Contrasting responses of Central Asian rock glaciers to global warming

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While the responses of Tien Shan glaciers – and glaciers elsewhere – to climatic changes are becoming increasingly well understood, this is less the case for permafrost in general and for rock glaciers in particular. We use a novel approach to describe the climate sensitivity of rock glaciers and to reconstruct periods of high and low rock glacier activity in the Tien Shan since 1895. Using more than 1500 growth anomalies from 280 trees growing on rock glacier bodies, repeat aerial photography from Soviet archives and high-resolution satellite imagery, we present here the world’s longest record of rock glacier movements. We also demonstrate that the rock glaciers exhibit synchronous periods of activity at decadal timescales. Despite the complex energy-balance processes on rock glaciers, periods of enhanced activity coincide with warm summers, and the annual mass balance of Tuyuksu glacier fluctuates asynchronously with rock glacier activity. At multi-decadal timescales, however, the investigated rock glaciers exhibit site-specific trends reflecting different stages of inactivation, seemingly in response to the strong increase in air temperature since the 1970s.

As a result of increasing air temperatures, glaciers in the arid Central Asian Tien Shan ranges have experienced strong mass loss over the past decades1,2, with possible impacts on freshwater availability during the drier summer months. Ice-rich permafrost bodies could gain relative importance for water supply in future summers, since they are assumed to store a similar amount of freshwater as the glaciers in the Tien Shan do3,4. A particularly important role in the regional hydrological cycle is hereby played by rock glaciers, i.e. frozen debris lobes that creep downslope under gravity5 and typically contain between 20 and 80 vol% of ice6. However, estimates on the ice content stored in rock glaciers are highly variable and uncertain7, and seasonal water releases from rock glaciers are generally lower and tend to fluctuate less due to their insulating debris layer8,9.

Rock glaciers are a widespread permafrost phenomenon in the Tien Shan; in northern Tien Shan alone (approximately 5'000 km²), more than 1'000 rock glaciers have been inventoried10,11. Knowledge about the response of rock glaciers to climate change is thus of great interest, but so far, only few studies have investigated the link between climate and rock glaciers in general and in the Tien Shan region in particular4,5,10,12. Geothermal observations at Zhusalykezen pass (3'337 m a.s.l.) in Kazakhstan have revealed an average recent rise in permafrost temperature by 0.1 to 0.2 °C a⁻¹ at depths of 10 and 25 m, respectively, over the period 1974–20046. Measurements of rock glacier front positions in the Tien Shan date back to 192313 and exhibit high mean frontal advance rates of up to several meters per year, with an accelerating trend since the mid-1980s3,10. This is in line with observations of rock glaciers in the European Alps, where a number of them have significantly accelerated since the 1980s, presumably due to a range of reasons, among them increasing permafrost temperatures14. Synchronicity of rock glacier activity as observed in the Alps14, however, has not yet been assessed in the Tien Shan, where knowledge on the long-term climatic impacts on rock glaciers remains highly fragmental.

Here we extend the current state of knowledge on rock glacier activity in the Tien Shan in the temporal and spatial dimensions, and present the world’s longest record of annual rock glacier activity. By combining growth anomalies in trees growing on rock glaciers, repeat aerial photographs and high-resolution satellite imagery, we reconstruct the activity of four rock glaciers in the Kyrgyz and Kazakh parts of the Tien Shan range over the past 120 years. The aims were to assess relations between the activity of these rock glaciers and climatic variations, to test for regionally synchronous periods of high and low rock glacier activity in the Tien Shan, and to decipher their possible climate sensitivity and development status.
As a peculiarity in regard to many other periglacial regions, the investigated rock glaciers reach down below the tree line (Fig. 1, Table S1). The rock glacier fronts are located close to the zero-degree-isotherm of mean annual air temperature at around 2'700 m a.s.l., i.e. at elevations where permafrost does not usually occur outside the rock glaciers themselves and where the rock glaciers are probably only slightly below the freezing point. As a consequence, these bodies exhibit comparably low viscosity, fast movement rates and a potentially particular sensitivity even to minor changes in surface energy balance and ground temperatures. The steep terminal fronts with loose boulders and "drunken trees" growing on the rock glaciers indirectly confirm the high activity of the investigated rock glaciers (Figs. S1–2).

The approach presented here capitalizes the fact that trees growing on rock glaciers suffer from enhanced rock glacier activity. Horizontal and vertical movements are recorded in the growth-ring series of trees and can thus be used as a proxy of rock glacier activity with annual resolution. Based on the tree-ring records of 250 Tien Shan spruces (Picea shrenkiana) and 30 junipers (Juniperus sp.) growing on the rock glaciers investigated in this study, we document more than 1500 growth anomalies induced by past rock glacier movements (Tables S2 and S3, Fig. S3). We use the annual ratio between the number of reacting and the total number of sampled trees (I1 index; Figs. S4–7) as a proxy of rock glacier activity. Effects of summer air temperature on rock glacier activity from 1895 to 2011 are quantified using distributed lag models, which account for lagged effects of air temperature over several years. The results were then complemented with displacement rates derived from image cross-correlation of repeat aerial photographs from Soviet archives dating back to the year 1943, declassified CORONA satellite images of around 1970, and high-resolution, present-day satellite images (Table S4).

Results and Discussion
At decadal timescales, the frontal zones of the investigated rock glaciers show a common signal of enhanced and reduced activity since 1895, and reveal particularly active periods in the 1940s and 1990s (Fig. S8, Animation S1). The synchronous behavior of the rock glacier movements suggests that internal and topographic characteristics are superimposed by an external driver, decadal climate variations in the present case. Increasing rock glacier surface speed is largely a consequence of rising ground temperatures, which decrease the viscosity of the rock glacier ice core. However, the effect of climatic changes on the different energy balance components and eventually on ground temperature involves complex processes and interactions, most importantly related to snow cover timing and thickness, and energy exchange within the blocky surface layer.

In spite of the complex coupling between climatic variations and ground ice temperatures, rock glacier activity has previously been shown to increase in comparably direct response to warm summers in a number of cases. Such immediate coupling between the atmosphere and movement of thermally inert permafrost could be fostered by increasing lateral or vertical water percolation during warm summers, for instance from increased ice or snow melt, through related heat advection or even hydraulic mechanisms.

The previously observed high correlation of rock glacier surface speed and variations in air temperature is confirmed by our results: we find that increasing summer (JJA) air temperatures correlate with increasing rock glacier activity at annual (Fig. S9) and decadal timescales (Fig. 2). The highest summer air temperatures
Figure 2 | Periods of high rock glacier activity correspond well with periods of warm summers and negative mass balance at Tuyuksu glacier (1895–2011). Above and below average 5-year-running-means are indicated in red and blue, respectively; annual data is shown in grey. Rock glacier activity is shown as the mean I index of Karakorum, Ordzhonikidze and Turgen Aksu rock glaciers (Fig. S8). Summer air temperature is the mean of June-August air temperatures in Almaty (Fig. 1). Mass balance of Tuyuksu glacier is in meters water equivalents (m w.e.). Data sources: Supplementary Information.
energy balance. Roughly constant displacement rates have been observed in the lowest part, where a new equilibrium with a reduced ice core on a flat bed-topography seems to have been established a while ago.

**Conclusion**

The decadal-scale activity of the four observed rock glaciers is synchronous and reveals a positive association with summer air temperatures. Such a direct signal is remarkable in view of the rock glaciers’ surface insulation by the rocky active layer and the thermal inertia of the ice core. These dampening effects are probably outweighed by the particularly large deformation sensitivity of ice-rock mixtures close to the melting point, with water being a potential coupling agent.

On multi-decadal scales, the different trends of surface velocities among and within the rock glaciers reflect different site-specific conditions and phases of rock glacier response to the strong increase in air temperature, i.e. the stabilization of rock glacier frontal zones due to topographic inactivation, insufficient debris supply or a reduction of the deformable ground ice content, or a combination thereof.

Figure 3 | Contrasting activity trends of rock glaciers in the first (a, Karakorum) and second phase (b, Ordzhonikidze) of inactivation (1895–2011). Shown are Mann Kendall trend matrices with the standardized test statistic (t) and significance levels (two-sided p-values) for different start and end years and a minimum period of 30 years.
The implications on freshwater availability are ambivalent: On the one hand, the recent warming in Central Asia and the related melting of ice in the frontal parts of the investigated rock glaciers, as indicated by our study, implies that freshwater storage at the lower limit of sporadic permafrost in the Tien Shan is decreasing, as a thinner and deeper-lying ice core decreases the release of seasonal water. On the other hand, as all investigated rock glaciers terminate in rivers, the formation of rock-glacier dammed lakes, like Zhayak Kol twenty kilometers upstream of Karakorum rock glacier, is probable – in particular for the accelerating Karakorum rock glacier, but potentially also for the other three advancing rock glaciers. Under continuing glacier shrinkage, these lakes could become alternative water reservoirs, but they also hold a flood danger, which adds to the hazard arising glacier shrinkage, these lakes could become alternative water reservoirs, but they also hold a flood danger, which adds to the hazard arising  

Methods

Dendrogeomorphology. We followed standard dendrogeomorphic field methods to collect and prepare increment cores and cross-sections from 30 junipers (Juniperus sp.) and 250 Tien Shan spruces (Picea shrenkiana (Fisch. & C.A. Mey.) subsp. tianshanica (Rupr.)) growing on or at the front of rock glaciers. As a rule, two cores or one cross-section were sampled from each tree. The LINTAB system (Rinntech) was used to measure ring widths, which were then cross-dated with a reference chronology collected from 30 undisturbed spruces growing in the immediate vicinity of Ordzhonikidze rock glacier. Kugalan Tash rock glacier was excluded from the regional signal analysis (Fig. 5B) due to limited availability of trees for sampling. In a next step, the year and intensity of growth anomalies on all samples were identified and summarized per tree. Reactions occurring within 4 years on samples of the same tree were summarized and noted as one reaction in the year of first occurrence so as to account for reaction lags, which are common with e.g. growth decreases and compression wood.

Statistical analysis. As a proxy for rock glacier activity, we then calculated the I-index as the ratio between the number of trees showing a reaction (R) and the total number of sampled trees (A) on a rock glacier in any given year (t):

\[ I_t = \frac{R_t}{A_t} \times 100\% \]

(1)

As climate data cover the past century and sample size is low before that time, we limited our analysis to the period 1895–2011. Periods of high and low activity were identified from above- and below-average values of the 5-year running mean of the I-index.

Long-term trends of rock glacier activity were analyzed with the two-sided non-parametric Mann-Kendall trend test at the 20, 10 and 5% significance levels. With the help of moving time windows, the multiple trend tests were computed for the I-indexes of the investigated rock glaciers and for mass balance of Tuyuksu glacier for time windows of at least 30 years in length during the common 1895–2011 period. Effects of summer (JJA) air temperature on rock glacier activity from 1895 to 2011 were quantified using distributed lag models. Temporal lag effects were considered by shifting the series of summer temperature forward in time from zero to five years. For each rock glacier, we fitted a generalized linear model (GLM) with a binomial distribution as defined by the probability mass function:

\[ f(A_t, R_t; \psi) = \binom{A_t}{R_t} \times p^{R_t} \times (1 - p)^{A_t - R_t} \]

(2)

The probability \( p_t \) of a tree showing a reaction in year t was modelled with a logit-link function:

\[ \ln \left( \frac{p_t}{1 - p_t} \right) = \text{intercept} + \sum_{k=1}^{7} ns(\text{str} - k \times 2 \text{df}) + ns(\text{year}; 7 \text{df}) \]

(3)

where \( \ln \) is the natural logarithm and \( p_t \) is the odds in year t. A natural cubic spline (ns) function with 2 degrees of freedom (df) allowed for non-linear relationships and was applied to summer temperature (t) lagged from 0 to 5 years. To control for long-term patterns of rock glacier activity due to e.g. topographic inactivation, the variable “year” was included in the model with an ns function with 7 df. These distributed lag non-linear models were fitted with functions included in the packages “dlnm” (version 2.0.6) and “splines” (version 3.0.2) from the statistical computing software R. Model output is presented as odds ratios, i.e. the ratio of the odds of a specific temperature to the odds of a reference temperature (here the lowest temperature measured in the series) is shown. The odds ratios are not affected by the scale of the predictor variable, e.g. standardizing the summer air temperature with the mean and the standard deviation does not change the odds ratios.

Photogrammetry. In a first step, orthoimages with a spatial resolution of 0.5 to 2 m have been produced from the available Soviet era aerial photos and high-resolution satellite images (see SI). In a second step, displacements of trees, groups of trees, or other distinct visual features close to sampled trees were tracked within these stacks of co-registered orthoimages through image cross-correlation, where image quality was sufficient, or manually digitized. In addition, distinct features close to the moving targets but on assumed stable ground outside of the rock glaciers were tracked to reference the moving targets and thus minimize the effects of residual co-registration deficiencies or distortions from inaccuracies of the ASTER GDEM, which was used for orthorectification. The accuracy of the displacements of each target was estimated as the mean offset of the displacement path from a straight line. This estimate is conservative as any real, and well expected, deviation from straight target motion is included in the error budget.

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Acknowledgments
We thank T. Bolch for the fruitful discussions, C. Corona for statistical assistance and G. Shalpykova, V. Shatragrin, I. Shesterova, L. Sorg and Z. Urech for help in the field. This study was supported by the ACQWA and ICEMASS projects (Framework Program 7 of the European Commission under Grant Nrs. 212250 and 320816).

Author contributions
The study concept was developed by A.S. and M.S.; the dendrogeomorphic data were collected and processed by A.S. and A.R.; A.K. carried out the photogrammetric analysis and C.B. performed the statistical analysis. All authors were involved in the analysis, paper writing and revision process.

Additional information
Supplementary information accompanies this paper at http://www.nature.com/.

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Sorg, A., Kaßb, A., Roesch, A., Bigler, C. & Stoffel, M. Contrasting responses of Central Asian rock glaciers to global warming. Sci. Rep. 5, 8228; DOI:10.1038/srep08228 (2015).

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