Temporal Characteristics of Different Cryosphere-Related Slope Movements in High Mountains

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Abstract

Knowledge of processes and factors affecting slope instability is essential for detecting and monitoring potentially hazardous slopes. The overall aim of this study is to detect and characterize different slope movements in alpine periglacial environments, with the ultimate goal to understand the broad range of phenomena and processes encountered. In this article, our measurement-setup and our strategy for analyzing the spatio-temporal (seasonal and intra-annual) velocity fluctuations of various slope movements is explained and initial results are presented.

GPS (Global Positioning System) devices have been developed and deployed to continuously measure the velocity of slope movements within an Alpine study site. The measurement devices have the potential to operate for several years. Since December 2010, first devices are successfully measuring. Based on these measurements, high-accuracy daily differential GPS-positions and the corresponding velocities are calculated. A steep rock-glacier tongue showed a steady decrease in velocity in winter and a strong acceleration in May during the snowmelt period. These first results demonstrate the importance of continuous (here daily) measurements over longer periods and their potential to enable the inference of factors and processes controlling slope movement.

Keywords

Mass movements • Cryosphere • Differential GPS

Introduction

Permafrost slopes are sensitive to climate change and permafrost degradation can develop or accelerate slope instabilities. With predicted global climate change, it must be anticipated that instabilities of rock slopes and movement of ice-rich debris will increase (Haeberli and Burn 2002).

In the last decades an increasing number of slopes in periglacial environments developed into fast mass movements (e.g. Lewkowicz and Harris 2005). Further, for many rock glaciers, acceleration could be observed (e.g. Roer et al. 2008; Delaloye et al. 2008), probably due to increasing air-temperatures (e.g. Roer 2006). Additionally, it seems that the number of large rock falls (e.g. Ravanel and Deline 2010) and debris flows (e.g. Jomelli et al. 2004) starting in permafrost areas has increased. While some factors controlling slope stability, such as topography or lithology, remain rather constant over time, others undergo rapid changes in response to climate forcing and may cause unexpected types of lope movements (Gruber 2011). Examples of these are ground temperature, precipitation or melting of surface and subsurface ice.

Hazard assessment and early warning can be improved when it is understood where and when slopes can develop

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into destructive mass movements. So far, most scientific studies concentrate on one specific type of mass movement (e.g. rock glaciers, solifluction, debris flows or fast landslides). In contrast, the overall aim of this study is to analyze slope movements in alpine environment within a broader range of phenomena and processes.

Newly developed methods of terrestrial and aerial surveying increase the ability to observe slope movements in alpine regions (e.g. Kääb et al. 2005; Strozzi et al. 2010). GPS devices allow to continuously measuring the displacement of single boulders (Limpach and Grimm 2009) and, therefore, to analyze the temporal variability of slope movements. This study is part of *X-Sense*, a joint research project between different research groups (geodesy, computer engineering, remote sensing and geography). Within *X-Sense*, new low-cost GPS devices suitable for high mountain environments have been developed (Beutel et al. 2011). The measurement-setup (described in a later section) allows continuously measuring highly accurate positions and tilt-angles of moving boulders with high temporal resolution and coverage (several years). Based on these measurements at least one highly accurate position fix per day can be achieved.

To increase process-understanding of slope movements, the high temporal resolution and coverage are of great value. Mainly because short-term velocity fluctuations of permafrost creep are still poorly understood (Haeberli et al. 2006), although it has been recently discovered that they can be higher than inter-annual variations (Perruchoud and Delaloye 2007). Moreover it has been investigated that seasonal variations can even occur when no inter-annual variability can be observed (Matsuoka 2003; Delaloye et al. 2008). Thus the high temporal resolution allows detecting velocity-variations within short time-period, e.g. seasonal or even sub-seasonal variations. Detecting the timing of acceleration and deceleration of various measurements points allows building and testing hypotheses concerning influencing factors, such as melt water infiltration.

In the following, we explain the research strategy to analyse the spatio-temporal variability of cryosphere-related slope movements, with the main focus on the seasonal and intra-annual velocity-fluctuations. Further, we give an overview of the study site and the setup of the GPS-stations. In addition, preliminary results are shown.

Research Strategy

Studied Phenomena

A range of different types of slope movements will be investigated. While some movements can be clearly related to a certain geomorphological feature, for others the underlying processes are unknown. The term ***c**ryosphere-related slope movements in high **m**ountains (CM-movements)* is therefore introduced to describe slope movements studied within this work. Slope movements in steep bedrock are excluded. Investigated CM-movements have the following common characteristics:

- Located in high mountains
- Cryosphere-related: i.e. strongly influenced by the occurrence of permafrost, glacier-debuttressing and/or snow
- At least partly debris-covered

Planed Methodology

A schematic overview of planned methods is given in Fig. 1. We will include various CM-movements in the analysis, and for each movement type several GPS-locations are chosen. To investigate if the velocities of one single GPS location are representative for the whole feature, the GPS solutions will be compared to other displacement-measurements (e.g. InSAR-derived velocities or mobile periodical GPS measurements of additional boulders). In comparison to previous studies (e.g. Delaloye et al. 2008; Delaloye 2010), the main advantages of our measurements are the high temporal resolution and temporal coverage. Our measurement-setup allows detecting the exact time of velocity-changes and learning about important common characteristics of various CM-movements. This helps to increase the understanding of controlling factors and processes. The setup of the GPS stations is described in a later section.

The GPS-data analysis will have two parts: In *Part A*, statistical methods will be used to describe the temporal characteristics. Mainly intra-annual and seasonal velocity-changes will be analyzed together with auxiliary data (e.g. measured subsurface temperature and data from weather-stations). We will on the one hand analyze the temporal characteristics of each movement type. On the other hand we will study the differences and common characteristics of various movement types in the test site (e.g. rock glacier vs. open fractures). In *Part B*, we will investigate the factors and processes causing CM-movements. This will partly be based on explorative data analysis, but mainly based on hypotheses-testing with statistical models, e.g. multivariate regression models. Hypotheses will be formulated based on first results (of Part A) and literature study. Auxiliary data for the analysis will include measured as well as modelled variables. The model GEOtop (Rigon et al. 2006; Dall' Amico et al. 2011), a physics-based distributed energy balance model, will be applied for this. Modelled auxiliary data include factors, which are rather difficult to measure in the field, but have an influence on movements, e.g. pore water pressure or ground temperature at various depths.

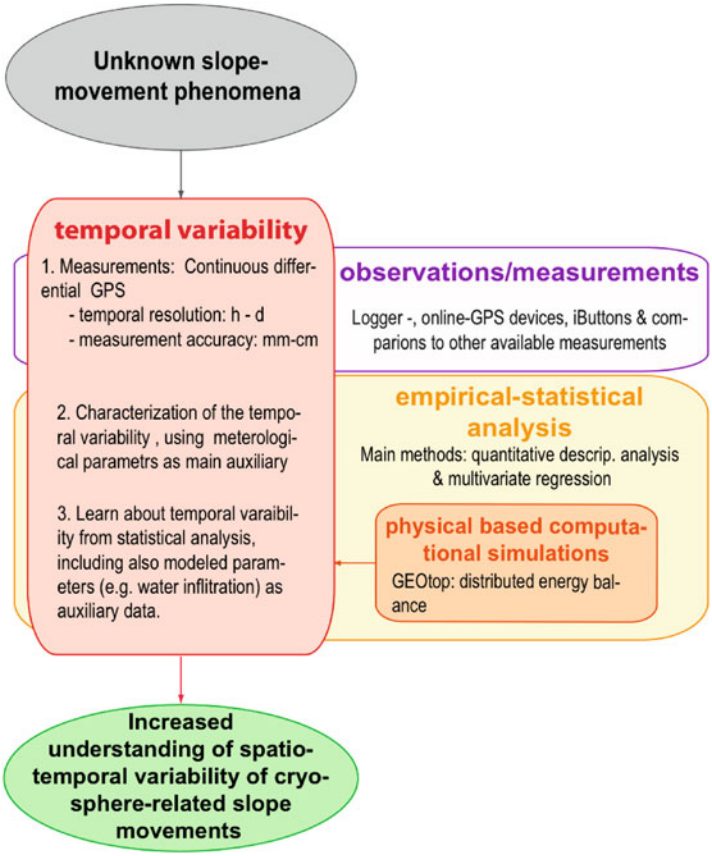

Fig. 1 Schematic overview of the methods, which are included in the study, and how we will combine them

Study Site and Field Instrumentation

The main study site is the *area of Dirruhorn,* located at the orographic right side of the Matter Valley, above Herbriggen/Randa, Switzerland (Fig. 2). The mainly westerly exposed slopes range from 2,600 to 3,200 m a.s.l.. Permafrost is abundant in this area (BAFU 2006; Böckli et al. 2011). The lithology is strongly weathered Gneiss and the main geological structure is oriented approximately parallel to the main slope. The field area includes various CM-movements: e.g. exceptionally fast and potentially dangerous rock glaciers moving up to 10 m/a (Delaloye 2010), and slopes where clear evidence for movement exists but the underlying mechanisms are unclear. Figure 3 shows the geomorphological map of the main study site.

Figure 2 gives an overview of installed GPS stations in the *area of Dirruhorn*. In December 2010, the first three GPS stations were installed (DI2, DI7 and Base). The station *Base* serves as GPS reference station. In March 2011 an additional GPS station was deployed at position DI5. Since May 2011, 11 more GPS stations, mounted on moving boulders continuously measure position and tilt-angle. Additional equipment, such as a base-station for data transmission purposes, a webcam and a weather station, were installed. Nearby each GPS station five iButtons (simple temperature data loggers) were distributed, following the procedure outlined by Gubler et al. (2011), to measure the near-surface ground temperature. The GPS stations are placed in the field such that various types of slope movements are covered. Within the area of one movement type the stations are positioned in such a way that the displacement is as representative as possible (e.g. in the middle of the rock glacier; not at the front). It is planned to expand the setup with further GPS stations and one to two high-resolution cameras. The cameras will deliver important information about actual surface characteristics, such as snow cover. Since 2007 Delaloye (2010) has made mobile GPS-measurements twice per summer in the *area of Dirruhorn*. In the following description of our GPS locations, all given velocities refer to the measurements of Delaloye (2010).

GPS stations DI2, DI5 and DI7 are located on the *Dirru* rock glacier (Fig. 2), which consists of different tongues (Fig. 3). DI5 and DI7 are located on the lower part of *Dirru*, with a slope angle between 30° and 40°. DI5 is located on an inactive tongue, as we assume based on the existing sparse vegetation and as can be seen from the GPS results in Delaloye et al. (2008). DI7 is located on an active steep tongue, which potentially became destabilized in the last years. In 2009 the mean velocity of locations close to

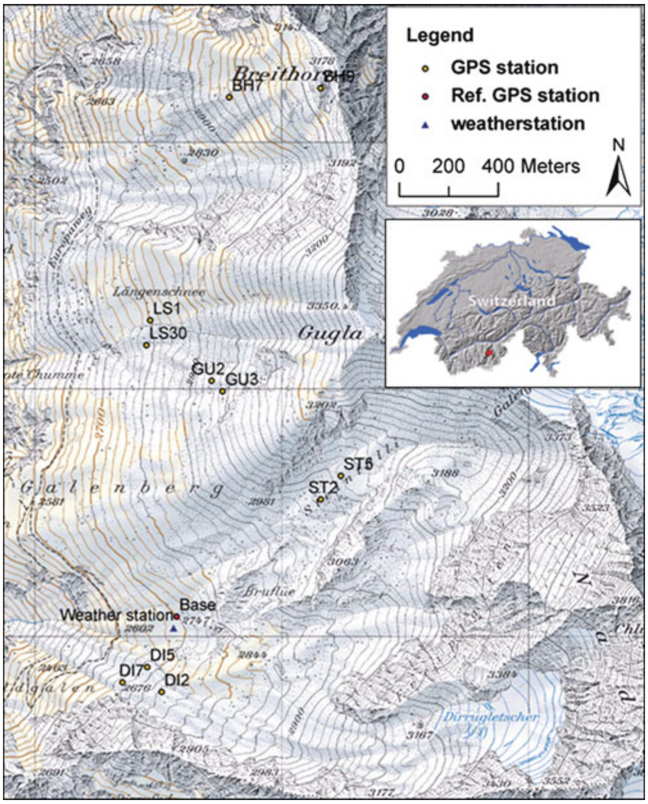

Fig. 2 Overview of the study site *area of Dirruhorn*. The study site is located in the Matter valley, Valais, Switzerland. Topographic map LK 1:25'ooo of Swisstopo

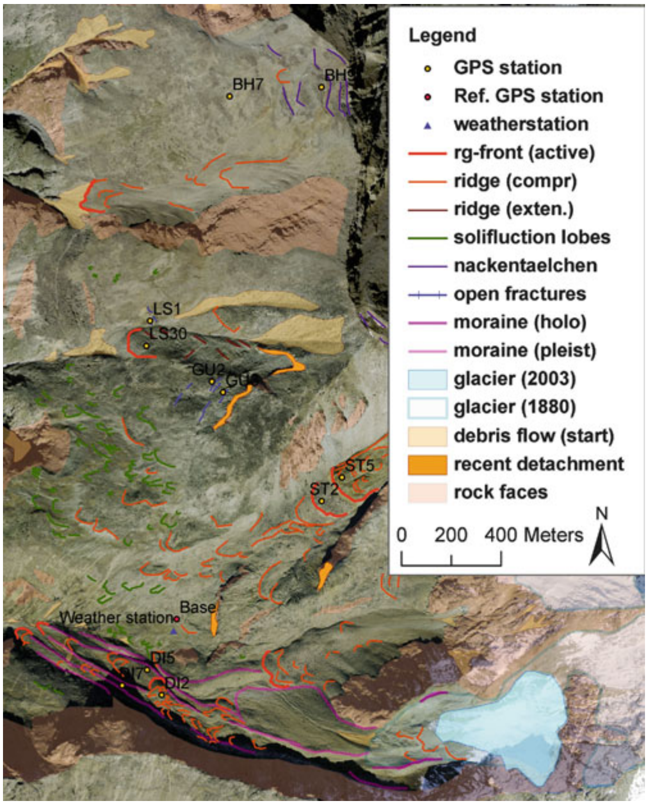

Fig. 3 Geomorphological map of the study site *area of Dirruhorn*. Orthophoto from the year 2005 of Swisstopo

DI7 was assessed to be more than 9 m/a. DI2 is located on the upper part of Dirru, with a gentle slope (< 15°) and mean velocity of approximately 3 m/a (measured in summer 2009). Since 2009 the velocities of *Dirru* rock glacier have been observed to be slightly decreasing at all measured locations.

GPS station LS30 is positioned on the *Gugla* rock glacier. This rock glacier has depressions, which indicate extensive flow (Figs. 2 and 3).

GPS stations ST5 and ST2 are mounted on two rock glaciers in the Steintälli (Figs. 2 and 3). The upper rock glacier (ST5) overrides the lower one (ST2). Both rock glaciers have typical ridges and furrows, indicating compressive flow.

GPS stations GU2 and GU3 are mounted upon "Nackentälchen", located below a recent slope failure zone, in the westerly exposed slope of *Gugla* (Figs. 2 and 3). The geomorphological feature "Nackentälchen" is similar to a double-ridge with a small valley in between, but is not located close to a mountain-ridge.

At *Breithorn* (BH9 and BH7) geomorphological features (e.g. Kellerer-Pirklbauer et al. 2010) indicate a deep-seated gravitational slope deformation. BH9 is positioned upon a double-ridge (Figs. 2 and 3), BH7 in the central part of the landslide. Velocities measured in 2008/2009 at Breithorn were between 0.05 and 0.3 m/a.

GPS Devices and Data-Processing

Measurement-Devices

The measurement system consists of distributed GPS loggers that autonomously collect and log GPS data, inclination of the antenna, and system status information over extended periods. At selected positions (DI5, DI7), powerful testbeds (Buchli et al. 2011) have been installed along with the loggers. These prototype sensors, equipped with wireless radios, permit design investigation of a planned online GPS system to provide real-time data for on-the-fly analysis.

The custom GPS logger electronics feature an off-the-shelf GPS receiver that can output data suitable for the differential post-processing algorithm employed within this study. GPS data is currently logged at a sampling interval of 30 s. All sensors are mounted elevated on a mast of 0.5–1.5 m to allow the reception of GPS signals also in deep snow cover. To disambiguate between lateral displacement and tilting of the mast, two inclinometers, for X- and Y-axis, are also logged periodically.

Fig. 4 GPS station at position DI7, on the destabilized tongue of the *Dirru* rock glacier. Station DI7 includes a logger, two inclinometers and a prototype online sensor, all mounted on the same mast. Energy supply is given by a photovoltaic energy harvesting system

The energy to operate the device is provided by a photovoltaic energy harvesting system, and backed by a battery (Fig. 4). The battery acts as buffer that permits running the system during times without solar input. To handle energy fluctuations, the devices have two operating modes. The high-power mode logs continuously to the SD card as long as the battery has an energy content above a given threshold (>11.8 V for 12 V AGM cells). Once the battery capacity drops below this threshold, the device enters an energy-saving mode. In this mode, the GPS receiver is powered only during a statically configured fraction of the measurement period, e.g. 2 h/day. With this setup, the lifetime of the logger is limited only by the SD card capacity.

GPS Data Processing

The GPS data processing is based on single-frequency differential carrier phase techniques. A local GPS reference station, placed within a stable area, is used for the differential computation of the coordinates of the moving GPS stations. Kinematic coordinates with sampling intervals down to 30 s (the sampling interval of the GPS devices) are computed, as well as daily station coordinates. The achieved positioning accuracies are at mm-level for the daily solutions and cm-level for the 30 s solutions (Limpach and Grimm 2009). Based on the GPS station displacements (Fig. 5), 3D-velocities (Fig. 6) are computed using *least-squares smoothing spline* parameterizations and their analytical derivatives.

Preliminary Results and Interpretation

Here we present first results of the GPS stations DI5, DI7 and the reference station *Base*. The data cover the time period from 19 December 2010 until 25 May 2011. The temporal resolution of the preliminary displacement solutions shown is 24 h (Fig. 5). For all GPS stations the standard deviation of the daily GPS solutions was 1 mm in the horizontal and 2 mm in the vertical. The inclinometer measurements were not yet included in the analysis.

The position of the reference station (629575/108081, 2,697 m a.s.l., Swiss coordinate system CH1903) was stable over the entire observation period.

The GPS station DI5, positioned on an inactive tongue of the *Dirru* rock glacier, did not move either and the position (629456/107877, 2,706 m a.s.l.) remained static. This observation is consistent with previous GPS results of Delaloye et al. (2008). The mm-level standard deviation of the daily solutions with respect to the static mean position over the entire period demonstrates the excellent repeatability of the GPS results.

In contrast, measurements of GPS station DI7 showed a total displacement (3D) of 1.43 m from 19 December 2010 to 25 May 2011 (Fig. 5). The total vertical displacement was 0.69 m. Until the middle of April the velocity was approximately linearly decreasing. The mean 3D-velocity (velocity along the main displacement) was ~1.0 cm/day in December and ~0.6 cm/day during the first half of April (Fig. 6). At the end of April the velocity started to increase. The 3D-velocity reached a value of 1.9 cm/day in the middle of May. The acceleration again decreased towards the end of May to a 3D-velocity of 1.5 cm/day.

Air temperatures were measured at the weather station (Fig. 2) since March 2011. Until the end of March, the daily mean air temperature in the area *Dirru* rock glacier was mainly below zero degrees, with the exception of a short period in March (Fig. 7). At the beginning of April, air temperatures increased and were mainly positive for 2 weeks, dropping again to below zero degree in the middle of April. During May air temperatures mostly remained above zero degrees. On webcam images of the *Dirru* rock

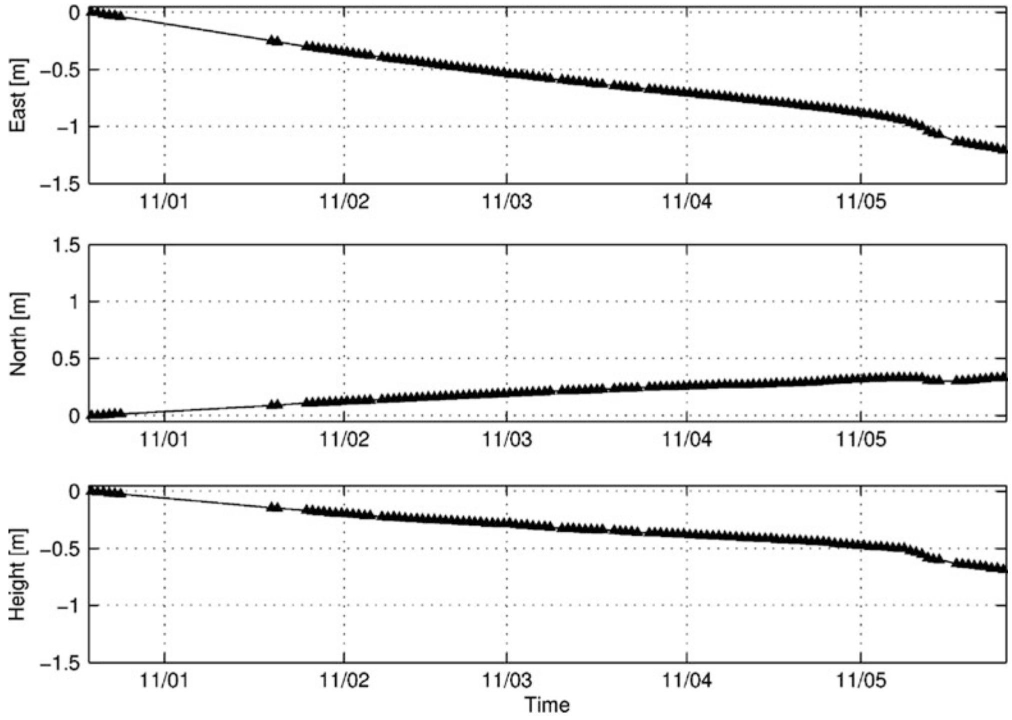

Fig. 5 Daily solutions of displacements of the GPS-device DI7, from differential GPS processing

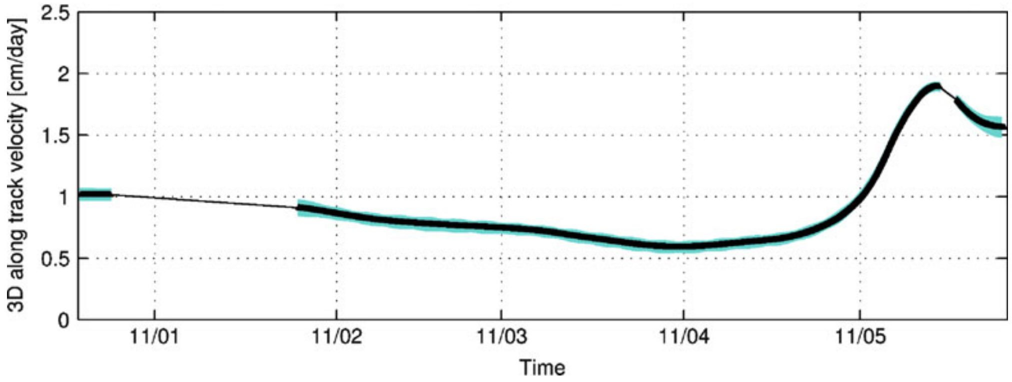

Fig. 6 3D-velocity along the main direction of displacement of GPS-device DI7. The blue error bar shows the uncertainty interval

glacier it is visible, that snow started to disappear in April. In the middle of May many parts of the rock glacier were already snow free.

Our results support previous findings (e.g. Delaloye et al. 2010) that the tongue of *Dirru* rock glacier, where the GPS-device DI5 is located, is inactive. Further, based on first observations we formulate the hypotheses, (a) that the acceleration at position DI7 at the end of April and middle of May was caused by the infiltration of snow meltwater. And (b) that in May due to the lack of meltwater from snow the velocity decreased. (c) The high acceleration in May most probably was accompanied by a tilt of the mast. This rotation of the boulder can explain the sudden change of displacement from north to south around May 20 (Fig. 5). We assume therefore that actual velocity was slightly smaller in the middle of May than shown here.

Conclusions

Within the *X-Sense* project new low-cost GPS devices including two inclinometers have been developed to continuously measure the position and tilt angle of moving boulders. The novelty of obtained data is that they have a high temporal resolution and can cover several years.

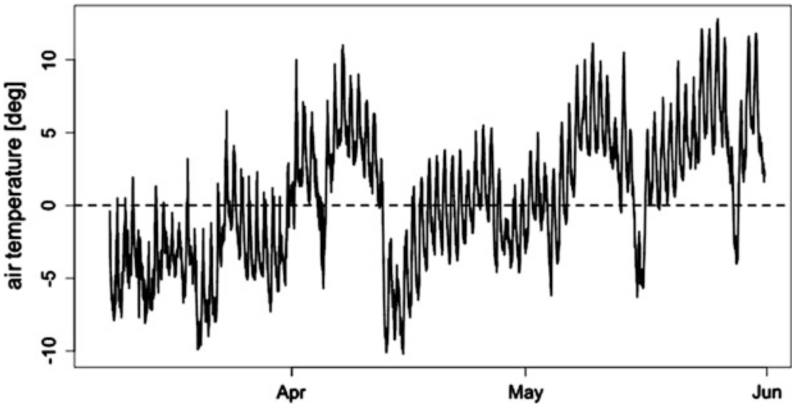

Fig. 7 Air temperatures measured at the weather station next to the *Dirru* rock glacier at 2,697 m a.s.l

This makes it possible to identify both velocity variations (a) within a short period (e.g. week or season) and (b) between different years. The exact timing of acceleration can help to detect influencing factors, such as snowmelt. The low costs per GPS-device allow measuring at many locations. The high number of measurement points, located upon various slope movement types, will help to find common characteristics of cryosphere-related slope movements in high mountains.

First results show high short-term velocity fluctuations in spring. The velocity of a potentially destabilized tongue was slightly linearly decreasing in winter. From the end of April, with increasing air-temperature and the disappearance of the snow cover, velocities increased up to nearly 2 cm/day in the middle of May, but again decreased to ~1.5 cm/day.

Outlook

So far we could only present data from two locations on two different tongues of Dirru rock glacier without inclination-measurements. Nevertheless, the acceleration of position DI7 in May confirms the importance of high temporal resolution and coverage to increase process understanding. The observation that the displacement at station DI7 was most probably accompanied by a rotation of the boulder depicts the importance of measuring the tilt-angle of the GPS-mast. The next analysis will include a more quantitative comparison of GPS data from the different locations and meteorological data, using descriptive statistical methods. To increase process understanding, we will apply statistical methods to combine measured data with physical modelling. Data will cover a longer time-span (from spring to summer).

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