Regional quantification of rock glacier movement in Austria using governmental GIS data

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Abstract—**This paper demonstrates (1) how the kinematics of rock glaciers can be monitored at a regional scale using multi-temporal governmental GIS data, such as digital orthophotos and digital elevation models, and (2) how this geometric information can be exploited in climate change studies. Research was carried out in a 125 km² mountain area in Central Austria characterized by widespread permafrost and active rock glaciers. Our main conclusions are: (1) rock glacier monitoring using governmental GIS data is possible, with certain restrictions in the significance level due to reduced data quality and limited data availability, (2) flow velocities have increased significantly within the observation period, and (3) temporal change of flow velocity is correlated with temperature although mean annual rates computed by averaging velocities over several years mask high inter-annual variations in climatic conditions.**

I. Introduction

Active rock glaciers are creep phenomena in high-relief environments under permafrost conditions moving slowly down-valley or downslope. Morphologically, rock glaciers are commonly characterized by distinct flow structures with ridges and furrows at the surface [1, 2]. Permafrost is defined as perennially frozen ground with a seasonally unfrozen surface (active layer). According to [3], the global permafrost area is about 16-21 × 10^6 km² including Antarctic and sub-sea permafrost. Flow velocities of active rock glaciers are typically in the range of a few centimeters up to several meters per year. The magnitude of the creep/flow velocity and its spatio-temporal change is influenced by different parameters, such as air and ground temperature, topography, ice content, and hydrology [1, 4, 5].

Inactive rock glaciers do not move at present but are still under widespread permafrost conditions. Active and inactive rock glaciers are jointly termed as intact rock glaciers [1] because a lack of adequate data makes it difficult to judge whether a rock glacier is moving or not. In contrast, relict rock glaciers are no longer under permafrost conditions and are considered as non-moving, paleo-permafrost indicators.

II. Study area

The study area (125 km^2) is located in the central part of the Schober Mountains, Hohe Tauern Range, Central Austria (Fig.1). According to a recently elaborated rock glacier inventory [6], 64 intact and 35 relict rock glaciers are located within the area of interest. Permafrost is a widespread thermal phenomenon in this region as shown by numerous intact rock glaciers, local ground temperature monitoring [7], and regional permafrost models [8] indicating a possible lower limit of permafrost at c. 2200 m a.s.l..

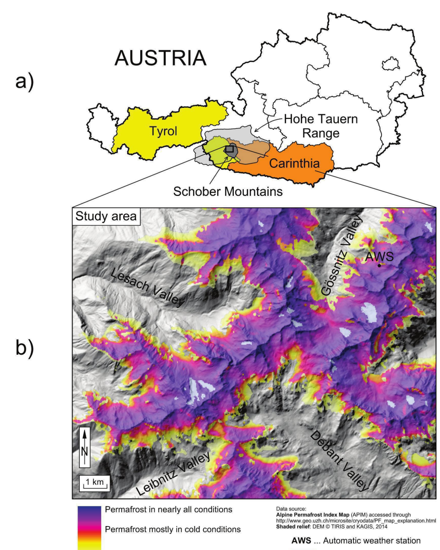

Figure 1. a) Location of the study area in the central Schober Mountains, Hohe Tauern Range, Austria. b) Permafrost distribution in the study area. AWS-automatic weather station; Data source: [8]; TIRIS and KAGIS (GIS data providers).

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III. Materials and methods

A. Multi-temporal digital orthophotos

Digital orthophotos of three different epochs (2002, 2009, 2012) covering the area of interest were made available by the authoritative GIS data providers of the regional governments of Tyrol and Carinthia (Fig. 1, Tab. 1). Image data was provided as tiled jpg-compressed files, with each tile covering an area of 6.25 km^2. All tiles of each epoch were mosaicked together to assemble a large image file. A common ground sampling distance (GSD) of 50 cm was chosen to limit file sizes and thus computational work load. Local analyses, however, were carried out with 20 cm GSD for several test sites. RGB data was converted to grayscale for subsequent use in the image matching software. Image data of 2012 was low-pass filtered using a Gaussian kernel to approximate smoothness of the 2002 and 2009 image data.

TABLE I. Multi-temporal digital orthophotos Used

Date	Original GSD (cm)	Spectral bands	Type of camera
Sept. 18, 2002	25	RGB	Analog
Sept. 7, 2009	25	RGB	Analog
Aug. 25, 2012	20	RGB NIR	Digital

B. Multi-temporal digital elevation models

The GIS data providers also made available digital elevation models (DEMs) derived from airborne laser scanner (ALS) data with a grid spacing of 10 m for the whole study area and 1 m for selected test sites. Due to administrative reasons, the DEM data of Austrian provinces is strictly confined by provincial boundaries, however with a small overlap to the neighboring province. Elevation data from the Tyrolean and Carinthian part of the study area dates from August/September 2009 and the year 2012, respectively. The precise dates of ALS data acquisition were not available . The overlapping zone of the two grids in the border area is approximately 700 m in width. This part was then used in our change detection analysis.

C. Computation of displacement vectors

Information about the geometric change of the Earth's surface can be derived by different measuring techniques. Remote sensing techniques from air or space are highly appropriate to efficiently retrieve such information on a regional scale, e.g. for a whole mountain group. In this study we applied multi-temporal orthophotos and DEMs. The computation of horizontal displacement vectors using orthophotos of at least two different acquisition dates has been reported for many earth science applications (e.g. [4]). Image matching is preferably carried out using the normalized cross-correlation coefficient as a similarity measure for searching homologous points [9].

We have implemented our software in Matlab R2012b. In order to uniformly measure surface displacement over a larger area, a variable grid of measuring points can be defined. For the purpose of efficiently screening the given study area we chose a grid spacing of 12.5 m. This setting provides sufficient geometric resolution for all rock glaciers of the inventory. The size of the correlation window is crucial and has been set to 31 by 31 pixels, which relates to an areal coverage of 15.5 m by 15.5 m.

A threshold of greater than 0.4 for the correlation coefficient defines potential good solutions. Furthermore, sub-pixel accuracy in image registration is achieved by parabolic interpolation. All prospective matches are cross-checked by back-matching using the same procedure as outlined above. Special emphasis was put on automatically detecting any remaining outliers in the final result. In order to detect these outliers we have defined a small set of rules of exclusion. These rules are primarily based on the smoothness assumption of the overall deformation and slope information derived from the DEMs. The rules turned out to be very useful in attaining an automatic procedure without significant loss of correct measurements. All rules are bound to the general significance level of the computed displacements. More dense and accurate displacement vector fields were computed for several other test sites within the study area following the workflow outlined above. Due to both the small areal extent and the general higher measurement precision, the displacement vectors computed for stable areas outside the rock glacier were used to detect small systematic offsets of the orthophotos involved and to quantify the attainable precision. In a few incidences a significant horizontal shift of the orthophotos was detected and corrected for.

Three-dimensional displacement vectors can also be derived from multi-temporal DEMs. The small overlapping area of the two DEMs (grid spacing of 1m) was used to validate any potential movement detected by means of orthophoto comparison in this area. In principle, the same image matching technique was applied as above. Height or gradient values (kind of shaded relief) may serve as gray values in the matching process. Our example is numerically based on the direct use of height values. Grid spacing was set to 5 m and the correlation window was 21 pixels, providing high spatial correlation. Stable areas around the suspected mass movement were analyzed to quantify maximum attainable precision.

D. Meteorological data

An automatic weather station (AWS) was installed in the study area in 2006. The station is located 2655 m a.s.l. in close vicinity to a highly active rock glacier (Fig. 1). We used air temperature data for the period September 2006 to September 2012. Data gaps were closed by using correlation analysis and temperature data from the meteorological observatory Hoher Sonnblick (SON) located 15 km northeast of AWS. Due to the high correlation of mean monthly air temperature data between AWS and SON, mean monthly values for AWS were furthermore estimated for the time period October 2002 to August 2006. See [4] for further methodological details. No ground temperature data were used in this study due to the lack of continuous ground temperature data between 2002 and 2012.

IV. RESULTS

Two thematic maps were produced showing the mean annual horizontal flow velocity of all rock glaciers of the study area for the two consecutive time periods 2002-2009 and 2009-2012. Figure 2 displays the map for the first period. Twelve intact rock glaciers revealed significant movements in both periods. The rock glaciers with the highest flow velocities (labeled as 1, 2 and 3 in Fig. 2) show mean horizontal flow velocities of up to 440 cm/a. The comparison of the two periods shows a general trend of higher velocities during the second period (by a factor of 1.4 to 1.8).

As an example of additional large-scale studies conducted in the study area, results from the Tschadinhorn rock glacier are depicted in Fig. 3. The maximum velocity of this rock glacier increased from 117 cm/a during the first period to 177 cm/a during the second period. The kinematics of an additional, previously unknown mass movement (label 4 in Fig. 2) detected outside the rock glacier areas was re-evaluated using the two DEMs of 2009 and 2012. Maximum flow velocities of up to 69 cm/a were calculated for this mass movement. This result

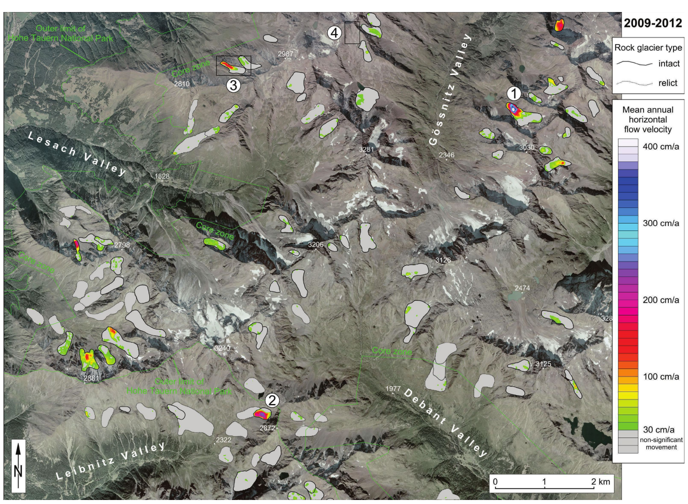

Figure 2. Thematic map showing the mean annual horizontal flow velocity of rock glaciers located in the study area for the time period 2009-2012.

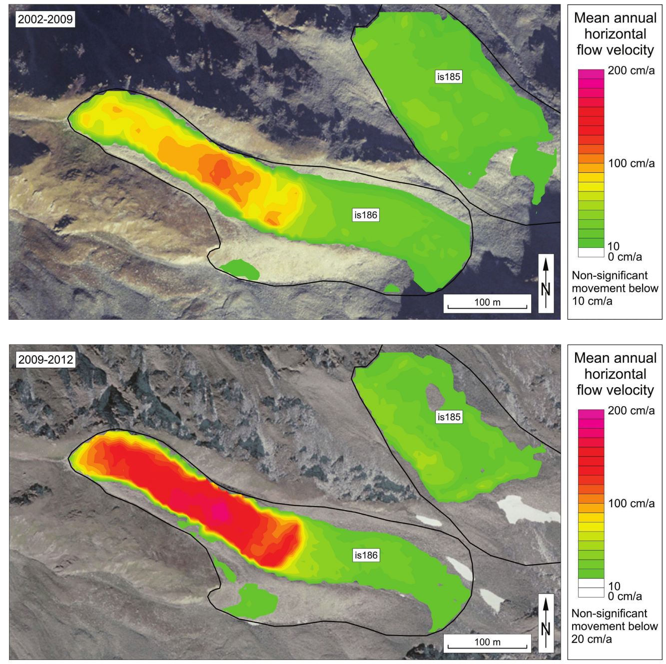

Figure 3. Mean annual horizontal flow velocity of Tschadinhorn rock glacier (is186) for the time period 2002-2009 (top) and 2009-2012 (bottom). For location see Fig. 2, label 3.

confirms the orthophoto-based deformation analysis.

Mean annual air temperature (MAAT) values at AWS were calculated for each hydrological year between 2002 and 2012. All hydrological years indicate a negative mean annual value. 2006-2007 (-0.1°C) was by far the warmest year, followed by 2011-2012 (-0.9°C), whereas the coldest year was 2003-2004 (-2.3°C). Apart from the values of 2002-2003 (rather warm), 2006-2007 (very warm), and 2009-2010 (rather cold) one might see a warming trend during the 10-year period. Furthermore, the mean annual value for 2002-2009 is 0.2°C lower than for 2009-2012, despite the “outliers” of the three hydrological years mentioned above. This observation further suggests a warming trend in the area.

V. DISCUSSION AND CONCLUSIONS

A. *Data availability and accuracy*

Multi-temporal orthophotos are available for the study area from governmental GIS data providers for at least three different epochs at GSDs of 50 cm, 25 cm and 20 cm. High spatial and also high radiometric resolutions can only be expected from recent digital orthophotos which are derived from aerial photographs taken with digital aerial cameras. Accuracy analysis of the orthophotos used has shown that geometric quality is generally high. Animated GIFs of orthophoto time-series and also calculated displacement vectors suggest, however, that the geometric quality of the orthophotos is mostly reduced by erroneous or low-resolution DEMs used in the rectification process. It was found that the orthophoto geometry was quite poor in some local areas. As a rule of thumb we can expect a mean relative registration error of ±60 cm for any two orthophotos taken at different times. Assuming a time interval of 3 years, the mean annual flow velocities computed would have an accuracy of approx. ±20 cm/a (1σ), which means that this kind of image data (3-year interval) do not allow detection of slow moving rock glaciers. The significance level can, however, be increased dramatically by using contemporary DEMs derived from the aerial photographs themselves or by at least using the high resolution DEMs derived from ALS data. Anticipated accuracies are in the range of a few cm/a as shown in other pilot studies, e.g. [10].

The current availability of multi-temporal governmental DEMs is limited. Nonetheless, this kind of data offers great potential in change detection.

B. Rock glacier speed-up and climate relationship

This study shows that almost all fast moving rock glaciers in the study area have increased their mean annual velocities between the two time periods despite the fact that the multi-annual averaging (7 and 3 years, respectively) masks inter-annual changes. This multi-annual trend is also confirmed by field-based (total station and RTK-GNSS) annual movement measurements at some of the rock glaciers in the study area. As shown by published [5] and unpublished data, rock glaciers in the study area showed slower movement in 1999-2002, higher rates in 2002-2005, deceleration and lower values in 2005-2009, and continuous speed-up since then. The field-based movement measurements revealed a 1.5 fold increase between the first (2002-2009) and the second (2009-2012) period. This is in accordance with the regional signal revealed in this study (1.6 times between the first and second period). This regional signal is also confirmed on an Alpine-wide scale. Reference [11] reported comparable relative velocity changes of a large number of rock glaciers in the European Alps supporting the climatic dominance of rock glacier velocity changes. This study and some previous studies [e.g. 5, 12] indicate that warmer temperatures favor higher velocities of rock glaciers. However, this reaction might have a time lag of several months or even years reflecting the delay in propagation of the temperature signal deeper into the rock glacier body. Furthermore, higher temperatures cause higher deformation rates of the ice contained in the rock glacier body and might influence the quantity of liquid water lubricating rock glacier movement.

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