks statistically analyzed? It would be much better to check the relationships between meteorological parameters and the strength of the peaks.

A-R3C10: The aim of the statistical analysis was to detect meteorological situations that lead to the formation of peaks. Investigating the strength of the peak is another focus. Further, the statistical analysis of the strength of the peak is more delicate, as peaks in winter (with lower velocities) have a larger smoothing window and thus the strength of the peak is probably underestimated. In addition, the number of peaks is limited (N=37, limited data-input) and, thus, results are likely not significant. However, to account for this comment we tested a multivariate linear regression model with strength of the peak as response variable and including as explanatory variables, those variables that were used in the final logistic regression model with highest AUC (position, log(Prec.0), PDD_{GST}.0, snow.ind and zc.ind). The R-square of this model is very small (0.14) and none of the variables were significant.

R3-C11: (p. 480, l. 19): What does “position” indicate in this analysis?

A-R3C11: Position in the statistical analysis accounts for possible differences between the two positions (R2b and R7c). For example we found that precipitation has a stronger influence on the odds at the position R7c than at R2b. To make this clearer we added the following sentence to the caption of Table 4 (Table 6 in the new manuscript): “In addition an index with the GPS position (R2b or R7c) is applied for potential differences between the two rock glaciers. “

R3-C12: (p. 481, ll. 8-27): If authors want to verify the SNR-t and t_p values, the section 3.1 should be revised. In addition, show the section of “Sensitivity tests” at the beginning of the result chapter, then declare that SNR-t = 40 and tp = 6 are adopted in this study.

A-R3C11: As proposed by R#3 we moved this section to the beginning of the results section (4.1 in the new manuscript). The main aim of the sensitivity test was to investigate the influence of SNR-t and t_p on the detection of peaks. Section 3.1 describes the velocity estimations applying SNRT. For the velocity estimates we adopted SNR-t of 40 from the previous study (Wirz et al., 2015). However, the approach for the detection of peak is new in this paper and t_p is not adopted from a previous study.

R3-C13: (p. 482, l. 13): "an additional years's worth of data" Not years's but year.

A-R3C13: Done, we changed years to year.

R3-C14: (p. 483, ll. 5-16): The authors guess if the temporal resolution of velocity measurements was high, most rock glaciers would show asymmetric annual velocity fluctuation and short velocity peaks. However, symmetric seasonal fluctuation of velocities without any short peaks cannot be ruled out. Because irregular fluctuations probably result from water infiltration in a permafrost body, (temperature-depending) regular fluctuation of the movement is anticipated for rock glaciers containing an impermeable permafrost body.

I personally hope to consider possibility of phase shift in rock-glacier motion from sinusoidal slow phase controlled by ground temperatures to asymmetric fast phase induced by long-lasting water infiltration during snowmelt, both of which depends on so-called permafrost creep. Then, some rock glaciers have reached collapsing phase when water can infiltrate more drastically (and frequently). The extremely fast motion of the last phase should be treated as shear of a continuously fractured plane (or planes) rather than creep of a so-called shear horizon (actually not a horizon but a zone; the description in Fig. 1 is a wrong example). If the authors tested this phase-shift hypothesis, the paper would have markedly high originality! Thus, I think that the different patterns of motion among the six points and the three years are worth to discuss from rheological viewpoints in the near future. To do that, the first author should learn more about rheology in glaciology and landslide science.

A-R3C14: We argue that for the stations with a coarser temporal resolution we cannot exclude that a lacking asymmetric cycle or short-term peaks would exist if velocity estimates would have a higher temporal resolution. This does not mean that we can rule out such patterns. We changed Fig. 1 to better show that the shear horizons are a zone.
Regarding the phase shift hypothesis we think that without any data from depth (e.g., temperature, material properties such as ice content and thermal conductivity, inclinometer data, or water pressure at depth) we cannot robustly and statistically test the process relation of the phase shift. Based on the argument of response/reaction times we describe such potential relationships in discussion but highlight uncertainties and the need for data at depth.

R3-C15: (p. 486, ll. 20-23): "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)." This sentence suggests that it has been confirmed that water vertically passes through a creeping permafrost body within a few hours. Is this true? The authors seem to misunderstand something in the previous studies.

A-R3C15: We did not mean that water vertically passes through the creeping permafrost body. But we meant that water infiltrated into the rock glacier flows through the rock glacier (ground water flow) and is discharged at its snouts within few hours, potentially on top of the frozen matrix. We also wrote:" They further observed that water flows in direct contact with the ice (Krainer et al., 2007), which might indicate that ground ice acts as flow barrier."

R3-C16: (p. 501):"As potential important time we used during the peak, ... " Add "days" between "used" and "during."

A-R3C16: Done, we inserted "days".

R3-C17: (p. 503): It is curious that R2b and R7c have same number of days of snow-free, snow and zc. It would be better to add the maximums, minimums, means and mediums of strength of peak (diffp) for snow-free, snow and zc, respectively.

A-R3C17: We now calculated snow cover, and zero curtain for the analysis of the peaks based on the local GST measurements (see also A-R1C6) and updated Table 4. In addition, we included min, max, mean and median of the strength of the peaks for the individual periods (snow-free, snowcover and zero curtain) in Table 4. Further, we updated the manuscript based on the new numbers (mainly section 4.2.2, 4.3.2).

R3-C18: (p. 504) What is pos55?

A-R3C18: We changed pos55 to posR2b. This variable (R2b/R7c) includes potential differences between the two stations. The negative coefficient for R2b indicates that the probability for a peak is weaker for R2b than for R7c (more peaks were detected at R7c than at R2b).

R3-C19: (p. 508): The photographs are too small to see topography on the rock glaciers.

A-R3C19: We increased the size of the photographs.

R3-C20: (p. 509): The color differences between R7a and R7c and between R2a and R2b are not clear. How did the authors detect single snow-cover duration for six different sites? Where is the "small figure" indicated in the last sentence?

A-R3C20: We changed the colours to increase readability of this figure. This figure showed the zero curtain detected within the entire study site (from first day when at iButton zero curtain was detected to last day when for an iButton zero curtain was detected). We now removed zero curtain and snow cover in this figure to increase readability. There is no small figure and we removed this sentence.

R3-C21: (p.501): The figure is too small.

A-R3C21: (should p.501 be p510?) We split this figure up into three figures to increase readability.

R3-C22: (p. 502): It is very difficult to check the synchrony of many parameters represented by dots in this figure.

A-R3C22: (should p.502 be p511?) We increased the size of this figure.

New/updated Tables

Table 1. 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 l982	$\sim$ 3 months	yes	?	?	Haeberli (1985)
Furggentaelti (Bernies Alps, Switzerland)	32	Tachymetry	autumn 1998–1999 (one year)	monthly	yes	yes	yes	Mihajlovic et al. (2003) Krummenacher et al. (2008)
Muragl (Grison, Switzerland)	20	Total station	1998–2001	$\sim$ 4 months	yes	no	no	Kääb et al. (2003) Kääb et al. (2005)
Muragl (Grison, Switzerland)	2	Borehole inclinometer	1999–2000	$\sim$ monthly	yes	no	no	Arenson et al. (2002)
Reichenkar (Stubai Alps, Austria)	3	GPS	Jul–Sep 2003 and (Jun–Oct 2002)	10 s (87 d)	no	no	no	Krainer and He (2006)
Huhh1 in Hungerlitälli (Valais, Switzerland)	25	Terrestrial geodetic survey	Jul–Aug 2003	36 days	yes	?	?	Roer (2005)
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	$\geq$ 8 months	yes	?	?	Lambiel and Delaloye (2004) Lambiel et al. (2005)
Becs-de-Bosson (Valais, Switzerland)	6(85[1])	GPS	2004–2006	30–60 days	yes	yes	yes	Perruchoud and Delaloye (2007) Delaloye et al. (2010)
Mount Gibbs (Sierra Nevada, USA)	1	InSAR	Apr 2007–May 2008	48–138 days	yes	?	?	Liu et al. (2013)
Furggwanghorn (Valais, Switzerland)	1	Borehole inclinometer	Oct 2010–May2011	daily	yes	yes	yes	Buchli et al. (2013)
Büz North (Grison, Switzerland)	1	Borehole inclinometer	2000–2003/05	3 h	yes	yes	yes	Ikeda et al. (2008)

[1]: since 2005: 85 measurement points.

Table 2. Main characteristics regarding topography, morphology and kinematics of the three investigated rock glaciers (Wirz et al., 2013; Delaloye et al., 2010, 2013; Wirz et al., 2015). Description of kinematics is based on expert knowledge (Dr. Hugo Raetzo, Federal Office for the Environment) and published observations (Delaloye et al., 2008b; Strozzi et al., 2009a, b; Delaloye et al., 2010, 2013; Wirz et al., 2015). In addition for each GPS station the average velocities from summer 2011 to summer 2015 are given.

Rock glacier unit	Topograpy	Morhpology	Kinematics
Breithorn R2	Situated in valley between the slopes of Breithorn and Gugla; convex topography, where $\sim$100 m above the front the slope angle rapidly increases from about 20 to 35°	The unit consists of various lobes; The main lobe can be divided in two main zones: upper flatter zone (R2a): transverse furrows and ridges indicating compressive flow; lower zone (R2b): destabilised tongue with open cracks	Upper zone with average velocities of several decimetres (R2a: $1.7\mathrm{m\,a^{-1}}$); lower steep zone (tongue) with velocities of several meters per year (R2b: $6.8\mathrm{m\,a^{-1}}$)
Steintälli R6	Situated in a small valley below the peak Chli Dirruhorn; the upper lobe (R6a) is slightly steeper (20 °) than the lower lobe (11 °, R6b)	Two main lobes of different lithology: one above the other; steep fronts and transversal furrow and ridges indicating compressive flow on both lobes; both lobes may originate from ice-cored moraines	The upper lobe, moving at several decimetres per year (R6a: $0.6\mathrm{m\,a^{-1}}$), currently overrides the lower lobe, moving at few decimetres per year (R6b: $0.2\mathrm{m\,a^{-1}}$)
Dirru R7	Below Dirru glacier, on the orographic right side of Dirrugrat; convex topography, where $\sim$400 m above the front the slope angle rapidly increases from about 15 to 35°	The unit includes various tongues and lobes from different generations with different degree of activity (inactive–destabilised); the currently active lobe can be divided in an upper flatter zone (R7a) with several ridges and furrows, partly nested (both transversal and longitudinal) and various depressions; and a lower steep zone (R7c) with few longitudinal ridges, but no transversal ridge-furrow structure	Upper flatter part moving at velocities of several decimetres per year (R7a: $1.2\mathrm{m\,a^{-1}}$); the steep fast-moving tongue with velocities of several meters per year (R7c: $4.9\mathrm{m\,a^{-1}}$)

Table 5. Peaks observed at R2b and R7a during the three different study years. For each year and for both stations the duration (days) of the snow-free, the snowcover, and the zero curtain period, the number of peaks per period (snow-free, snowcover, zero curtain; the number outside the brackets refers to the total number during this study year), and summary statistics of the strength of the peaks (diff_p) for the different periods is given. The first number in brackets refers to the snow-free, the second to the snowcover (excluding days with zero curtain), and the third to the zero curtain period. Both, winter snowcover and zero curtain period are derived from GST measurements next to the GPS station (Sect. 3.2).

Study year	Duration:		N Peaks:		min (diff_p):		max (diff_p):		mean (diff_p):		median (diff_p):	
	R7c	R2b	R7c	R2b	R7c	R2b	R7c	R2b	R7c	R2b	R7c	R2b
2011/12	(143,197,26)	(126,220,20)	5 (4,0, 1)	5 (2,3,0)	(7,NA,314)	(7,9,NA)	(37,NA,314)	(11,98,NA)	(19,NA,314)	(9,57,NA)	(15,NA,314)	(9,56,NA)
2012/13	(130,176,59)	(142,172,51)	7 (5,0, 2)	5 (3, 1,1)	(37,NA,50)	(6,7,30)	(155,NA,52)	(14,7,30)	(75,NA,51)	(10,7,29)	(49,NA,51)	(11,7,30)
2013/14	(154,154,57)	(157,148,60)	8 (7,0, 1)	7 (5, 1,1)	(22,NA,33)	(7,12,11)	(2424,NA,34)	(16,12,12)	(548,NA,33)	(10,12,12)	(102,NA,33)	(10,12,12)
Total			20(16/0/4)	17 (10/5/2)	(7,NA,33)	(6,7,12)	(2424, NA,314)	(17,98,30)	(268, NA, 213)	(10, 38, 21)	(46, NA, 51)	(10, 12, 21)

Table 6. 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. An overview of all variables and its meaning is given in Table 3. In addition an index with the GPS position (R2b or R7c) is applied for potential differences between the two rock glaciers.

	final model 1	final model 2
(Intercept)	-0.06 (0.70)	-1.27 (0.36)***
Prec.0	1.80 (0.44)***	0.74 (0.24)**
PDD_{gst}.0	-0.21 (0.10)*	
zc.ind	2.58 (1.29)*	
snow.ind	-3.02 (1.34)*	
posR2b	-0.69 (0.47)	-0.83 (0.47).
Prec.0:PDD_{gst}.0	-0.20 (0.05)***	
Prec.0:zc.ind	1.18 (0.38)**	
Prec.0:snow.ind	-1.85 (0.44)***	
Prec.0:posR2b		-0.73 (0.24)**
AUROC	0.85	0.75
AIC	148.5	168.53

Significance of Wald test: $^{*} < 0.05$, $^{**} < 0.01$, $^{***} < 0.001$.

New/updated Figures

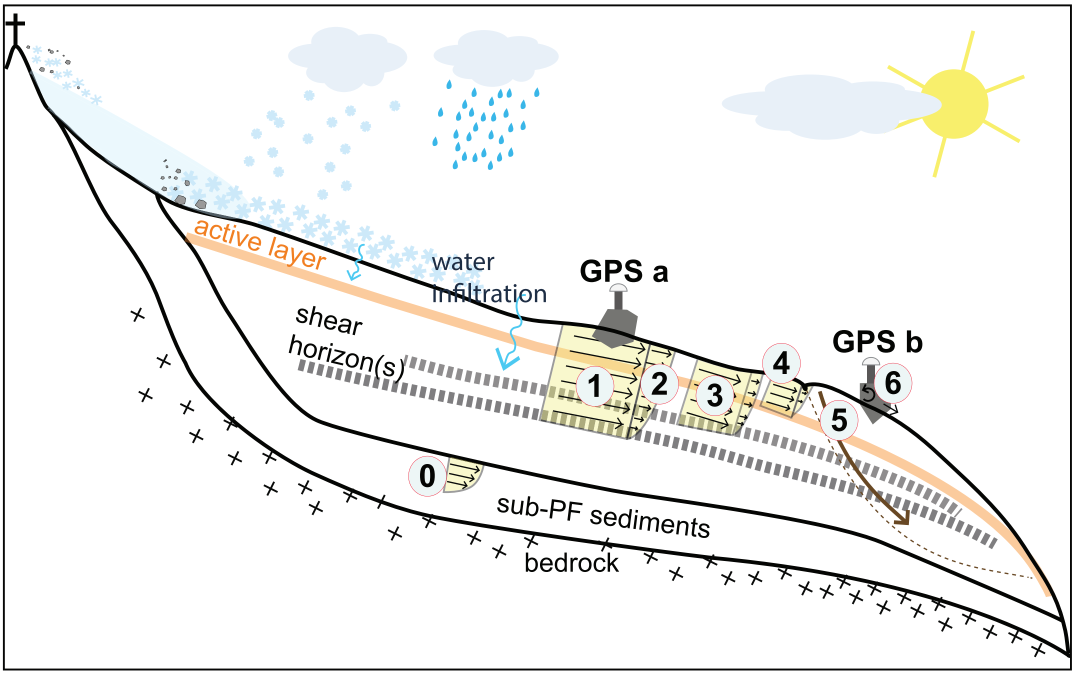

Figure 1. Schematic profile of a rock glacier. The observed movement at the surface might result from move- ment at different depths of the rock glacier (cf. Roer et al., 2008): (0) Deformation of sub-permafrost sediments (cf. Roer et al., 2008), (1) displacement within main shear horizon (e.g., Arenson et al., 2002), (2) (little) in- ternal 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) dis- placement due to rotational slide (e.g., Roer et al., 2008), and/or (6) displacement/rotation of boulder at surface (Lambiel and Delaloye, 2004). Thick dashed lines within the rock glacier body indicate potential shear horizons.

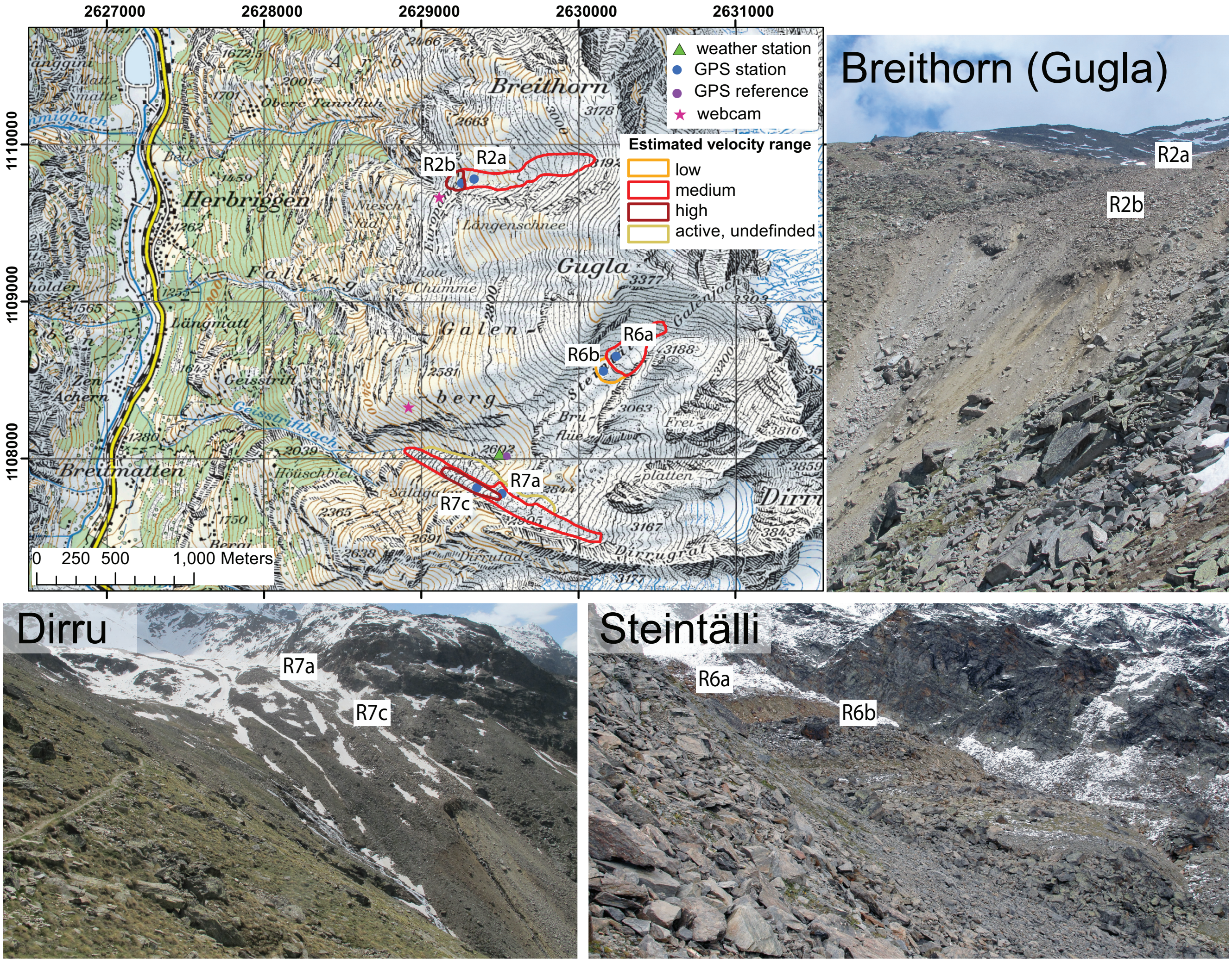

Figure 2. Overview of study site and main instrumentation. Estimated velocity range are for *low* a few decimetres per year, for *medium* several decimetres per year and for *high* more than a metre per year. This was esti- mated based on field observations, expert knowledge (Dr. Hugo Raetzo, Federal Office for the Environment), and published observations (Delaloye et al., 2008b; Strozzi et al., 2009a, b; Delaloye et al., 2010, 2013; Wirz et al., 2015). Right and bottom: 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.

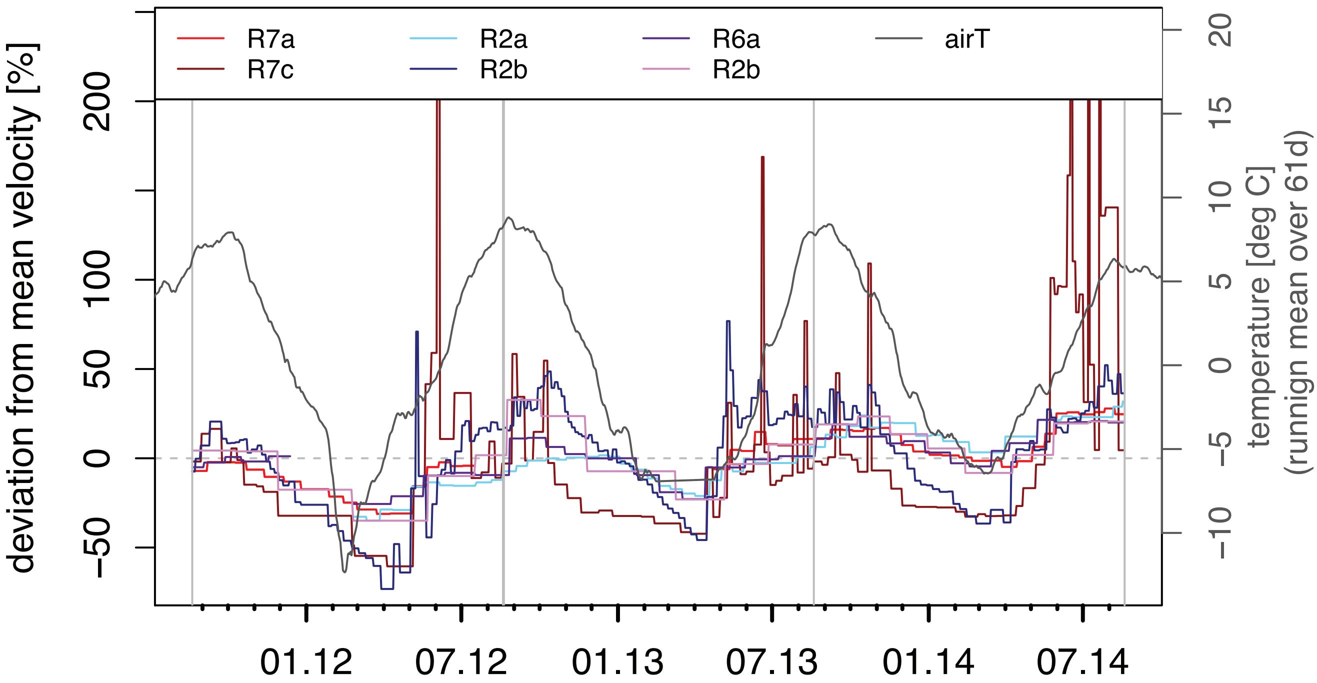

Figure 3. Intra-annual variability of horizontal velocities. Left y axis: intra-annual variability, expressed as deviation from MAV_{12-14}. Right y axis: filtered air temperature (running mean over 61days). Vertical grey lines separate the three different years of observation (2011/12, 2012/13, 2013/14).

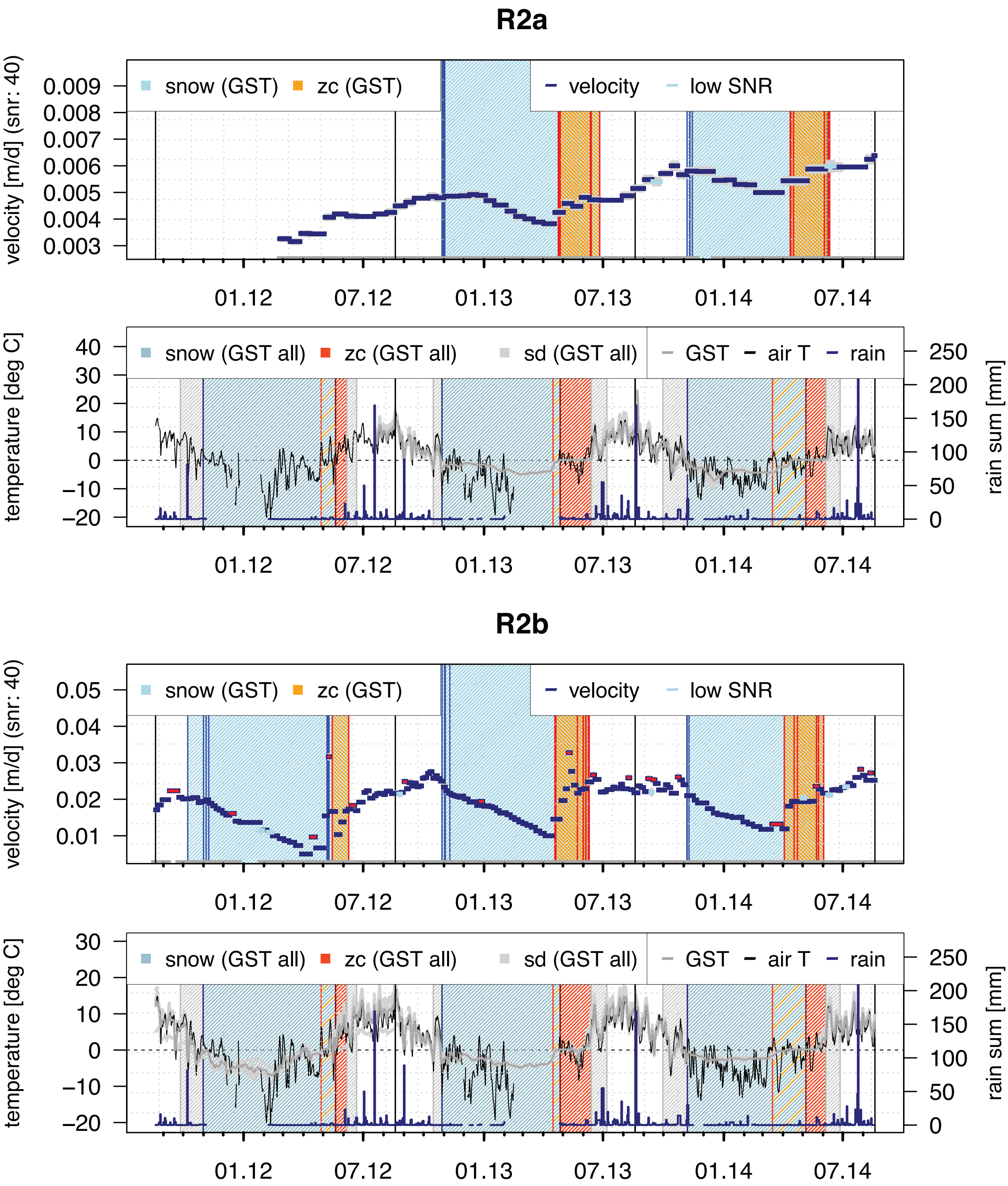

Figure 4. Comparison of the horizontal velocities to meteorological factors for Breithorn rock glacier (R2a and b). Vertical back lines separate the three different years of observation (2011/12, 2012/13, 2013/14). Top: horizontal velocity (darkblue), its standard deviation (grey), and velocity periods detected as peaks (red dots), periods with a SNR below SNR-t are indicated in ligthblue. Grey dots at the bottom indicate days with avail- able GPS positions. Zero curtain period (orange) and insulating snowcover (light blue), both estimated from individual iButtons next to the GPS station (the vertical blue lines indicate the start of an insulating snowcover at the individual iButton and the vertical orange line the end of the zero curtain period). Bottom: daily sum of liquid precipitation (darkblue bars), air temperature (black line) and GST (grey line, of iButtons next to GPS station, bold line refers to the median over all iButtons). Insulating snowcover (blue, earliest in grey) zero cur- tain periods (dark orange, earliest shadowed in orange, latest in grey) as derived from all iButtons in the study area.

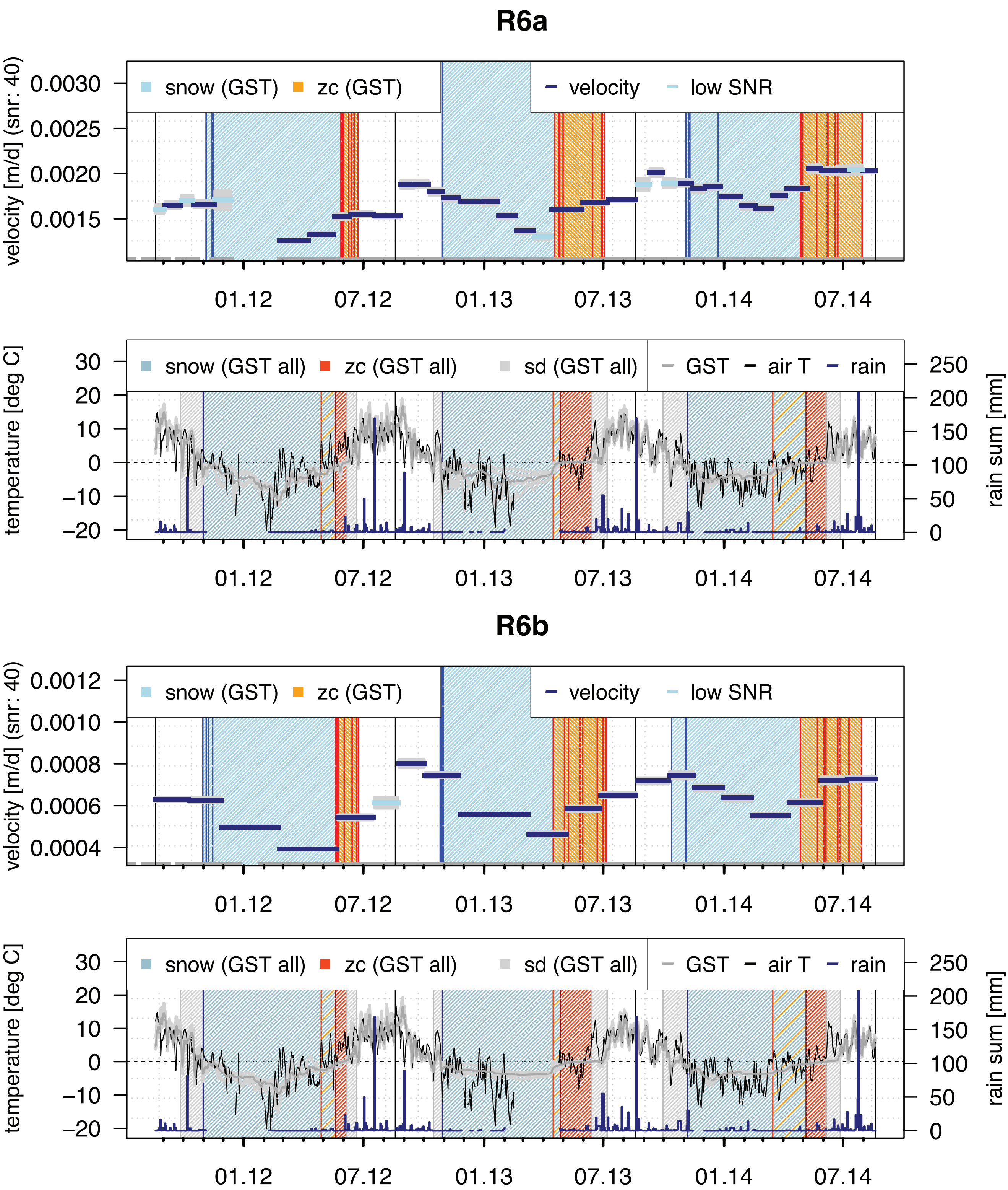

Figure 5. As Fig. 4, but for rock glacier Steintälli (R6a and b).

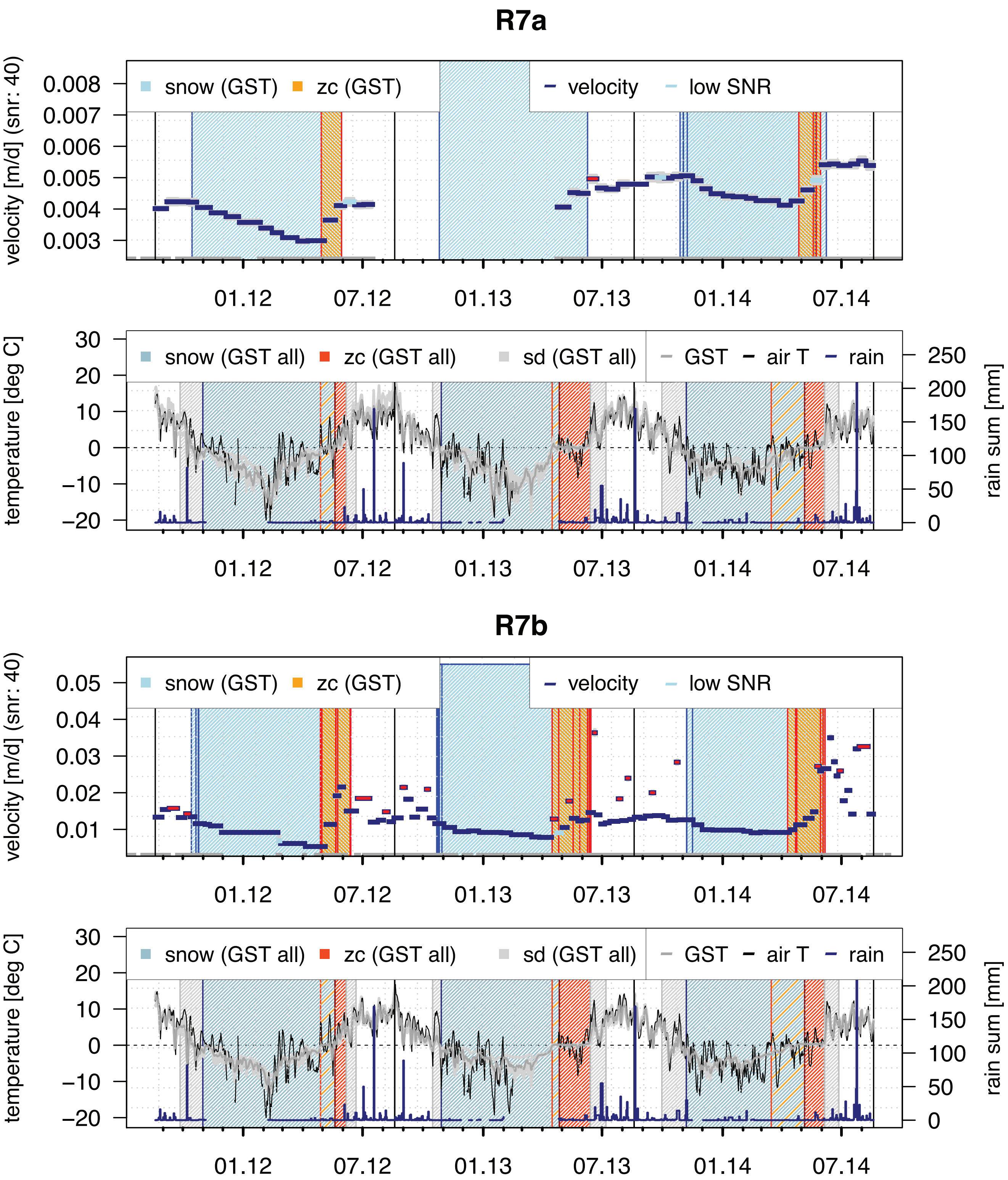

Figure 6. As Fig. 4, but for rock glacier Dirru (R7a and b).

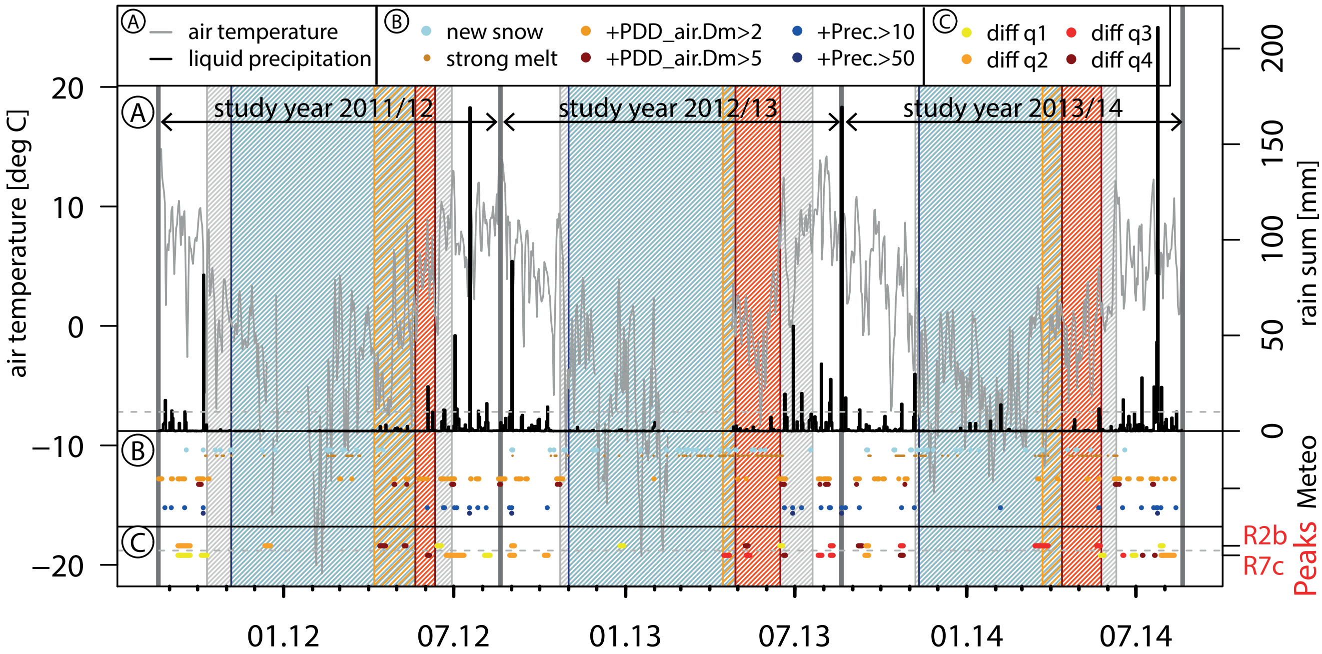

Figure 7. Comparison of velocity peaks at R2b and R7c to meteorological factors. (A) Air temperature and liquid precipitation, both measured at the weather station within the study. Vertical grey lines separate the three different years of observation (2011/12, 2012/13, 2013/14). (B) In the middle of the plots, the colored dots refer to the occurence of exceptional values of meteorological factors: newsnow: on this day fresh snow was clearly visible on webcam images, strongmelt: on this day strong melt was clearly visible on webcam images, $+PDD_{air}$. Dm ≥ 2: the difference of PDD_{air} on that day compared to the monthly mean of PDD_{air} was above 2˚C, $+PDD_{air}$.Dm≥5: the difference of PDD_{air} on that day compared to the monthly mean of PDD_{air} was above 5 ˚C, +Prec ≥ 10: the daily sum of liquid precipitation was 10 mm or more, +Prec ≥ 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 $diff_p$).

Figure 10. Visible cracks (left, from September 2011) and depressions (middle left, from June 2013) at the front of the rock glacier Breithorn, visible water outflow (middle right) at front of rock glacier Dirru (from June 2013), and a webcam image of the front of rock glacier Breithorn (right, from 14.06.2013).