Impacts of climate change on glaciers, rock glaciers and water availability in the Tien Shan, Central Asia

Sorg, Annina

UNIVERSITÉ DE GENÈVE
Institut des sciences de l'environnement

FACULTÉ DES SCIENCES
Professeur Martin Beniston

UNIVERSITÉ DE BERNE
Institut de géologie

FACULTÉ DES SCIENCES
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THÈSE
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par

Annina Sorg

de

Lindau (ZH)

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La Faculté des sciences, sur le préavis de Monsieur M. BENISTON, professeur et codirecteur de thèse (Institut des sciences de l'environnement), Monsieur F. SCHLUNEGGER, professeur et codirecteur de thèse (Institut de géologie, Université de Berne), Monsieur M. STOFFEL, docteur (Institut des Sciences de l'Environnement et Section de physique, Université de Genève et Institut de géologie, Université de Berne, Suisse), Madame N. SALTZMAN, docteure (Institut de géographie, Université de Zürich et de Fribourg, Suisse) et Monsieur J.-I. LOPEZ-MORENO, docteur (Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas, Universidad de Zaragoza, España), autorise l'impression de la présente thèse, sans exprimer d'opinion sur les propositions qui y sont énoncées.

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Thèse - 4677 -

Le Doyen

Doctorat en co-tutelle avec l'Université de Berne

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Abstract

The Tien Shan ranges play a pivotal role in supplying freshwater for the Central Asian region. During the dry summer season, water from melting snow and glaciers and from thawing permafrost renders agriculture in the arid, densely populated forelands possible. But the Central Asian water tower, as the Tien Shan is also called, is subject to considerable alterations, with climate-driven streamflow changes having direct implications on freshwater supply, irrigation and hydropower potential. This is particularly precarious as most rivers originating in the Tien Shan have become transboundary rivers after the break-down of the Soviet Union, but a regional strategy of water allocation has not yet been put in place. Against that background, it is essential to have reliable information on the current and future state of glaciers, permafrost and water availability to understand how water resources will change in Central Asia.

The objective of this thesis is to assess the impacts of climate change on glaciers, rock glaciers and water availability in the Tien Shan region, Central Asia. For this purpose, a comprehensive literature review has been carried out as a basis for a climate change impact case study in the Chon Kemin valley. Observational time series covering most of the 20th century have been combined with satellite-derived snow cover data to calibrate all relevant processes in a glacio-hydrological model. Unprecedented for Central Asia, the model has then been forced with a downscaled climate data ensemble of the latest coupled model intercomparison project (CMIP5) to obtain scenario-based glacier and runoff projections up to the end of the 21st century. In a next step, the 20th century activity of four rock glaciers in Northern and Central Tien Shan has been reconstructed based on a novel method combining the analysis of tree rings (dendrogeomorphology) and aerial photographs (photogrammetry). Results were then compared

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with climate data to retrieve potential drivers of high rock glacier activity. In a last step, all findings have been analyzed in a socio-political context to identify major challenges in future water allocation and to evaluate potential adaptation measures.

We report that glaciers are shrinking most drastically in the relatively low-lying periphery of the Tien Shan near the major cities of Almaty, Bishkek, Tashkent and Ürümqi. Changes in seasonal and overall water availability will thus affect some of the most densely populated urban regions in Central Asia. Modeling results confirm that glaciers in the peripheral Tien Shan ranges might in a worst-case-scenario disappear completely by the end of the 21st century and that summer runoff will decrease in the future – even in the most optimistic scenarios. Seasonal water shortages might be attenuated by an increasing contribution of thawing permafrost, e.g. rock glaciers. We show that rock glaciers react directly – much like glaciers – and regionally synchronously to climatic fluctuations, particularly temperature. We also report that the lower parts of the investigated rock glaciers exhibit different stages of inactivation from melting ice cores as a response to the strong temperature increase that has been observed since the 1970s. Rock glaciers at higher elevations, however, are likely to serve as freshwater reserves beyond the 21st century.

These findings call for mitigation measures to assure long-term water security in Central Asia and to avoid an exacerbation of geo-political conflicts. While artificial reservoirs could partly take over the role of glaciers as seasonal water redistributors, the core challenge in the ongoing upstream-downstream conflict in Central Asia will be to agree on how much water should be discharged, at what time and for what purpose. As a precondition for sound water allocation, studies like this thesis provide indispensable background information.

Résumé

Le massif du Tien Shan joue un rôle principal pour l'approvisionnement en eau douce en Asie centrale. La fonte des neiges, des glaciers et du pergélisol permettent l'agriculture dans les plaines arides et densément peuplées pendant la saison sèche. Le Tien Shan, aussi appelé « château d'eau d'Asie centrale », est sujet à des changements considérables. Les variations du débit des cours d'eau induits par le changement climatique ont de nombreuses répercussions, tant sur l'approvisionnement en eau potable que l'irrigation ou le potentiel hydroélectrique. Ces variations sont d'autant plus critiques que la majorité des rivières prenant leur source dans le Tien Shan sont devenues transfrontalières après la chute de l'Union soviétique il y a vingt ans. Cependant, une stratégie régionale pour l'allocation de l'eau n'est pas encore en place. Sur cette trame, il est essentiel de disposer d'informations fiables sur l'état actuel des glaciers, leur évolution, la fonte du pergélisol et la variation des cours d'eau pour comprendre comment les ressources d'eau évolueront en Asie centrale.

L'objective de cette thèse est d'analyser l'impact du changement climatique sur les glaciers, les glaciers rocheux et les débits d'eau dans la région du Tien Shan, Asie centrale. A cet effet, une revue de littérature étendue a été passée pour établir la base d'une étude d'impact dans la vallée du Chon Kemin. Des mesures observées durant la plupart du 20$^{\text{ème}}$ siècle ont été combinées avec des données nivologiques provenant de satellites pour calibrer tous les processus pertinents dans un modèle glacio-hydrologique. Une première dans la région d'Asie centrale, le modèle a été forcé avec un ensemble des données climatiques du « coupled model intercomparison project » (CMIP5) pour obtenir des scénarios sur l'évolution des glaciers et des débits d'eau jusqu'à la fin du 21$^{\text{e}}$ siècle. Dans un autre sous-projet, l'activité de quatre glaciers rocheux dans les massifs

nord et central du Tien Shan ont été reconstruits pour le 20ème siècle sur la base d'une nouvelle méthode qui combine la dendrogéomorphologie et la photogrammetrie. Les résultats ont été comparés avec des données climatiques pour identifier les facteurs potentiels qui causent une haute activité des glaciers rocheux. A la fin, tous les résultats ont été analysés dans un contexte socio-politique pour identifier les défis futurs concernant l'approvisionnement en eau douce et pour évaluer des mesures adaptives.

Nous constatons que le retrait des glaciers le plus important a été observé en périphérie des montagnes Tien Shan à basse altitude, près des grandes villes d'Almaty, de Bishkek, de Tashkent et d'Ürümqi. Des changements des débits annuels et saisonniers mettront donc à mal les régions urbaines les plus peuplées dans l'Asie centrale. Les résultats du modèle glacio-hydrologique confirment que les glaciers dans la périphérie du Tien Shan pourraient, dans un « worst-case scénario », disparaître entièrement vers la fin du 21e siècle et que le débit du cours d'eau diminuera à l'avenir – même dans les scénarios les plus optimistes. Les épisodes de sécheresses estivales pourraient être atténués par une plus forte fonte du pergélisol, par exemple des glaciers rocheux. Nous montrons que les glaciers rocheux réagissent directement – comme les glaciers de glace – et de façon régionalement synchrone aux fluctuations climatiques, notamment de température. Nous rapportons aussi que les parties les plus basses des glaciers rocheux analysés exhibent des différents stages d'inactivation suite à la fonte de l'intérieur glaciaire après l'augmentation considérable des températures depuis les années 1970. Les glaciers rocheux à haute altitude, au contraire, serviront probablement encore de réserves d'eau potable au-delà du 21e siècle.

Ces résultats exigent des mesures de mitigation pour assurer la sécurité de l'approvisionnement en eau à long terme et pour éviter une aggravation des conflits géopolitiques dans l'Asie centrale. Si des réservoirs artificiels pourraient reprendre partiellement le rôle des glaciers comme régulateurs des fluctuations saisonnières, le défi principal dans le conflit d'intérêt entre les pays en amont et en aval sera d'établir un accord sur l'allocation de l'eau. Comme condition préalable pour une allocation d'eau adaptée, des études comme cette thèse figurent comme une source d'information d'arrière-plan indispensable.

1. Introduction

"Knowledge is an unending adventure at the edge of uncertainty."

Jacob Bronowski

1.1 Thematic background

Streamflows originating in glacial- and periglacial mountain areas play an important role for freshwater supply in regions with little summer precipitation, as glaciers and permafrost release water when other sources such as snowmelt are depleted (Barnett et al. 2005, Immerzeel et al. 2010, Kaser et al. 2010). This situation is well reflected in the Tien Shan, where meltwater contributes considerably to freshwater supply for the densely populated, arid lowlands in Kyrgyzstan, Kazakhstan, Uzbekistan, Turkmenistan and Xinjiang/China (Hagg et al. 2007, Braun and Hagg 2009). With the demise of the USSR in 1991, all major rivers originating in the Tien Shan have become transboundary rivers. The sudden power vacuum and the breakdown of the state-controlled subsidized provision system among the former republics have led to regional instability (Libert et al. 2008, Bichsel 2011). Up to now, the upstream- and downstream countries have not yet agreed on a regional strategy for water allocation (Luterbacher et al. 2007). Thus, water distribution in Central Asia has become a source of conflict (Mosello 2008) that has been fuelled by the recently resumed constructions of hydropower dams in the upstream countries, Kyrgyzstan and Tajikistan.

Glaciers in the Tien Shan currently occupy an area of ~15'000 km^2 (Kuzmichenok 1993, Aizen et al. 2007). Approximately half of this glacierized area is located in Kyrgyzstan (UNDP 2009), thus covering roughly 4% of the country's surface. In recent decades, however, these glaciers have been rapidly shrinking as a result of rising temperatures (Khromova et al. 2003, Aizen et al. 2006, Narama et al. 2006, Bolch 2007), thus raising concern about the long-term availability of freshwater for irrigation and household consumption during summer (Immerzeel et al. 2010, Siegfried et al. 2012).

Climatic trends of the past decades are likely to continue in the future: the climate scenarios envisioned in the 4th report of the Intergovernmental Panel on Climate Change (IPCC) predict a 4 to 7% decrease in summer precipitation in Central Asia by 2050 (Cruz et al. 2007). Winter precipitation, however, is projected to increase by 4 to 8%. Both summer and winter air temperatures are expected to increase further through to the 2050s (+3.1 to +4.4 °C and +2.6 to +3.9 °C, respectively) and beyond.

These considerable climatic changes give reason to assume that glacier shrinkage will continue in the future, with immense repercussions on the quantity and seasonal distribution of water (Braun and Hagg 2009, Baraer et al. 2012). While melting glaciers in a first phase release an increasing amount of water, the reduction of glacier volume will eventually reduce the amount of available glacial meltwater, thus leading to a tipping point or *peak water* (Gleick and Palaniappan 2010) in glacial runoff (Fig. 1).
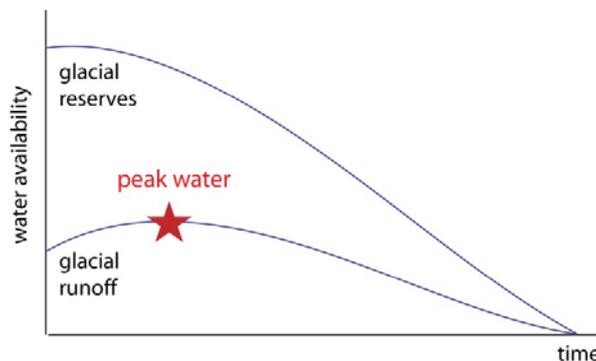

Fig. 1: Tipping point (peak water) in glacial
runoff under continuing glacier shrinkage.

Although peak water in *total* runoff can be derived from long-term observations, peak water in *glacial* runoff is more difficult to ascertain and requires sophisticated modelling approaches. The main challenge here is that trends in glacial runoff can be outbalanced or amplified by compensating effects such as changes in precipitation, evaporation, groundwater storage, human water uptake and / or changes in the amount of water released from thawing permafrost (Fig. 2).
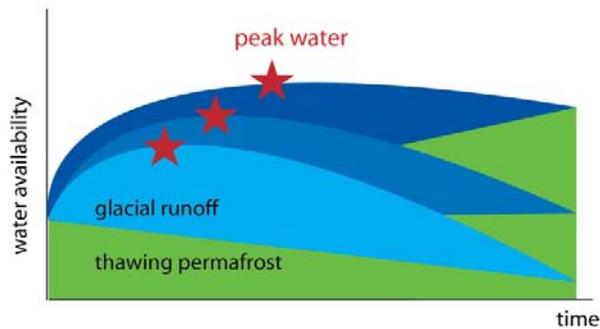
Fig. 2: Impact of a changing amount of water
released from thawing permafrost on *peak water*.

Under continuing glacier wasting, permafrost is likely to gain importance as a freshwater reserve. It is estimated that permafrost bodies store a similar amount of water as the currently existing glaciers in the Tien Shan do (Bolch and Marchenko 2009, Kotlyakov and Severskiy 2009). A particularly prominent role in the hydrological cycle is played by rock glaciers (Barsch 1996, Burger et al. 1999), which contain between 20 and 80 vol% of ice and are a widespread permafrost phenomenon in the Tien Shan (Marchenko et al. 2007). In Northern Tien Shan alone, more than 1000 rock glaciers have been inventoried, of which at least 850 are active (Gorbunov et al. 1992, Marchenko et al. 2007). Knowledge about the response of these rock glaciers to climate change is thus of great interest, but so far, only very few studies have investigated the link between climate and rock glaciers in the Tien Shan.

A note on data availability in the Tien Shan

In the international scientific community, the Tien Shan is generally known as a data-sparse region. This is not entirely true, as the Soviet era has left a heritage of abundant and very long in-situ climatic and hydrological data series. Most of these data, however, only exist in analogous form and are thus difficult to access – even more because of their secret status during the Soviet era. Unfortunately, most data series have been discontinued as a result of the break-down of the Soviet Union, but they nevertheless represent a treasure that has to be saved from perdition by making them known to a broad audience.

1.2 Context

This thesis was conducted within the EU-FP7 ACQWA project (Assessing Climate Impacts on the Quantity and quality of WAter, 2008-2014; www.acqwa.ch). ACQWA aimed at quantifying the influence of climatic change on river discharge and at analyzing the impact on society and economy in mountainous regions such as the Alps, the Andes and the Tien Shan. Coordinated by the University of Geneva, ACQWA gathered 35 research teams in Europe, Central Asia and South America. In addition to this thesis, research in the Tien Shan has covered the fields of regional climate modelling (International Centre for Theoretical Physics ICTP in Trieste, Italy), runoff modelling (University of L'Aquila, Italy), analysis of snowcover- and landuse changes (Laboratoire d'Etude des Transferts en Hydrologie et Environnement LTHE in Grenoble, France) and transboundary water management (University of Geneva, Switzerland, and Academy of Sciences in Bishkek, Kyrgyzstan).

1.3 Aims and structure

In the light of continuing glacier shrinkage and runoff regime changes, reliable information on the current and future state of glaciers and permafrost is crucial for decision-makers to allocate water resources and to reduce conflict potential. The objective of this thesis is thus to assess the impacts of climate change on glaciers, rock glaciers and water availability in the Central Asian Tien Shan. The main part of this thesis consists of four articles (Chapters A-D), each covering a part of the three investigated aspects of climate change impacts (Table 1).

Table 1: Climate change impacts covered by Chapters A-D.

Glaciers	Rock glaciers	Runoff	
▮		▮	A Climate change impacts on glaciers and runoff in Tien Shan (Central Asia)
▮		▮	B The days of plenty might soon be over in glacierized Central Asian catchments
	▮		C Contrasting responses of Central Asian rock glaciers to global warming
		▮	D Coping with changing water resources: The case of the Syr Darya river basin

Different methods are combined and further developed to retrieve novel results – starting with a comprehensive literature review (Chapter A) as a basis for a climate change impact model case study on glacier and runoff evolution (Chapter B) and for an experimental, fieldwork-based dendrogeomorphic assessment of rock glacier activity (Chapter C), before completing the circle with a combined climatic-hydrological and socio-political essay on challenges in future water allocation and on potential adaptation measures (Chapter D).

Chapter A – Climate change impacts on glaciers and runoff in Tien Shan (Central Asia) – is an extensive literature review with the aim of identifying the state of knowledge regarding climate, glaciers and runoff in the Tien Shan. This chapter forms the basis for the subsequent three chapters and answers the following three key questions:

- How does climate change affect the Tien Shan mountains and what responses of glaciers and rivers have been observed?

- Which alterations in glaciers and runoff can be expected based on future climate scenarios and what are the uncertainties?

- What are possible impacts of altered water availability on social and political stability in Central Asia?

Chapter B – The days of plenty might soon be over in glacierized Central Asian catchments – is a follow-up study to Chapter A and focuses on a particularly sensitive region, the low-lying Chon Kemin valley in the headwater catchment of the Chu river providing water for Kyrgyzstan's capital Bishkek. By combining a multitude of available long-term measurement series and data from satellite images, the response of glaciers and runoff to changing climate was modelled at a high temporal and spatial resolution to respond to these three key questions:

- How will glaciers in the Chon Kemin valley evolve until the end of the 21st century under different climate scenarios?

- What will the likely implications be on seasonal and annual runoff?

- What are the uncertainties of a refined distributed runoff model with a multi-variable calibration?

Chapter C – Contrasting responses of Central Asian rock glaciers to global warming – is an experimental, fieldwork-based reconstruction of rock glacier activity with the aim of assessing the major drivers of rock glacier activity in the Tien Shan. Four rock glaciers in Northern and Central Tien Shan have been investigated with dendrogeomorphic and photogrammetric methods to address the following three key questions:

- How are rock glaciers responding to climate change?

- Do periods of high rock glacier activity occur regionally synchronously?

- Which are the predominant drivers for rock glacier activity?

Chapter D – Coping with changing water resources: The case of the Syr Darya river basin in Central Asia – is an essay combining climatic-hydrological and socio-political aspects of the Central Asian water problem. Challenges in future water allocation and potential adaptation measures have been addressed by answering the following three key questions:

- What are current challenges of water governance?
- What is the impact of future climatic trends on the Syr Darya runoff regime?
- What will be the main adaptation challenges and options for water governance and management in the Syr Darya river basin?

1.4 Study region

This thesis investigates glaciers, rock glaciers and runoff in the Central Asian water tower, the Tien Shan ranges ("Celestial Mountains" in Chinese). While Chapters A and D address climatic changes and impacts over the whole region, Chapters B and C are case studies in Northern and Central Tien Shan (Fig. 3).
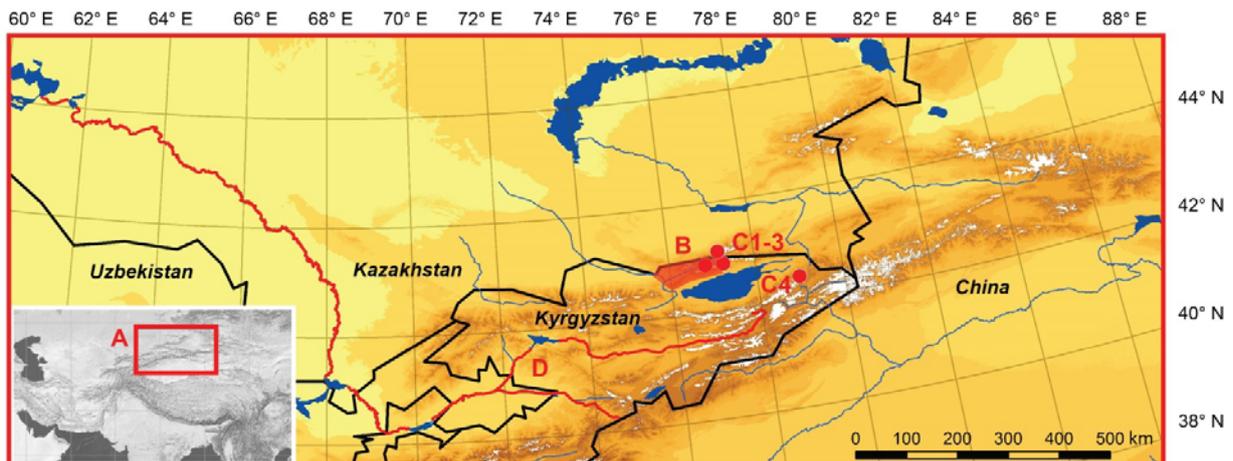

Fig. 3: Study sites of Chapters A-D. A: Tien Shan, Central Asia; B: Chon Kemin valley; C: Ordzhonikidze, Karakorum, Kugalan Tash and Turgen Aksu rock glaciers; D: Syr Darya River.

The literature review in Chapter A provides an overview of glacier and runoff changes in whole Central Asia, with a focus on the Kyrgyz part of the Tien Shan. The glacier evolution and runoff model in Chapter B is set up as a case study for the Chon Kemin valley in Northern Tien Shan (Kyrgyzstan). The reconstruction of rock glacier activity in Chapter C is based on fieldwork on Ordzhonikidze, Karakorum, Kugalan Tash and Turgen Aksu rock glaciers in Northern and Central Tien Shan (Kazakhstan and Kyrgyzstan). The impact essay in Chapter D again broadens the perspective to the whole Syr Darya River Basin, with a focus on the headwater catchment in the Kyrgyz part of the Tien Shan. All study sites are described in more detail in the respective chapters.

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2. Research papers

A

Climate change impacts on glaciers and runoff in Tien Shan (Central Asia)

Annina Sorg, Tobias Bolch, Markus Stoffel, Olga Solomina and Martin Beniston

COVER IMAGE

Regional glacier retreat, such as that being seen for the Eastern Aksu Glacier (Aksu Vostochnyi) in Northern Tien Shan, Kyrgyzstan (shown on the cover), has implications for glacier-fed stream-flow regimes which include freshwater supply, irrigation and hydropower potential. This environmental change from continuing glacier retreat could exacerbate regional conflicts.

Review Article p725
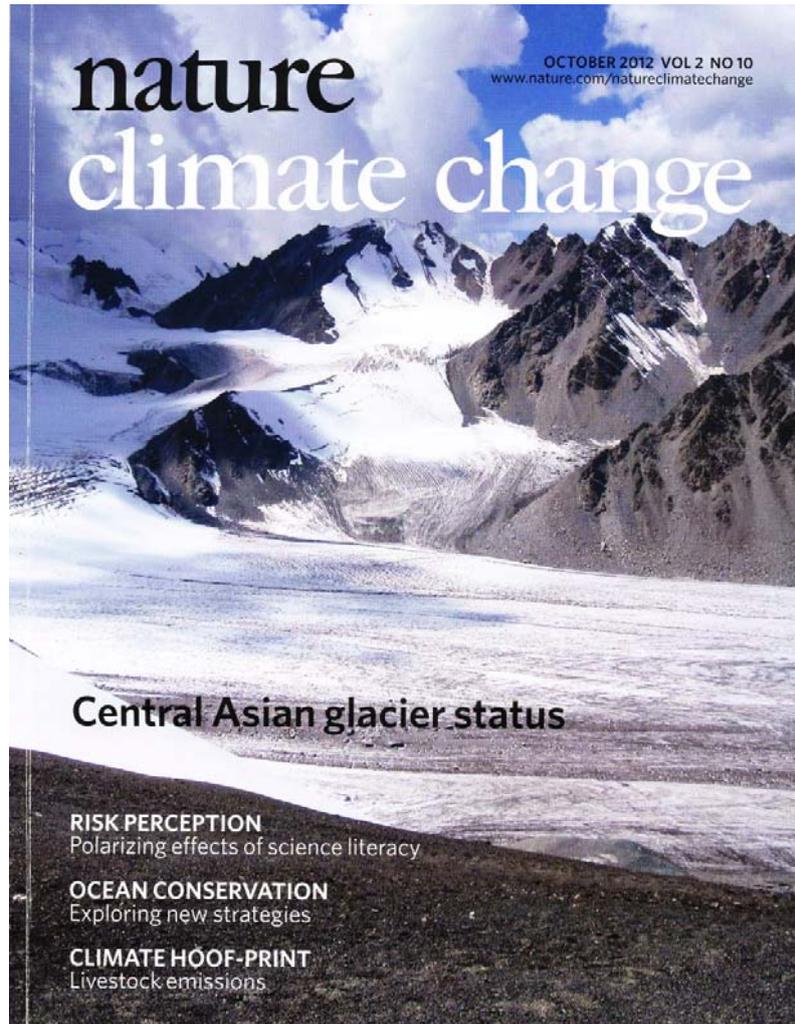
Cover Image: Annina Sorg
Cover Design: Karen Moore

Climate change impacts on glaciers and runoff in Tien Shan (Central Asia)

Annina Sorg[1,2]*, Tobias Bolch[3,4], Markus Stoffel[1,2], Olga Solomina[5] and Martin Beniston[1]

Climate-driven changes in glacier-fed streamflow regimes have direct implications on freshwater supply, irrigation and hydropower potential. Reliable information about current and future glaciation and runoff is crucial for water allocation, a complex task in Central Asia, where the collapse of the Soviet Union has transformed previously interdependent republics into autonomous upstream and downstream countries. Although the impacts of climate change on glaciation and runoff have been addressed in previous work undertaken in the Tien Shan (known as the 'water tower of Central Asia'), a coherent, regional perspective of these findings has not been presented until now. Here we show that glacier shrinkage is most pronounced in peripheral, lower-elevation ranges near the densely populated forelands, where summers are dry and where snow and glacial meltwater is essential for water availability. Shifts of seasonal runoff maxima have already been observed in some rivers, and it is suggested that summer runoff will further decrease in these rivers if precipitation and discharge from thawing permafrost bodies do not compensate sufficiently for water shortfalls.

In regions with little summer precipitation, glaciers play an important role in streamflow regimes, as meltwater from the ice is released when other sources such as snowmelt are depleted[1–3]. This situation is well reflected in the Tien Shan (Chinese for 'Celestial Mountains'), where glaciers contribute considerably to freshwater supply during summer in the densely populated, arid lowlands in Kyrgyzstan, Kazakhstan, Uzbekistan, Turkmenistan and Xinjiang/China[4,5].

As in many other parts of the world, glaciers in the Tien Shan have been retreating since the end of the Little Ice Age (LIA) in the mid-nineteenth century[6–8] — a tendency that has accelerated since the 1970s[9,10]. Intensified glacier melt strongly affects the quantity and seasonal distribution of runoff in Central Asia's glacier-fed watersheds[11,12]. Although in the first instance shrinking glaciers supply ample quantities of water in the form of increased glacial runoff, reduced glacier volume will ultimately result in a decrease in both glacier-fed and total runoff, if there are no increases in water amount from other sources, for example precipitation and/or thawing of ice-rich permafrost, to offset water deficiency from reduced glacier melt. As a consequence, continued glacier shrinkage will eventually transform glacial–nival runoff regimes in the Tien Shan into nival–pluvial regimes, with a much larger year-to-year variability in water yields[13]. Such an alteration in runoff may not only intensify ecological problems such as the drying of the Aral Sea[14–16] but also add to political instability in Central Asia[17].

Only a limited number of studies currently address the timing and evolution of expected glacier shrinkage[18,19] and related changes in runoff[20,21]. In this Review, we explore the range of changes in glaciation and related discharge in different climatic regions of the Tien Shan. Based on existing data, we present a comprehensive perspective by addressing the following key questions: (1) How does climate change affect the Tien Shan mountains and what responses of glaciers and rivers have been observed? (2) Which alterations in glaciers and runoff can be expected based on future climate scenarios and what are the uncertainties? (3) What are possible impacts of altered water availability on social and political stability in Central Asia?

Climate of the Tien Shan

The Tien Shan mountains cover a large fraction of Central Asia, spanning regions from Uzbekistan to Kyrgyzstan and from southeastern Kazakhstan to Xinjiang/China (Fig. 1a). The range constitutes the first montane barrier for northern and western air masses travelling from Siberia and the Kazakh steppes to Central Asia[22] (Fig. 1b). The resulting barrier effects lead to a distinct continentality gradient with decreasing precipitation rates and mean temperatures from northwest to southeast[23]. Three main climatic subregions are identified (Fig. 1c and Supplementary Figure S1), namely (1) the outer ranges in Western and Northern Tien Shan with a relatively moist climate, as well as (2) the inner ranges in Central Tien Shan and (3) the eastern ranges in Eastern Tien Shan with a pronounced continental climate[7]. Maximum precipitation occurs earlier in the outer and eastern ranges (spring and early summer in Northern and Eastern Tien Shan, late winter to early spring in Western Tien Shan) than in the inner ranges (summer in Central Tien Shan)[24] (Fig. 1c,d). With increasing altitude, precipitation maxima occur later in the season, and average annual precipitation sums are higher[25]. The mean annual precipitation (MAP) measured at the highest meteorological station with long-term measurements for Central Tien Shan (3,614 metres above mean sea level, masl), however, is only slightly more than 300 mm.

Twentieth-century climate trends

Over past decades, contrasting climate-driven precipitation changes have been observed in Central Asia[9,26]. MAP has increased in the outer[22] and in the eastern ranges[27], but has decreased at higher altitudes in the inner ranges[28]. Changes in mean annual air temperature (MAAT) have been more uniform. Almost all meteorological stations have recorded rising temperatures since the 1970s. According to the IPCC Fourth Assessment Report AR4 (ref. 29), observed temperature changes in Central Asia (30–50° N, 40–75° E) reveal decadal trend coefficients between +0.1 and +0.2 °C. Warming is particularly pronounced during winter[25], probably reflecting a

[1]Institute for Environmental Sciences (ISE), University of Geneva, Route de Drize 7, 1227 Carouge, Switzerland; [2]dendrolab.ch, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1+3, 3000 Bern, Switzerland; [3]Department of Geography, University of Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland; [4]Institute for Cartography, Technische Universität Dresden, Helmholtzstrasse 10, 01069 Dresden, Germany; [5]Institute of Geography, Russian Academy of Sciences, Staromonetny pereulok 29, 119017 Moscow, Russia. *e-mail: annina.sorg@unige.ch
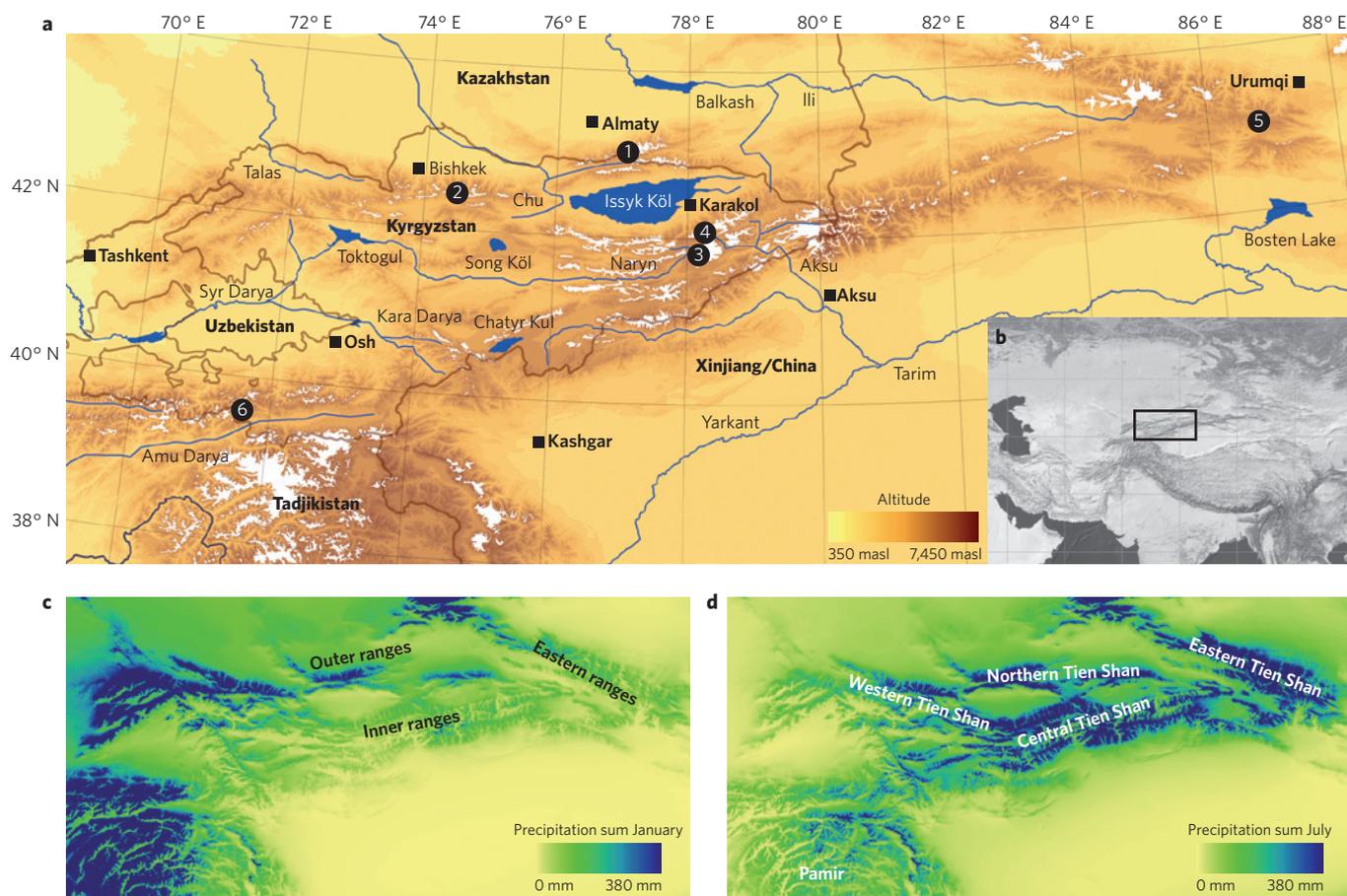
Figure 1 | Location map of the Tien Shan mountains and seasonal distribution of precipitation in Central Asia. a, Hydrological network in Central Asia, including glaciers, main lakes, reservoirs and rivers. Glaciers with mass balance measurements are indicated with numbers corresponding to Fig. 2. Sources: refs 30, 57. **b**, Location of Central Asia in the Eurasian continent. **c,d**, Main mountain ranges and monthly precipitation in January (**c**) and in July (**d**). Sources: refs 22, 95. All figures are based on digital elevation maps from the Shuttle Radar Topography Mission (http://srtm.csi.cgiar.org). Glacier outlines are from the Digital Chart of the World (accessed in May 2012).

weakening of the Siberian anticyclone[30,31]. Air temperatures in the melting season (June to August) have increased only slightly, but a remarkable temperature increase has been detected for the month of September throughout Central Asia, thus resulting in a prolonged melting season for Tien Shan glaciers[10,22,32].

Station data have been homogenized to reduce the effect of non-climatic factors[25,33,34], but other difficulties remain: meteorological records including the past 20 years are limited, as the relatively dense network of meteorological stations during the Soviet era has become largely dysfunctional since the early 1990s. This is also a problem for the stations located above 3,000 masl, where only three of eight stations have remained operational after the fall of the Soviet Union, thus making it even more difficult to draw any informed conclusions about observed climatic change at higher elevations. Moreover, ERA-40 (ref. 35), NCEP/NCAR[36] and GPCC[37] reanalysis data have so far been unable to fill this gap, as they fail to reveal any significant correlation with station data[19,38].

According to the IPCC scenarios for the lower and higher bounds of greenhouse-gas emission trajectories (IPCC SRES B1 and A1F1 scenarios, respectively[36,39]), future winter precipitation in Central Asia is likely to increase by 4 to 8% by 2050, whereas summer precipitation is expected to decrease by an equal amount (4 to 7%), which might in turn result in more frequent dry summers[29]. Both summer and winter air temperatures are expected to increase further through to the 2050s (+3.1 to +4.4 °C and +2.6 to +3.9 °C, respectively)[29] and beyond. Although these projections reflect the

current state of knowledge, changes in precipitation remain highly uncertain, and the level of temperature increase, especially at high altitudes and during summer, suffers from considerable disagreement between existing data.

Snowcover changes

Increasing air temperatures also have implications for the snow cover, such as a decrease in the proportion of solid precipitation and enhanced snowmelt[22,40]. In the second half of the twentieth century, both maximum snowcover thickness and snowcover duration have decreased at stations at all altitudes in Western[22,41] and Central[22,42] Tien Shan, whereas no trend has been detected at altitudes above 2,000 masl in Northern Tien Shan[22,43,44]. In Eastern Tien Shan, average snowcover duration has slightly increased[40]. These regionally diverging trends (see Supplementary Table S1) are probably a direct result of altered precipitation amounts: increasing precipitation rates in Northern and Eastern Tien Shan seem to have counterbalanced the negative effects from a higher MAAT. For the entire Tien Shan, however, maximum snowcover thickness has decreased by approximately 0.1 m and snowcover duration by 9 days, respectively, between 1940 and 1991 (mean values, figures derived from linear trend calculation of data from 110 hydroclimatic stations)[22]. Although this limited set of existing studies on snowcover changes[22,40,42] does not cover the recent past, preliminary analyses based on MODIS data for the period 2000–2007 confirm that the decrease in snowcover duration is persisting and that snowmelt now occurs earlier[45].
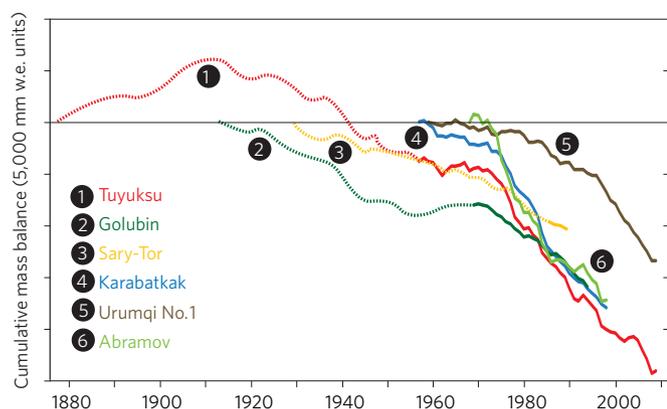
Figure 2 | Net mass balances for selected glaciers in Central Asia.
Long-term cumulative mass balances (solid lines) and reconstructions
(dashed lines) of Central Asian glaciers. The horizontal black line indicates
the level at first measurement. Sources: see Supplementary Table S3.

Glacier shrinkage

The Tien Shan mountains are heavily glaciated. Diverging figures
about the extent of glacier cover exists in the literature, ranging from
15,416 km[2] (refs 46,47) to 16,427 km[2] (ref. 7) with the latter includ-
ing the Chinese part of the Tien Shan. These data reflect past extents;
the Soviet Glacier Catalogue was finalized in 1973 based on aerial
photographs from the 1940s and 1950s[48], and the Chinese inven-
tory was established in the 1970s and 1980s[49] (see Supplementary
Table S2). Approximately half the glaciated surface (~8,000 km[2]) is
located in Kyrgyzstan[21], thus covering roughly 4% of the country's
surface. Updated data for the entire Tien Shan region have not been
published so far, but direct and indirect change assessments pro-
vide a valuable overview on recent glacier shrinkage and allow a
retrospective view back to the end of the LIA, when the Tien Shan
glaciers began to retreat[6–8]. Based on data from 20 reference glaciers,
total glacier area in the outer ranges was probably 50 to 90% greater
at the end of the LIA than currently, whereas glacier surfaces in the
inner ranges remained more stable (3 to 7% larger at the end of the
LIA than today)[50]. Similar differences were found for glacier retreat
and the rise of equilibrium line altitude (ELA)[50].

The majority of Tien Shan glaciers were quasi-stable from the late
1950s to the early 1970s[51]. In the mid-1970s, glacier wasting accel-
erated in the outer[10,25,52], inner[9,19,53] and eastern[54,55] ranges. Long-
term *in situ* measurements of mass balance on five glaciers in the
Tien Shan mountains and on one glacier in the Alay range reflect
this acceleration in the loss of ice (Fig. 2 and Supplementary Table
S3)[23,56–58]. Average annual net mass balance for the common period
of observation (1969–1994) was most negative on the Abramov
Glacier in the Alay range (–0.57 m w.e. a⁻¹, where w.e. = water equiv-
alent) and varied for the Tien Shan glaciers (–0.55 m w.e. a⁻¹ on the
Karabatkak Glacier, –0.49 on the Tuyuksu Glacier, –0.31 on the
Golubin Glacier and –0.17 m w.e. a⁻¹ on the Urumqi No. 1 Glacier)[57].
A recent study[59] based on gravimetric measurements (GRACE)
revealed a mass loss for the entire Tien Shan of –5 ± 6 Gt a⁻¹ (around
–0.32 ± 0.39 m w.e. a⁻¹) for the period 2003 to 2010. Despite the large
uncertainties involved in the approach, GRACE estimates are in line
with measured mass balance data, although on a spatially averaged
scale: relatively strong mass losses in the outer and eastern ranges
(–0.42 m w.e. a⁻¹ on the Tuyuksu Glacier and –0.56 m w.e. a⁻¹ on the
Urumqi No. 1 Glacier, average 2003–2009[57]) are partly counterbal-
anced by smaller losses in the inner ranges (where no recent mass
budget measurements exist). Indirect data from remote sensing cor-
roborate the mass balance data, thus revealing striking regional var-
iations[7,60] (Fig. 3 and Supplementary Table S4). The strongest annual
area shrinkage rates since the middle of the twentieth century were
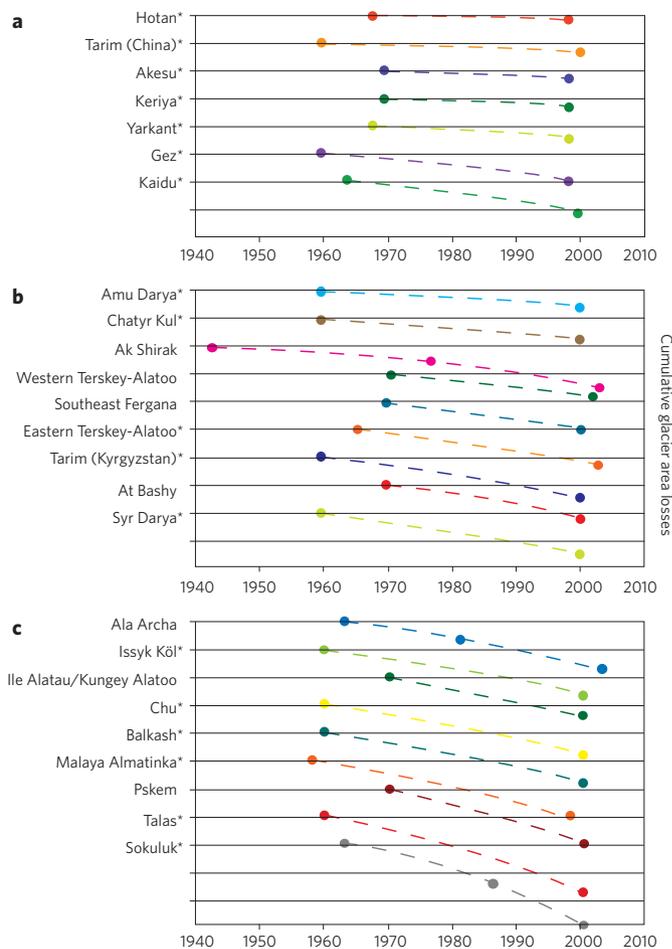

**Figure 3 | Recent area changes of selected glaciers in the Tien Shan
mountains.** Glacier shrinkage during the past decades has been smallest
in the eastern ranges (**a**), moderate in the inner ranges (**b**) and most
pronounced in the outer ranges (**c**). Lines represent 10% units; the first
measurement equals 100% of glacier area in the reference year. The top-
down order of datasets reflects the severity of glacier area loss. Studies
relying on the Soviet or Chinese Glacier Inventory or on topographic
maps as a reference have been marked with an asterisk (*). Sources: see
Supplementary Table S4.

found in the outer ranges (0.38 to 0.76% a⁻¹), whereas smaller rates
are reported for glaciers in the inner (0.15 to 0.40% a⁻¹) and eastern
ranges (0.05 to 0.31% a⁻¹). The overall range of annual area changes
is similar to those for the Himalaya–Karakorum region, which rep-
resent the southern margin of the Asian high mountains complex
(0.1 to 0.7% a⁻¹)[61].

The regionally non-uniform response to climate change implies
that glacier shrinkage is less severe in the continental inner ranges
than in the more humid outer ranges. Glaciers in the inner ranges
react with larger time lags to climate change[7,9,58], because accumula-
tion and thus mass turnover of the mainly cold glaciers are rela-
tively small. Moreover, shrinkage is especially pronounced on small
or fragmented glaciers[25], which are widely represented in the outer
regions[46,62]. The relative insensitivity of glaciers in the inner ranges
is further accentuated by the higher average altitude[60], as the ELA
varies from 3,500 to 3,600 masl in the outer ranges to 4,400 masl in
the inner ranges[63].

Glacier melt can be significantly altered by debris cover, but
knowledge about the fraction and thickness of debris cover on Tien
Shan glaciers is still sparse. The most extensive debris cover has been
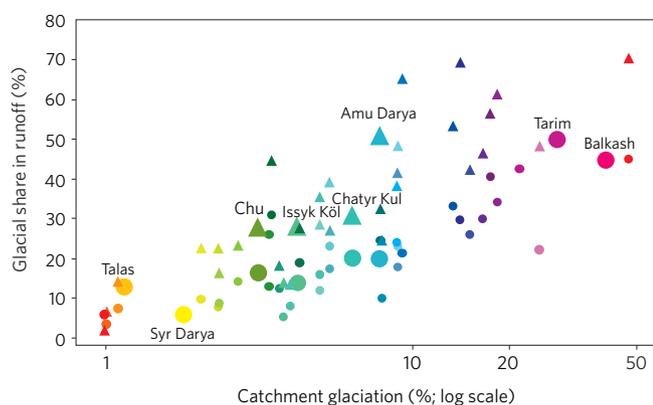reported for the largest glaciers of the inner ranges such as Inylchek

Figure 4 | Glacial runoff contribution in Kyrgyzstan. Catchment glaciation inherently controls the glacial share in rivers. Glacial contribution can be 1.5 to 3 times as high during summer (triangles) as in the annual average (circles). The eight basins making up the hydrological system in Kyrgyzstan are named and marked with larger symbols. Sources: see Supplementary Table S5.

and Tomur Glaciers. In these cases, although a thick debris cover generally attenuates mass loss[64,65], downwasting (glacier thinning due to melting of ice) can still be considerable, as has been shown for heavily debris-covered glaciers in the Himalaya where significant surface lowering occurred throughout the glacier tongues[66,67] and as a result of ice melt at supra-glacial ponds and ice cliffs[68]. Such features are also common on large debris-covered glaciers in the Tien Shan, and short-term measurements at the Koxkar Glacier (inner ranges) reveal average surface lowering rates of −494 and −384 mm for 2003–2004 and 2004–2005, respectively[69].

Limitations in glacier change assessments

Glacier change assessments often rely on data of different origins and are thus subject to a range of methodological approaches (Supplementary Information). Glaciated area has been partly over-estimated in the Soviet Glacier catalogue[10,48], probably as a result of misinterpreted seasonal snowcover on aerial photographs, and studies using the Soviet Glacier catalogue as a reference are thus prone to over-emphasize glacier shrinkage, for example, in the outer ranges[10,25,70]. Assessed glacier area changes also strongly diverge in the Ak-Shirak region in the inner ranges[71,72], where possibly mis-interpreted fresh snowcover and the neglect of debris cover on gla-ciers have resulted in a distorted image in one of the studies[71]. In an attempt to convey a realistic impression of glacier shrinkage from the existing literature, datasets that have been disproved[10,25,57,58] by more recent studies[9,53,72] are not included in this Review (see also comments to Supplementary Table S4). Continued *in situ* mass bal-ance and ice thickness measurements are currently conducted for only a few glaciers. Efforts should therefore be encouraged to ensure the continuation and re-establishment of mass balance measure-ments on reference glaciers, as is currently the case at Karabatkak, Abramov and Golubin glaciers.

Glacial runoff

Glaciers play a crucial role in Central Asia's hydrological cycle[3,73]. It has been demonstrated that even a basin whose glacier fraction is less than 5% can provide a significant contribution from ice melt to summer runoff[12], when water is most needed for irrigation. The continued glacier shrinkage that can be expected in a warming cli-mate has therefore raised concerns about the future role of Tien Shan glaciers as a source of freshwater. An estimated 15% of runoff in Kyrgyzstan originates from glaciers, but this glacial contribution can be even 1.5 to 3 times larger during the melting season[4,74,75] and accounts for as much as 80% of total runoff in heavily glaciated headwater catchments (Fig. 4, Supplementary Figure S2 and Tables

S2 and S5). These percentages include snow-, ice- and firn-melt as well as liquid precipitation on glacial surfaces, as most hydrologists and glaciologists in the countries of the former Soviet Union have used the term 'glacial runoff' in this sense.

Long-term average annual runoff in Kyrgyzstan has increased from 47.1 km³ (~1947–1972) to 50 km³ (1973–2000)[26]. In past dec-ades, increasing runoff has also been measured in several headwater catchments and rivers draining from the inner ranges[26] (for exam-ple the Tarim river[27,49,76]), whereas runoff has remained relatively stable in the outer ranges (for example the Chu and Talas rivers[26]). The annual trends in the rivers of the outer ranges mask the fact that runoff during the ablation season has recently been decreas-ing, but is compensated for by higher winter runoff from increased liquid precipitation[26]. The observed lower summer runoff could be a result of pronounced glacier shrinkage[2,5], as has been reported for the Ile Alatau (also known as Zailiyskiy Alatau) in the outer ranges, where glacial runoff has presumably been decreasing since the early 1940s[70,77].

Compensating effects such as changes in precipitation and evaporation as well as anthropogenic influences (for example water uptake) hamper the identification of factors controlling discharge. There is a need for more integrative studies addressing changes in all runoff components (that is, precipitation, groundwater, and melt-water from snow, glaciers and permafrost) for better appraisal of the degree of glacial depletion and subsequent changes in glacial runoff.

Considerable uncertainties

Glaciers and runoff are likely to undergo further alterations in the decades to come, if the twentieth-century trends in climate con-tinue. As yet, the incidence of such changes has been addressed in only a very limited number of studies, all of which are fraught with uncertainties. As a result of projected increasing MAAT and insignificant changes in MAP, glaciers in the Tien Shan will most probably continue to lose mass in the coming decades. Even with increasing MAP, further mass loss can be expected, as the effect of increasing MAAT on glacier melt is likely to surpass the effect of the increased MAP, as observed in the eastern Tien Shan and North-West China during the past 20 years. Quantitative change assessments for future glacier degradation are inherently sub-ject to great uncertainty, in terms of both future climate projec-tions and distorting effects such as black carbon and debris cover. Accordingly, the few existing studies span a large range of possible futures for glacier shrinkage in the Tien Shan mountains. If the current annual rates of decrease were to continue, glaciers of the Sokuluk watershed in the outer ranges would probably lose 50% of their current surface area by 2050 (ref. 18) and glaciers in the Terskey Alatoo in the inner ranges could shrink by 30% by the end of the twenty-first century[19]. Under the high greenhouse-gas emissions SRES A2 scenario, 31 ± 4% of today's glacier volume in the Syr Darya catchment may melt by 2050 (ref. 78). Under the SRES B1 and A1F1 scenarios, a study commissioned by UNDP[21] projects glacier area loss in Kyrgyzstan in the range of 52 to 70% in the first half of the twenty-first century and a total of 70 to 86% by the end of the twenty-first century[21]. These projected changes are comparable to the Nepalese Himalaya[1], but slightly higher than in most other parts of the Himalaya[61]. But the results of the UNDP study are plagued with large inaccuracies resulting from the coarse resolution (0.5 km²) and the approximations used: current glacia-tion was estimated from correlation analysis between the Soviet Glacier Inventory and subsequently monitored individual gla-ciers, and future glaciation was calculated from expected shifts in the ELA, thus neglecting the distribution of ice thickness and ice dynamics.

Despite the shortcomings of the above estimations and irrespec-tive of the approaches used, all currently existing studies anticipate comparable short- and long-term impacts of climate and glacier

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change on runoff in the main Tien Shan rivers. The current level of total runoff (50 km³, average 1973–2000; ref. 26) is likely to remain stable in the near future[20,79] or could even increase slightly[21,80]. By the end of the twenty-first century, however, total runoff is projected to be smaller than today[5,9,21,63], although a significant and probably hypothetical increase in precipitation (+20%) and a moderate increase in temperature (+3 °C) could result in an increase in total runoff (+4.7%, thus amounting to 52 km³)[81]. Within the range of the IPCC SRES B1 and A1F1 scenarios, runoff is expected to decline to between 38 and 44 km³ by 2050 and to 32–41 km³ by 2100 (ref. 21), mainly as a result of the increasing evaporation rates assessed in the model. As evaporation is not easily reproduced in simulations of present-day runoff, however, estimates of future evaporation are likely to be open to even larger uncertainties, as is the case for future precipitation.

To establish sound conclusions related to changes in future glaciation and runoff, modelling efforts need to integrate improved reanalysis data spanning recent decades and a representative multi-model ensemble of downscaled climate models. The impact of snowcover changes on glacier degradation — for example reduced accumulation input and increased ablation as a result of earlier snowmelt — needs to be studied in detail and included in the model. Currently unresolved issues such as the impact of black carbon[82] and debris cover[61,64,83] on glacier shrinkage as well as the role of thawing permafrost bodies on runoff[10,20,84] also need to be addressed when further developing fully distributed, physically based runoff models[12,85]. Only with such model approaches, reflecting transient changes in climate, snowcover, glaciation and runoff, can appropriate adaptation and mitigation strategies be developed within a realistic time horizon.

Ecological, social and economic implications

Although all currently available quantitative runoff projections have large levels of uncertainty, it is likely that Tien Shan river systems will undergo an unfavourable seasonal distribution, if the climate projections developed by IPCC prove to be true[12,41,78]. Thus, the river systems might partly lose their glacier buffering mechanism, which is particularly important during dry spells, and react more directly to variations in precipitation[5]. Hence, the water regimes will transform from glacial–nival to nival–pluvial, with a much larger year-to-year variability in water yields[20] and with a seasonal redistribution in runoff[12,78]. Owing to earlier and more intense snowmelt at higher elevations, the runoff peak will shift from spring and early summer towards late winter and early spring[12,78,79]. Advanced deglaciation could eventually result in water deficits during hot and dry summer periods[5], although the degree of reduction in late summer runoff varies according to different model projections[12]. Extreme runoff events may well occur more often, especially in spring, thus leading to more frequent flood and debris flow events[5]. The formation of moraine-dammed lakes and their potential sudden bursting (glacier lake outburst floods) represent another hazard related to glacier retreat[79,86–88].

Mitigation measures for altered water availability in Central Asia will be required, as seasonal changes in water availability and related implications at the ecological, social and economic scales can be expected before the end of the twenty-first century. The timing of water release from upstream hydropower dams in Kyrgyzstan and Tajikistan will remain a sensitive political issue in Central Asia[89], although the projected increases in winter runoff might somewhat improve the situation for the upstream countries. Water shortages in summer will place the entire region's agricultural system under pressure, thus fuelling tensions that have existed since the collapse of the Soviet Union in the early 1990s[17]. The high water demand for irrigation has already transformed downstream sections of powerful rivers such as the Syr Darya, Amu Darya and Ili into small rivulets, thus exacerbating the

drying-out of the Aral Sea[14] and Lake Balkash[46,90]. Anthropogenic influences have also become manifest in the Tarim basin, where downstream runoff has decreased in the past decades in spite of an increase in headwater runoff formation[15,27,76]. Another imminent threat is emerging through a possible impairment of the fragile ecosystems of the arid lowlands, such as along the Tarim river[91] and around Issyk Köl lake[80,92,93]. The latter is a UNESCO Biosphere Reserve and includes a wetland protected under the Ramsar Convention. The situation in the periphery of the Tien Shan mountains, where water demand in rapidly growing urban centres such as Almaty, Bishkek, Tashkent and Urumqi is increasing at a high pace[9], needs to be investigated in more detail. The population in these arid and semi-arid foothill zones strongly depends on the streamflow buffering capacity of glacial water for irrigation, industry and hydropower[46,94].

In conclusion, increasing air temperatures and heterogeneously changing precipitation rates have led to diverging effects on the seasonal snowcover in the Tien Shan region. Glacier shrinkage has been observed in all regions (although at different rates) and is likely to continue with the temperature increase expected in coming decades. Seasonal alterations in runoff have been measured in some rivers, but annual runoff has not yet undergone significant changes because of a number of compensating factors such as changes in precipitation and evaporation as well as anthropogenic influences. A decrease in runoff, at least during the summer months, can be expected by the end of the twenty-first century as a result of depleted glaciers and increasing water uptakes. The seasonal redistribution of runoff and the potentially higher frequency of geo-hazards will require appropriate adaptation responses. The development of mitigation measures will require reliable data from *in situ* and remote-sensing based measurements, as well as simulated results from coupled climatic, glaciological and hydrological models.

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Additional information

The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to A.S. Supplementary Information accompanies this paper on www.nature.com/natureclimatechange.

Climate change impacts on glaciers and runoff in Tien Shan (Central Asia)

Annina Sorg[1,2], Tobias Bolch[3,4], Markus Stoffel[1,2], Olga Solomina[5] and Martin Beniston[1]

[1] Institute for Environmental Sciences (ISE), University of Geneva, Switzerland

[2] dendrolab.ch, Institute of Geological Sciences, University of Berne, Switzerland

[3] Department of Geography, University of Zurich, Switzerland

[4] Institute for Cartography, Technische Universität Dresden, Germany

[5] Institute of Geography, Russian Academy of Sciences, Moscow, Russia

Supplementary figures
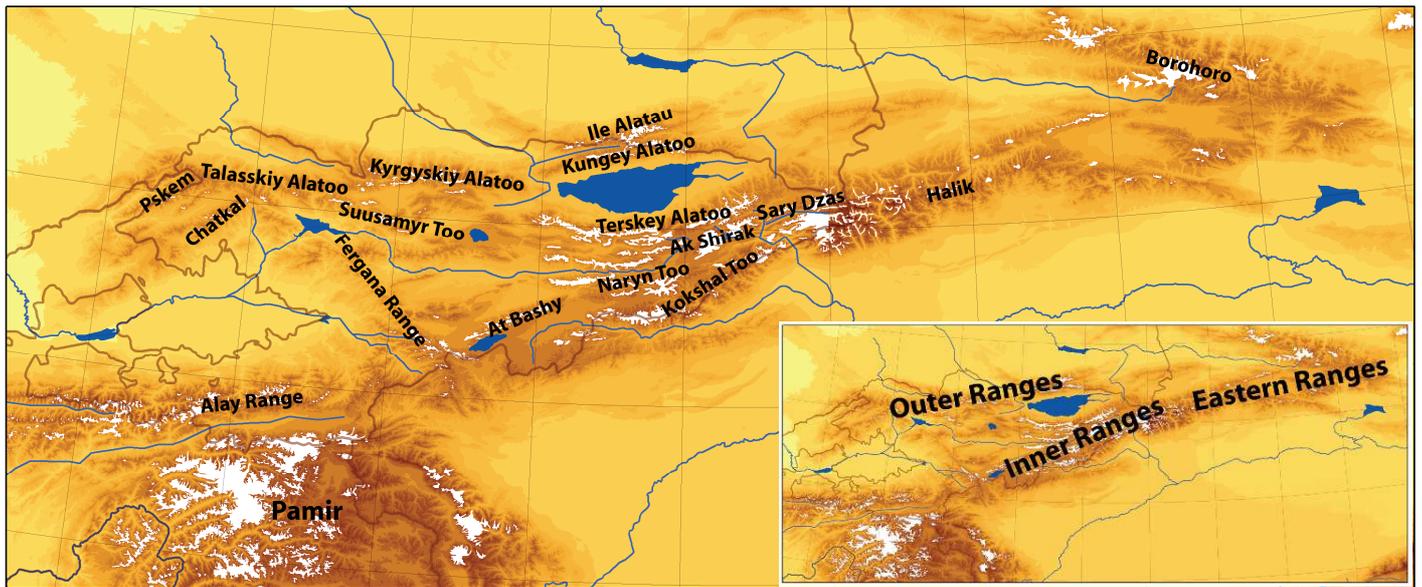
Figure S1 ¦ Mountain ranges in the Tien Shan. The extensive Tien Shan mountains have been geographically organized in many different ways. For this article, we defined three sub-regions:

Outer ranges
- Western Tien Shan (Talasskiy Alatoo, Pskem, Chatkal and Fergana range)
- Northern Tien Shan (Kyrgyzskiy Alatoo, Kungey Alatoo, Ile Alatau)

Inner ranges
- Inner Tien Shan (Susamyr Too, Naryn Too, At Bashy)
- Central Tien Shan (Kokshal Too, Sary Dzas)

Eastern ranges
- Eastern Tien Shan (Halik, Borohoro)

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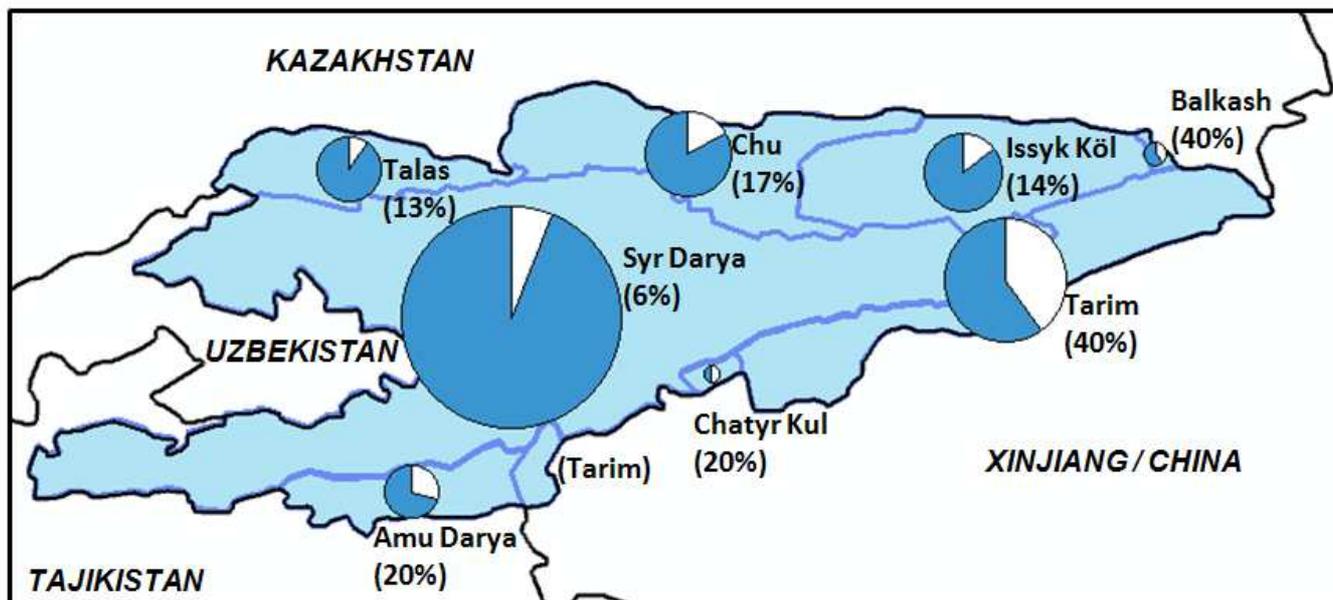
Figure S2 ¦ Glacial contribution of major Tien Shan rivers to total runoff. Estimated glacial contribution (white) to total runoff in the eight major basins of Kyrgyzstan. The size of the circles represents total runoff volume in each basin. Data sources see Table S2.

Supplementary tables

Table S1 ¦ Evolution of snowcover duration and maximum snowcover thickness in the Tien Shan.

Region	Trend	Observed period	Source
Western Tien Shan (Oygaing meteorological station)	Annual snow cover duration decreased from ~185 to ~175 days.	1965-2005	Glazirin 2009
Central Tien Shan (Karabatkak Glacier)	Maximum snow cover has thinned from 400 to 250 mm w.e. (long-term average on the middle part of the glacier).	1960-1995	Dikich 2004
Eastern Tien Shan	Annual snowcover duration increased by 0.0221 days over the measured period.	1951-1997	Qin et al. 2006
Central, Northern, Western Tien Shan	Long-term anomalies of snow cover duration and snow thickness, their centrally weighted moving averages and statistically significant linear trends in the Tien Shan.	1940-1991	Aizen et al. 1997

Table S2 ¦ Hydrological and glaciological key figures for the Tien Shan mountains. Glacier area and volume as well as total and glacial runoff assessed for the Tien Shan mountains reveal large uncertainties, which are a result of methodological variations and unclear delineations of regions.

	Tien Shan	Kyrgyz-stan	Issyk Köl	Chu	Talas	Syr Darya	Tarim	Chatyr Kul	Amu Darya	Balk-hash	Source
BASIN [1,000 km²]											
Area		192.7	15.4	22.3	10.8	110.8	24.1	0.9	7.7	0.7	Kuzmichenok 2009
Area							1,020				Chinese Glacier Inventory, in Liu et al. 2006; Shangguan et al. 2009 ("Tarim interior river basin" including Pamir)
GLACIER AREA [km²]											
2000		6,813.9	538	582	113	1,982	2,992	2.6	604	0.3	UNDP 2009
2000			650	895		2,381	3,496		678		Mamatkanov et al. 2006
1960/70s	16,427										Liu and Han 1992
1960/70s	15,416										Kuzmichenok 1993; Aizen et al. 2007 (based on the Soviet and Chinese Glacier Inventory)
1960/70s							19,878				Chinese Glacier Inventory, in Liu et al. 2006; Shangguan et al. 2009 ("Tarim interior river basin" including Pamir)
1960/70s		8,0076	636	707	155	2,356	3,507	2.8	643	0.3	UNDP 2009 (calculated)
		85.1	*84.6*	*82.3*	*72.7*	*84.1*	*85.3*	*93.4*	*94*	*82.3*	*UNDP 2009; Change in % between 1960/1970s and 2000*
GLACIER VOLUME [km³]											
2000		417.1	24.0	26.0	5.0	101.0	219	0.1	42	0.008	UNDP 2009
2000					200.0						Siegfried et al. 8.10.2011
1960/70s	1,369										Liu and Han 1992
1960/70s	1,048										Aizen et al. 2007
1960/70s							2,313				Chinese Glacier Inventory, in Liu et al. 2006 ("Tarim interior river basin" including Pamir)
1960/70s		493	28.9	32.3	7.0	121.4	258.3	0.1	44.9	0.01	UNDP 2009 (calculated)
		84.6	*83.1*	*80.4*	*71.5*	*83.2*	*84.8*	*92.6*	*93.5*	*80.4*	*UNDP 2009; Change in % between 1960/1970s and 2000*
RUNOFF [km³ a-¹]											
Total		48.4	3.88	3.53	1.72	29.8	7.25	-	1.93	0.36	Mamatkanov et al. 2006
Total		47.5	3.35	4.03	2.33	27.31	8.43	0.14	1.60	0.29	Kuzmichenok 2009
Glacial		7.1	0.55	0.58	0.22	1.79	2.90	-	0.39	0.14	Mamatkanov et al. 2006 (calculated)
Glacial		6.9	0.47	0.66	0.30	1.64	3.37	0.03	0.32	0.12	Kuzmichenok 2009 (calculated)
		14.6	*14.1*	*16.5*	*13*	*6.0*	*40*	*20*	*20*	*40*	*Glacial runoff [%] from table S5 (Kemmerikh 1972; Dolgushin and Osipova 1989; Dikich et al. 1995)*

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Table S3 ¦ Mass balance series in Central Asia. In the Central Asian mountains, long-term mass balance measurements exist for a few glaciers only (figure 2). The mass balance data are made available through the World Glacier Monitoring Service (WGMS 2009 and earlier volumes). Authors of reconstructed mass balances have been taken from Mikhalenko 1997 and are listed in the table below.

N°	Glacier	Measured mass balance		Reconstructed mass balance	
		Measuring period	Common period		
853	*Urumqi N°1* Eastern Tien Shan (China)	1959-2009 -0.27 m w.e. a^{-1}	1969-1994 -0.17 m w.e. a^{-1}	-	-
817	*Tuyuksu* Northern Tien Shan (Kazakhstan)	1957-2009 -0.39 m w.e. a^{-1}	1969-1994 -0.49 m w.e. a^{-1}	1879-1964, 1937-1956	Makarevich 1969, Dyurgerov et al. 1996
753	*Golubin* Northern Tien Shan (Kyrgyzstan)	1969-1994 -0.31 m w.e. a^{-1}	1969-1994 -0.31 m w.e. a^{-1}	1914-1982	Aizen 1988
813	*Karabatkak* Central Tien Shan (Kyrgyzstan)	1957-1998 -0.44 m w.e. a^{-1}	1969-1994 -0.55 m w.e. a^{-1}	-	-
732	*Abramov* Pamir (Kyrgyzstan)	1968-1998 -0.57 m w.e. a^{-1}	1969-1994 -0.57 m w.e. a^{-1}	1882-1992 (not included in the figure)	Glazirin et al. 1993
805	*Sary-Tor* Central Tien Shan (Kyrgyzstan)	1985-1989 -0.14 m w.e. a^{-1}	-	1930-1988	Ushnurtsev 1991

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Mass balance series, which are not included in figure 2 (measuring period too short):

N°	Glacier	Measured mass balance		Reconstructed mass balance	
773	*Gregoriev* Central Tien Shan (Kyrgyzstan)	2006-2007	-0.25 m w.e. a^{-1}	1930-2007	Fujita et al. 2011
806	*Visyachie 1-2* Northern Tien Shan (Kazakhstan)	1986-1990	-0.47 m w.e. a^{-1}		
807	*Partizan* Northern Tien Shan (Kazakhstan)	1986-1990	+0.18 m w.e. a^{-1}		
808	*Mayakovskiy* Northern Tien Shan (Kazakhstan)	1986-1990	-0.19 m w.e. a^{-1}		
809	*Ordzhonikidze* Northern Tien Shan (Kazakhstan)	1986-1990	-0.26 m w.e. a^{-1}		
810	*Kosmodemya* Northern Tien Shan (Kazakhstan)	1986-1990	-0.32 m w.e. a^{-1}		
811	*Mametov* Northern Tien Shan (Kazakhstan)	1986-1990	-0.59 m w.e. a^{-1}		
812	*Molodyozhniy* Northern Tien Shan (Kazakhstan)	1986-1990	-0.72 m w.e. a^{-1}		
816	*Igly Tuyuksu* Northern Tien Shan (Kazakhstan)	1986-1990	-0.57 m w.e. a^{-1}		

Table S4 ¦ Glacier area changes in selected Tien Shan regions. Changes in glacier area have been assessed by various authors. We assembled the most relevant results in tables S4a-c and in figure 3 in the main article. A few studies have not been included in the figure, because they have been disproved by more recent studies for the same regions (highlighted with a grey background). All glacier changes are indicated in %, with the glacier extent in each study's reference year equaling 100%. Methods and data are discussed at the end of the supplementary information.

Table S4a ¦ Glacier area changes in the eastern ranges.

	Hotan, Tarim (Shangguan et al. 2004, in Liu et al. 2006)	Tarim (China) (Shangguan et al. 2009)	Akesu, Tarim (Liu et al. 2006)	Keriya, Tarim (Liu et al. 2006)	Yarkant, Tarim (Shangguan et al. 2004, in Liu et al. 2006)	Gez, Tarim (Liu et al. 2006)	Kaidu, Tarim (Liu et al. 2006)
1960		100				100	
…							
1963			100				100
…							
1968	100				100		
…							
1970				100			
…							
1998							
1999	98.6		96.7	96.7		90	
2000		97			95.6		88.4
Average annual shrinkage rate	**0.05**	**0.08**	**0.09**	**0.11**	**0.14**	**0.20**	**0.31**

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Table S4b ¦ Glacier area changes in the inner ranges.

	Amu Darya (UNDP 2009)	Chatyr Kul (UNDP 2009)	Ak Shirak (Aizen et al. 2006)	Western Terskey-Alatoo (Narama et al. 2006)	South-East Fergana (Narama et al. 2010)	Eastern Terskey-Alatoo (Kutuzov and Shahgedanova 2009)	Tarim (Kyrgyzstan) (UNDP 2009)	At Bashy (Narama et al. 2010)	Syr Darya (UNDP 2009)	Ak Shirak (Khromova et al. 2003)
1943			100							100
…										
1960	100	100					100		100	
…										
1965						100				
…										
1970					100			100		
…										
1971				100						
…										
1977			95.8							
…										
2000	94.0	93.4			91		85.3	88	84.1	
2001										74
2002				92						
2003			87.5			87.4				
Average annual shrinkage rate	**0.15**	**0.17**	**0.21**	**0.28**	**0.30**	**0.33**	**0.37**	**0.40**	**0.40**	**0.45**

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Table S4c ¦ Glacier area changes in the outer ranges.

	Ala Archa (Aizen et al. 2006)	Issyk Köl (UNDP 2009)	Ile Alatau / Kungey Alatoo (Narama et al. 2010)	Chu (UNDP 2009)	Balkash (UNDP 2009)	Ile Alatau / Kungey Alatoo (Bolch 2008; Bolch and Marchenko 2009)	Malaya Almatinka (Kishi Almaty) (Hagg et al. 2004)	Pskem (Narama et al. 2010)	Ile Alatau (Vilesov and Uvarov 2001)	Talas (UNDP 2009)	Sokuluk (Niederer et al. 2008)
1931									100		
...											
1955						100			86.2		
...											
1958							100				
...											
1960		100		100	100					100	
...											
1963	100										100
...											
1970			100					100			
...											
1979						81.5			68.8		
...											
1981	94.8										
...											
1986											86.7
...											
1990									61		
...											
1998							79.8				
1999						67.9					
2000		84.6	88	82.3	82.3			81		72.7	71.9
...											
2003	84.8										
Average annual shrinkage rate	**0.38**	**0.39**	**0.40**	**0.44**	**0.44**	**0.50**	**0.51**	**0.63**	**0.66**	**0.68**	**0.76**

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Table S5 ¦ Runoff and glacial contribution in selected Tien Shan catchment areas.

The literature related to river runoff in glaciated catchments in Central Asia is quite abundant. However, comparison of these data is often hampered by incomplete meta-information on *when* and *where* river discharge has been measured or modeled. Another difficulty is introduced by non-congruent definitions of "glacial runoff". Most hydrologists and glaciologists in former Soviet countries include meltwater from seasonal snowcover and liquid precipitation on the glacier surface (Glazirin 2009), but some authors (e.g. Schulz 1965) understood "glacial runoff" as ice melting exclusively. Unfortunately, most authors do not indicate in which sense they used the term „glacial runoff", which makes the comparison of data difficult, but probably does not skew the general tendencies. In this article, we consider "glacial runoff" as any water originating from surfaces covered by glaciers – be it snow-, ice- or firn-melt or liquid precipitation, as the majority of assembled studies has probably used the term in this sense.

For each of the eight major hydrological basins, we compiled available data from different sources in a synthesis (last line for each basin). We used data from Kuzmichenok 2009 and UNDP 2009 for total and glaciated area, respectively, and data from Kuzmichenok 2009 and Mamatkanov et al. 2006 for total runoff. All three sources were elaborated at the same time at the Institute of Water Problems and Hydropower (Bishkek, Kyrgyzstan) and are therefore best suited for comparison. Absolute values for glacial runoff were calculated from total runoff and an estimated glacial share (proportion total / glacial runoff), indicated in three different sources (Kemmerikh 1972; Dolgushin and Osipova 1989; Dikich et al. 1995).

River basin	Area (glaciated, quotient)		Annual runoff (total, glacial)		Glacial share (summer, year, quotient)			Figure 4	Source
	km2	%	km3	km3	%	%	-		
Amu Darya									
Abramov		51.00				56.0			Hagg et al. 2006
Total		6.10			48.0	21.0	2.3		Kemmerikh 1972
Total	604.0	6.59							UNDP 2009
Total			1.60						Kuzmichenok 2009
Total	678.0	7.40	1.93						Mamatkanov et al. 2006
Total	**604.0**	**7.84**	**1.60 – 1.93**	**0.32 – 0.39**	**50.0**	**20.0**	**2.5**	▲	**own synthesis**
Chu									
Ala Archa	36.0	15.45			42.0	26.0	1.6	▲	Aizen et al. 1995
Ala Archa		17.00			46.0	30.0	1.5	▲	Kemmerikh 1972
Ala Archa		36.00							Hagg et al. 2006
Chon Kemen		5.00			35.0	16.0	2.2	▲	Kemmerikh 1972
Djindisu	6.4	50.79			70.0	45.0	1.6	▲	Aizen et al. 1996
Total (1973-2000)			3.97						Yakimov and Kostenko 2003
Total (before 1973)			3.72						Yakimov and Kostenko 2003
Total	894.7	3.15			27.5	16.5	1.7		Usubaliev and Dikich 2009
Total			4.03						Kuzmichenok 2009
Total	894.7		4.95			16.5			Dikich et al. 1995
Total			4						Aizen et al. 2007
Total	582.0	2.61							UNDP 2009
Total	895.0	3.20	3.53						Mamatkanov et al. 2006
Total	**895.0**	**3.15**	**3.53 - 4.03**	**0.58 - 0.66**	**27.0**	**16.5**	**1.6**	▲	**own synthesis**
Tarim									
Glacier No 1	1.9	56.89				34.0			Hagg et al. 2006
Kaksaal	287.7	3.48			44.3	31.0	1.4	▲	Usubaliev and Dikich 2009
Sary-Dzas	2658.4	22.43			61.9	42.5	1.5	▲	Usubaliev and Dikich 2009
Usengu-Kuus					61.5	40.0	1.5		Usubaliev and Dikich 2009
Total	7177.1				80.0	38.2	2.1		Dikich et al. 1995
Total						40.0			Kuznezov 1968, in Aizen et al. 1997
Total			8.43						Kuzmichenok 2009
Total						40-50			Dolgushin and Osipova 1989
Total	2992.0	12.43							UNDP 2009
Total	3496.0	11.89	7.25						Mamatkanov et al. 2006
Total (China)	19878.0	1.95							Shangguan et al. 2009
Total (China)						39.0			Liu et al. 2006
Total	**7170.0**	**29.78**	**7.25 - 8.43**	**2.90 - 3.37**		**40.0**		▲	**own synthesis**

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River basin	Area (glaciated, quotient)		Annual runoff (total, glacial)		Glacial share (summer, year, quotient)			Figure 4	Source
	km2	%	km3	km3	%	%	-		

Syr Darya									
Alabuga	126.7	3.42			13.0	26.0	0.5	▲	Dikich 1999
Arys	35.8	0.56				3.9			Usubaliev and Dikich 2009
Arys	19.0	0.15				0.9			Glazirin 1996
Arys	36.0		1.43			3.9			Dikich et al. 1995
At Bashi	113.7	2.05			9.7	22.0	0.4	▲	Dikich 1999
At Bashi	114.0		1.05			9.7			Dikich et al. 1995
Bolshoi Naryn	607.9	10.65			31.0	52.0	0.6		Dikich 1999
Bolshoi Naryn	618.0	10.66	1.44			31.9			Dikich et al. 1995
Bolshoi Naryn		9.00			48.0	23.0	2.1	▲	Kemmerikh 1972
Chatkal	51.0		3.85			1.3			Dikich et al. 1995
Chatkal (Charvak)	36.0	0.51				6.4			Glazirin 1996
Chirchik	172.0	1.54				3.5			Usubaliev and Dikich 2009
Chirchik	179.0		7.16			3.5			Dikich et al. 1995
Kara-Darya			6.4						Aizen et al. 2007
Kara-Darya	86.5	0.69			9.4	5.0	1.9	▲	Usubaliev and Dikich 2009
Kara-Darya	75.0		3.19			3.3			Dikich et al. 1995
Kara-Darya (1973-2000)			7.91						Yakimov and Kostenko 2003
Kara-Darya (before 1973)			7.65						Yakimov and Kostenko 2003
Kekemeren	104.7	1.01			3.4	6.0	0.6	▲	Dikich 1999
Kekemeren	143.0		8.11			1.8	0.0		Dikich et al. 1995
Malenkoi Naryn	344.6	8.90			24.0	38.0	0.6	▲	Dikich 1999
Malenkoi Naryn	356.0	9.13	1.84			18.4			Dikich et al. 1995
Naryn / Karadarya (1973-2000)			7.40						Yakimov and Kostenko 2003
Naryn / Karadarya (before 1973)			7.21						Yakimov and Kostenko 2003
Naryn	1369.7	2.35			16.0	7.8	2.1		Usubaliev and Dikich 2009
Naryn	1360.0	2.33	15.00		22.0	7.8	2.8	▲	Krenke 1982
Naryn			14.4						Aizen et al. 2007
Naryn (1973-2000)			15.10						Yakimov and Kostenko 2003
Naryn (vor 1973)			14.20						Yakimov and Kostenko 2003
Naryn Uch Kurgan	1370.0	2.35			8.7	16.0	0.5	▲	Dikich 1999
Oigaing		7.00							Hagg et al. 2006
Oigaing						17.7			Glazirin et al. 1994
Oigaing		9.00				4.0			Aizen et al. 1995
Pskem		5.00			28.0	12.0	2.3	▲	Kemmerikh 1972
Pskem	128.0		2.59			7.7			Dikich et al. 1995
Pskem (Mouth)	102.0	3.60				17.1			Glazirin 1996
Total			27.31						Kuzmichenok 2009
Total	1658.4		26.99			5.9			Dikich et al. 1995
Total			27.5						Aizen et al. 2007
Total	1982.0	1.79							UNDP 2009
Total	2381.0	2.00	29.8						Mamatkanov et al. 2006
Total (1973-2000)			30.40						Yakimov and Kostenko 2003
Total (before 1973)			29.10						Yakimov and Kostenko 2003
Total	**2000.0**	**1.80**	**27.31 – 29.8**	**1.64 – 1.79**		**6.0**		**▲**	**own synthesis**

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River basin	Area (glaciated, quotient)		Annual runoff (total, glacial)		Glacial share (summer, year, quotient)			Figure 4	Source
	km2	%	km3	km3	%	%	-		

Issik-Kul									
Ak-Saj	46.1				-	47.8			Dikich 2004
Aksu	12.1				26.0	9.7	2.7		Dikich 2004
Aksu	68.0				87.0	17.9	4.9		Dikich 2004
Akterek		4.20	0.92	0.21		23.4			Dikich and Hagg 2004
Akterek	24.9				-	23.4			Dikich 2004
Akterek. Cickan	7.3				29.1	10.8	2.7		Dikich 2004
Bajsaur	4.4				27.7	8.9	3.1		Dikich 2004
Barskaun	34.7				45.2	20.9	2.2		Dikich 2004
Cholpon-Ata		9.30	0.40	0.09	64.7	21.3	3.0	▲	Dikich and Hagg 2004
Cholpon-Ata	10.3				64.7	21.3	3.0		Dikich 2004
Chon Aksu		4.00			13.0	8.0	1.6	▲	Kemmerikh 1972
Chon Aksu		21.10	1.60	0.59		36.7			Dikich and Hagg 2004
Chon Aksu	65.2				-	36.7			Dikich 2004
Chon Kyzylsu		19.00			61.0	34.0	1.8	▲	Kemmerikh 1972
Chon Kyzylsu		14.30	1.50	0.45	69.0	29.7	2.3	▲	Dikich and Hagg 2004
Chon Kyzylsu	43.3				69.0	29.7	2.3		Dikich 2004
Con-Džargylcak	12.9				-	-			Dikich 2004
Con-Kojsu	6.1				45.1	15.7	2.9		Dikich 2004
Cotkal	15.4				-	52.9			Dikich 2004
Dolonaty	4.0				-	9.9			Dikich 2004
Džerges. Bozucak	1.3				10.1	1.5	6.7		Dikich 2004
Džety-Oguz	33.1				45.5	17.7	2.6		Dikich 2004
Dzhyrgalan		1.00	1.47	0.03	5.6	1.7	3.3	▲	Dikich and Hagg 2004
Dzhyrgalan	2.5				5.6	1.7	3.3		Dikich 2004
Džuuka	47.9				44.3	18.1	2.4		Dikich 2004
Irdyk	4.0				41.1	13.8	3.0		Dikich 2004
Kabyrga	5.7				-	79.3			Dikich 2004
Kammenaja		3.80	0.49	0.03	13.5	5.2	2.6	▲	Dikich and Hagg 2004
Kammenaja	3.2				13.5	5.2	2.6		Dikich 2004
Karakol	58.3				49.1	20.2	2.4		Dikich 2004
Kici-Džargylcak	8.6				56.3	17.9	3.1		Dikich 2004
Kicine-Kyzyl-Suu	3.5				14.3	5.7	2.5		Dikich 2004
Orto-Kojsu	9.3				51.3	26.7	1.9		Dikich 2004
Tamga	5.5				30.8	16.6	1.9		Dikich 2004
Tjup	4.2				7.6	1.8	4.2		Dikich 2004
Ton	34.9				-	53.3			Dikich 2004
Tossor	20.1				66.3	25.2	2.6		Dikich 2004
Turgen-Aksu	33.2				29.1	11.6	2.5		Dikich 2004
Ulachol	2.4				5.7	2.1	2.7		Dikich 2004
Total	650.4	5.04			27.1	14.1	1.9		Usubaliev and Dikich 2009
Total	538.0								UNDP 2009
Total			3.35						Kuzmichenok 2009
Total	650.0		3.72			14.1			Dikich et al. 1995
Total		3.00							Dikich and Hagg 2004
Total			3.72-3.91						Alamanov et al. 2000, in Dikich and Hagg 2004
Total	650.0	5.00	3.88						Mamatkanov et al. 2006
Total	**650.0**	**4.22**	**3.35 – 3.88**	**0.47 – 0.55**	**27.0**	**14.1**	**1.9**	**▲**	**own synthesis**

River basin	Area (glaciated, quotient)		Annual runoff (total, glacial)		Glacial share (summer, year, quotient)			Figure 4	Source
	km2	%	km3	km3	%	%	-		

Balkash Lake

River basin	km2	%	km3	km3	%	%	-	Fig 4	Source
Aksai		7.90	0.07	0.02	32.1	24.5	1.3	▲	Vilesov and Uvarov 2001
Bolshaya Almatinka		9.00			41.0	18.0	2.3	▲	Kemmerikh 1972
Bolshaya Almatinka		9.30	0.15	0.04	44.7	26.8	1.7		Vilesov and Uvarov 2001
Burkhan		0.80				4.8			Vilesov and Morozova 2004, in Severskiy et al. 2006
Chemolgan		1.10	0.04	0.003	13.8	7.4	1.9	▲	Vilesov and Uvarov 2001
Chizhin		9.50				38.5			Vilesov and Morozova 2004, in Severskiy et al. 2006
Dzhungharia		4.70				17.4			Vilesov and Morozova 2004, in Severskiy et al. 2006
Issik		13.60	0.17	0.06	52.9	33.2	1.6	▲	Vilesov and Uvarov 2001
Kargalinka		5.40	0.02	0.00	38.8	23.2	1.7	▲	Vilesov and Uvarov 2001
Kaskelen		3.70	0.13	0.02	17.7	12.3	1.4	▲	Vilesov and Uvarov 2001
Khorgos		3.40				14.0			Vilesov and Morozova 2004, in Severskiy et al. 2006
Malenkaya		20.00				12.0			Aizen et al. 1995
Malenkaya		8.00			24.0	10.0	2.4	▲	Kemmerikh 1972
Malenkaya		5.40	0.07	0.01	26.6	17.3	1.5	▲	Vilesov and Uvarov 2001
Talgar		18.00	0.32	0.13	56.1	40.5	1.4	▲	Vilesov and Uvarov 2001
Talgar		26.00			48.0	22.0	2.2	▲	Kemmerikh 1972
Turgen		4.30	0.22	0.04	27.2	18.9	1.4	▲	Vilesov and Uvarov 2001
Tuyusku	7.0	25.00				21.0			Hagg et al. 2006
Tyshkan		10.10				28.8			Vilesov and Morozova 2004, in Severskiy et al. 2006
Usek		5.50				17.8			Vilesov and Morozova 2004, in Severskiy et al. 2006
Uzunkargali		2.70	0.11	0.02	22.8	14.0	1.6	▲	Vilesov and Uvarov 2001
Total			0.36						Mamatkanov et al. 2006
Total			0.29						Kuzmichenok 2009
Total						40-50			Dolgushin and Osipova 1989
Total	0.3	36.23							UNDP 2009
Total	**0.3**	**42.86**	**0.29 – 0.36**	**0.12 – 0.14**		**40.0**		**▲**	**own synthesis**

Talas

River basin	km2	%	km3	km3	%	%	-	Fig 4	Source
Total (Grodekovo)	117.0	1.27				10.2			Glazirin 1996
Total	113.0	1.05							UNDP 2009
Total			2.33						Kuzmichenok 2009
Total						12.9			Dikich et al. 1995
Total			2.3						Aizen et al. 2007
Total		3.20	1.72						Mamatkanov et al. 2006
Total (1973-2000)			1.72						Yakimov and Kostenko 2003
Total (before 1973)			1.72						Yakimov and Kostenko 2003
Total	**115.0**	**1.15**	**1.72 - 2.33**	**0.22 - 0.30**		**13.0**		**▲**	**own synthesis**

Chatyr-Kul Lake

River basin	km2	%	km3	km3	%	%	-	Fig 4	Source
Total	691.0	6.39			30.0	20.0	1.5		Kemmerikh 1972
Total	2.6	0.28							UNDP 2009
Total			0.14						Kuzmichenok 2009
Total	**2.6**	**6.40**	**0.14**	**0.03**	**30.0**	**20.0**	**1.5**	**▲**	**own synthesis**

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Supplementary methodological information

Glacier area

Data on glacier coverage in the Tien Shan mountains has first been systematically collected in the Soviet Glacier Catalogue (1973, with data from the 1940s and 1950s) and in the Chinese inventory (data from the 1970s and 1980s). Since this period, many authors have assessed changes in glacier area within the Tien Shan mountains, applying various methods and using different data as reference. In the following, we summarize the methods and data from literature compiled in this article (figure 3 in the main article and tables S4a-c in SOM):

Aizen et al. 2006; Aizen et al. 2007: The retreat of the Ak Shirak and Ala Archa glaciers was assessed from ground measurements (geodetic surveys from an expedition of the Russian Imperial Geographical Society) and from remote-sensing data. Latter include aerial photographs (1943, 1963, 1977 and 1981) as well as 1 : 25,000 scale topographic maps and SRTM and ASTER data (2000–2003).

Bolch 2007; Bolch 2008; Bolch and Marchenko 2009: The recent glacial ice coverage was automatically delineated using a Landsat ETM+ scene (August 1999). The outlines of debris covered glaciers and of glaciers with cloud cover were manually delineated. An evaluation was carried out in the Malaya Almatinka (new name: Kishi Almaty) valley, where a detailed map (1 : 10,000) was produced based on field measurements in the year 1998. Glacier outlines were then compared with data from the Soviet Glacier Inventory and glacier outlines based on topographic maps (1:100,000) (slightly improved with Landsat MSS data)
→ See main article for discrepancies with other studies in the same area.

Hagg et al. 2004: Two maps (1 : 10,000) of the Malaya Almatinka valley (Tuyuksu region) were compared. The Tuyuksu region was first mapped by a German-Soviet expedition in 1958, and then again in 1998 by the Commission for Glaciology of the Bavarian Academy of Sciences.

Khromova et al. 2003: Glacier area changes in the Ak Shirak range were assessed from aerial photographs (1943 and 1977) and ASTER imagery (September 2001). Long term glaciological and meteorological observations, including ground surveys and radio-echo sounding from the 1980s, as well as a glaciological map were further used to assess glacier area changes.
→ See main article for discrepancies with other studies in the same area.

Kutuzov and Shahgedanova 2009: The outlines and termini positions of 335 glaciers were mapped using a Landsat TM scene (31.07.1990) and two ASTER scenes (10.09.2003). The information on type and aspect was obtained from the Soviet Glacier Inventory. Changes in the extent of 109 glaciers between 1965 and 2003 were measured using the 1:25,000 scale topographic maps based on aerial photographs obtained in 1965, the 1990 Landsat, and 2003 ASTER images to enable a comparison with the results obtained for other regions in Central Asia.

Narama et al. 2006; Narama et al. 2010: The authors used high resolution remote sensing data such as Corona photographs, Landsat ETM+ images and ALOS PRISM and AVNIR satellite data sets. Hexagon and ASTER data were used for validation. Glacier outlines were manually digitized from pan-sharpened images of the respective period. Debris-covered glacier termini were identified using 3D images from Landsat 7 ETM+ and slope angle classification from the SRTM DEMs.

Niederer et al. 2008: A high-resolution image recorded by the KFA1000 sensor (August 1986) and a Landsat ETM+ scene (August 2000) were compared with Russian topographic maps (1 : 25,000), which are based on aerial photographs from 1963. Glacier outlines were automatically delineated using threshold ratio images. Glacier outlines on the topographic map and debris covered glaciers were digitized manually.

Shangguan et al. 2009: Digitized glacier outlines from the Chinese Glacier Inventory (topographical maps in the scale 1 : 100,000, based on aerial photos from 1962-1977) were compared with 28 Landsat ETM+ images (1999-2001). Some of the glaciers were automatically delineated using threshold ratio images, but most glaciers were digitized manually due to the significant debris cover.

Liu et al. 2006 (Shangguan et al. 2004, in Liu et al. 2006 / Shangguan et al. 2004, in Liu et al. 2006): The authors used topographical maps (1 : 100,000), which are based on aerial photographs acquired during the 1960s and 1970s, and Landsat TM and ETM+ images (1999-2001). Glacier boundaries on the corrected images were identified through visual interpretation. The boundary of the termini of debris covered glaciers was recognized based on the geomorphic pattern in the image draped over a DEM.

UNDP 2009: The research is based on results of the Soviet Glacier Inventory, which have been extrapolated with data from individual glaciers under monitoring. The glacier parameters received as a result of interpolation for the year 2000 were used as initial conditions for the further change assessment. Probable changes of glacier conditions were modeled using the height values of the firn-line as a climatic parameter.

Vilesov and Uvarov 2001: Glacier area changes assessed from aerial photos (1955, 1979 and 1990) were extrapolated back to 1930 using summer temperatures at 3800 masl as a proxy for ablation and glacier shrinkage.
→ See main article for discrepancies with other studies in the same area.

Glacier volume

Rough estimates of glacier volume exist for all 8 hydrological basins in Kyrgyzstan (UNDP 2009; see table S2 in SOM). More specific assessments have been done only for a few glaciers in the Tien Shan. The majority of these glacier volume assessments rely on area-volume scaling and do not include slope-dependent approaches (Haeberli and Hoelzle 1995) or modeling of the glacier-bed topography (Farinotti et al. 2009; Paul and Linsbauer 2012). According to the area-volume scaling method, glacier volume is calculated as a function of glacier area and mean thickness (Bahr et al. 1997). Latter is subject to great variation, which renders this method highly uncertain, especially in areas with heterogeneous topography.

Results are accordingly ambiguous: total glacier volume in Kyrgyzstan has probably decreased from 493 to 417 km^3, at an annual rate of 0.5%, within thirty years after the elaboration of the Soviet glacier catalogue (UNDP 2009). However, this rate is subject to large uncertainty and the current rate of volume reduction might as well be twice as high (1% a^{-1}) (Kotlyakov and Severskiy 2009) and thus similar to the Alps, where an average 1% volume loss per year has been reported for the period 1975 to 2000 (Zemp et al. 2006). Studies with a local or regional perspective corroborate this rate: glacier volume probably decreased by 36.7% between 1957 and 1998 (0.89% a^{-1}) on Karabatkak Glacier (Dikich 2004) and by 32.2% between 1955 and 1990 (0.92% a^{-1}) in the Zailisky Alatoo (Vilesov and Uvarov 2001).

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The days of plenty might soon be over in glacierized Central Asian catchments

Annina Sorg, Matthias Huss, Markus Stoffel and Mario Rohrer

The days of plenty might soon be over in glacierized Central Asian catchments

Author affiliations

Annina Sorg*[1,2]

Matthias Huss[3]

Markus Stoffel[1,2]

Mario Rohrer[4]

[1] Institute for Environmental Sciences (ISE), University of Geneva, Route de Drize 7, 1227 Carouge, Switzerland

[2] dendrolab.ch, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1+3, 3000 Bern, Switzerland

[3] Department of Geosciences, University of Fribourg, 1700 Fribourg, Switzerland

[4] Meteodat GmbH, Technoparkstrasse 1, 8005 Zurich, Switzerland

* Corresponding author

Annina Sorg

Institute for Environmental Sciences (ISE)

University of Geneva

Route de Drize 7

1227 Carouge

Switzerland

0041 76 400 30 69

annina.sorg@unige.ch

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Despite the fact that the fast growing population of Central Asia strongly depends on glacial melt water for fresh water supply, irrigation and hydropower production, the impact of glacier shrinkage on water availability remains poorly understood[1]. With an annual area loss of 0.36 to 0.76%, glaciers are retreating particularly fast in northern Tien Shan[2], thus causing concern about future water security in the densely populated regions of Bishkek and Almaty. Here, we use exceptionally long in-situ data series to run and calibrate a distributed glacio-hydrological model[3], which we then force with downscaled CMIP5 data[4]. We observe that even in the most glacier-friendly scenario, glaciers will lose up to two thirds (-60%) of their 1955 extent by the end of the 21st century. The range of climate scenarios translates into different changes in overall water availability, from *peak water* in the 2020s over a gradual decrease to *status quo* until the end of the 21st century. The days of plenty, however, will not last much longer, as summer runoff will likely decrease independent of scenario uncertainty. These results highlight the need for immediate planning of mitigation measures in the agricultural- and energy sectors to assure long-term water security.

As future summers are expected to become drier and hotter, the buffering capacity of glaciers will become more important for Central Asia's fresh water supply, irrigation, and hydroelectric potential[5]. However, the glacio-hydrological system of the region is currently undergoing a substantial change, as increased runoff from glacier wasting will eventually result in decreasing melt water amounts from strongly reduced glacier volume. A crossing of this tipping point (*peak water)* is expected to occur earlier in northern Tien Shan (e.g. Tuyuksu[6,7]) than in the higher inner and eastern Tien Shan ranges (e.g. Big Naryn[8] and Glacier No. 1[9]), but studies using sophisticated distributed glacio-hydrological models and state-of-the-art climate projections are still rare[10-12].

In this study, we assess glacier- and runoff changes forcing the distributed Glacier Evolution Runoff Model GERM[3] with downscaled data from the Phase five of the Climate Model Intercomparison Project CMIP5[4]. With a focus on the particularly susceptible northern Tien Shan, where fast melting glaciers provide fresh water to the densely populated cities of Bishkek and Almaty, we analyze future runoff in the unregulated Chon Kemin catchment (Fig. 1) between 1955 and the end of the 21st century. The Chon Kemin river is the most important

tributary to the Chu river providing Kyrgyzstan's capital Bishkek with fresh water before running further northwest to the Kazakh steppe.

Observed changes in climate and runoff. Enhanced shrinkage of Tien Shan glaciers has been demonstrated to be strongly correlated with increasing air temperatures[9,10,13]. Like in other parts of Central Asia, mean annual air temperature (MAAT 1937-1998: 4.9° C) and mean annual precipitation (MAP 1937-1998: 445 mm) have increased in the Chon Kemin valley over recent decades (Supplementary Fig. S2), probably as a result of the weakening of the Siberian anticyclone[14]. Runoff at Uste gauge in the Chon Kemin valley has also increased significantly during the same period. Increasing spring temperatures have likely caused enhanced snow melt and thus significant increases in spring discharge. Temperature and runoff have also significantly increased in summer and fall, thus indicating enhanced glacier melting and a prolongation of the melting period[13,15].

Projected changes in climate until 2099. MAAT and MAP are likely to increase further by +1.6 to +7.8 °C and -2 to +20%, respectively, according to the four global circulation model (GCM) runs spanning the range of dry-cold, dry-warm, wet-cold and wet-warm future CMIP5 climates (2081-2099 vs. 1961-1990; Supplementary Fig. S3). Similar to previous studies[10,16], we selected the four GCM runs spanning the 10th and 90th percentiles of changes in summer temperature and in total precipitation within the two most extreme representative concentration pathways scenarios, RCP 2.6 and RCP 8.5[17]. For the glacio-hydrological model, we downscaled the four scenarios with the delta-change approach[18] to obtain transient daily time series of temperature and precipitation until 2099 with the same resolution, characteristics and variance as the station data.

Glacio-hydrological modeling. These sets of transient climate time series were then used to force the distributed conceptual glacio-hydrological model GERM[3]. The model calculates all components of the surface water balance with a focus on accumulation and melt processes on glaciers. Transient 3D glacier geometry changes are explicitly calculated using a mass-conserving approach[19], which is particularly important when glaciers are not in balance with the prevailing climate. We performed a newly developed multi-variable calibration allowing a

realistic reproduction of each runoff component, which is necessary to reduce the problem of equifinality[12]. Although the Tien Shan mountains are generally referred to as a data-sparse region[1,10], we rely here on exceptionally long data series of temperature and precipitation (1937-1990), discharge (1951-1998) and annual glacier mass balance and equilibrium line altitudes (ELA; 1957-today). We also included annual snow cover duration from the Advanced Very High Resolution Radiometer (AVHRR; 1985-1989) and daily snow coverage from Landsat scenes (1977/1979) as well as information on high-altitude precipitation and basin evaporation[20] to calibrate all relevant parameters and processes (Supplementary Figs. S1, S4-S7 and Supplementary Tables S1-S3). All modeling results span the range of the four possible future scenarios and are compiled for the past (1955-1999), the present and near future (2000-2049) and the far future (2050-2099).

Projected changes in runoff until 2099. Changes in climate are projected to result in negative mass balance values and to cause a rise in ELA from 3922 (average 1955-1999) to 3976-4031 (average 2000-2049) and 3991-4409 (average 2050-2099) m above sea level, depending on the scenario, and thus cause significant losses in glacier areas and ice volumes. In the more "glacier-friendly", dry-cold and wet-cold scenarios, glaciers are projected to cover 38 and 53 km^2 by 2099, thus representing 29 and 40% of their extent in 1955, respectively. In the more pessimistic, dry-warm and wet-warm scenarios, glaciers in the Chon Kemin basin are expected to disappear completely by 2079 and 2085, respectively (Figs. 2a-b, Table 1).

The projected depletion of glacial reserves translates into three different response types of glacial- and total runoff (Fig. 2c, Table 1): According to the warm scenarios, releases from annual glacier storage change can be expected to culminate in the 2020s, with a subsequent drop of glacial and total runoff. The dry-cold scenario would lead to a gradual decrease in total runoff, despite fairly constant glacial runoff over the entire 21st century. The most glacier-friendly, wet-cold scenario results in almost no changes in glacial and total runoff until 2099. The timing of peak water in the warm scenarios is in line with a previous study[21], whereas results from the cold scenarios correspond more with comparable studies for higher altitude catchments in Central Asia[12] and the Himalayas[16].

These fundamental changes in the headwater catchment will ultimately influence seasonal runoff in the Chon Kemin river (Fig. 3) – and in many catchments in northern Tien Shan – with

potentially immense repercussions on agriculture and fresh water supply in the Bishkek area. Summer runoff (JJA) is projected to decrease by –4 to –15% (2000-2049), before reaching a total reduction of –9 to –66% (2050-2099) as compared to the past (1955-1999). Winter runoff is likely to decrease for the warm scenarios and to increase for the cold scenarios. In spring (MAM), increasing runoff amounts are projected for both the near and the far future (+7 to +23% and +18 to +62%, respectively, depending on the scenario). This increase is probably reflective of more winter precipitation and subsequently enhanced snowmelt. Hence, average annual snow cover duration is projected to decrease from 153 days (1955-1999) to 108-151 days (2050-2099), after having fluctuated between 145-161 days (2000-2049).

As a result of higher air temperatures, mean annual actual evaporation is projected to increase from 384 (past) to 405–496 and further up to 433–622 mm a^{-1} (averages 2000-2049 and 2050-2099, respectively), which is comparable to other studies carried out in the region[6,20]. The losses due to evaporation are thus becoming more important and will exacerbate the situation of reduced melt water availability.

Discussion

Uncertainties occur at all stages of glacier- and runoff modeling, and may stem from various sources[22]. We here discuss the influence of measured input and calibration data, glacio-hydrological model parameterization, climate models and downscaling and feedback mechanisms on uncertainty.

The errors in measured data are likely to be rather small, as the multi-variable calibration implemented in GERM would have unearthed unrealistic values. All data series were checked for inhomogenities and data gaps were filled where necessary and possible. Whereas the current glacier extent has been assessed with high precision, past glacier extent used for the initialization of the model calibration might be slightly overestimated due to misinterpreted snow cover on aerial photographs used for the 1950s topographic maps[2]. Simulation and calibration of daily and annual snow cover highly depend on the applied threshold of perceptible snow water equivalents on the satellite images, which were constrained based on literature[23].

Uncertainties also arise from the glacio-hydrological model. Although the model is fully distributed at a high spatial resolution, an even higher resolution could improve the results – at the costs of an exponential increase of computing time. Other enhancements could include the

use of climate data from high altitude meteorological stations, although they are located in neighboring valleys and are thus subject to differing climatic regimes. Calibration would certainly also benefit from more ground truthing in the catchment (e.g. mass balance, radio echo soundings of the ice thickness, seasonal precipitation gradients), but acquiring such data is laborious and can only cover short periods. As an alternative, simulated glacier volume change could be constrained with GRACE (Gravity Recovery and Climate Experiment) or by comparison of repeat high-resolution DEMs. At the bottom line, however, the energy-balance-based melt model and the calibration covering a multitude of very long data-series strongly reduce the issue of equifinality and strengthen the consistency of parameters over long time periods.

Structural differences among the GCMs, by contrast, are an important source of uncertainty, as models respond differently to the same external forcing[24]. In the past, uncertainty contribution from climate models has shown to outweigh the uncertainty stemming from glacier models[25] or to be comparable[10]. We therefore attempted to further limit climate model uncertainty through a representative selection of RCPs and GCMs spanning the full range of possible future climates. The selection was based on summer temperature and annual precipitation, both representing the key drivers of glacier mass balance.

Another important source of uncertainty are future changes in evaporation, for which both the direction and magnitude are highly debated[5]. Our projected changes in evaporation are in line with another study for this region[20], but it would certainly be most helpful to have more informed data on future evaporation in Central Asia.

Conclusion

Irrespective of scenario uncertainty, our study clearly points to significant glacier wasting until the end of the 21st century, which will translate into reduced water availability during summer. These results highlight the need for immediate planning of flexible mitigation measures in the agricultural and energy sectors to avoid an exacerbation of inter-state conflicts and to assure long-term water security for the Bishkek capital region, where more than a million people live. On the water supply side, existing dams and backup-reservoirs further downstream could partly take over the role of glaciers as intra- and inter-annual buffers in the hydrological cycle[26]. On the water demand side, a shift to less water-intensive crops and the restoration of the often outdated

irrigation channels could reduce water demand during summer. Although the Soviet legacy and the current political context complicate such approaches in Central Asia, transboundary collaboration projects like the Chu Talas basin agreement are encouraging steps towards a reasonable water allocation in a changing future.

Methods

For this study, we use the fully distributed, deterministic, conceptual glacio-hydrological Glacier Evolution Runoff Model (GERM)[3]. The model runs at high spatial and temporal resolutions (200 meters and one day, respectively). While requiring a minimum of input data, the model includes transient glacier changes, which is particularly important when glaciers are not in balance with the prevailing climate[3]. We use a simplified energy-balance approach[27], which outperforms temperature-index-methods for long modeling periods and in continental climates as it is less sensitive to temperature changes[27,28]. Ice thickness distribution for each individual glacier in the catchment as well as overall glacier volumes are derived from an inversion of surface topography based on the principles of ice flow dynamics[29]. Transient changes in 3D glacier surface geometry and ice volume are assessed with the empirical, mass conserving Δh-parameterization[19]. This function approximates glacier surface elevation changes in response to surface mass balance forcing as given by ice flow dynamics. By intersecting calculated elevation changes with local glacier bed elevation, glacier area change in the spatial domain is obtained. Glacier mass balance, basin evaporation and runoff are calculated in daily time-steps. The model is forced with measured daily temperature and precipitation data for the calibration period (1955-1999). We developed a new multi-variable calibration and validation approach allowing a realistic reproduction of each runoff component, which reduces the problem of equifinality[12]. The model is manually calibrated and validated according to Supplementary Table S1 to determine the key model parameters (Supplementary Table S2). In a first step, c*limate parameters* are constrained based on values from a previous study[20] to reach a realistic level of mean annual runoff. Then, the *melt parameters* are calibrated to accomplish a reasonable reproduction of the accumulation and ablation processes. Last, the *routing parameters* are tuned to seasonally distribute runoff. The calibrated model is then forced with daily time series of temperature and precipitation from a downscaled set of GCMs from CMIP5[4]. More details on method and on the data sets used can be found in the Supplementary Information.

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Author Contributions

The concept was developed by A.S., M.H. and M.S.; M.H. provided and further developed the model and M.R. helped with the pre-processing of the CMIP5 data. All authors were involved in the paper writing process.

Competing Financial Interests statement

The authors declare no competing financial interests.

Figures

Fig. 1. Overview of the glacierized Chon Kemin catchment in the Kyrgyz-Kazakh border region.

Fig. 2. Glacier and runoff evolution in the Chon Kemin catchment in the past (1955-1999; green), the present and near future (2000-2049; orange) and the far future (2050-2099; red): **a**, Changes in glacier extent at the end of each period (outlines are from 1955). **b**, Glacier area and ice volume evolution relative to 1955. **c**, Total basin runoff and annual glacier storage change (negative in years with positive mass balance, positive in years with glacier mass loss).

Fig. 3. Averaged monthly runoff distribution in the past (1955-1999), the present and near future (2000-2049) and the far future (2050-2099) including all simulated scenarios.
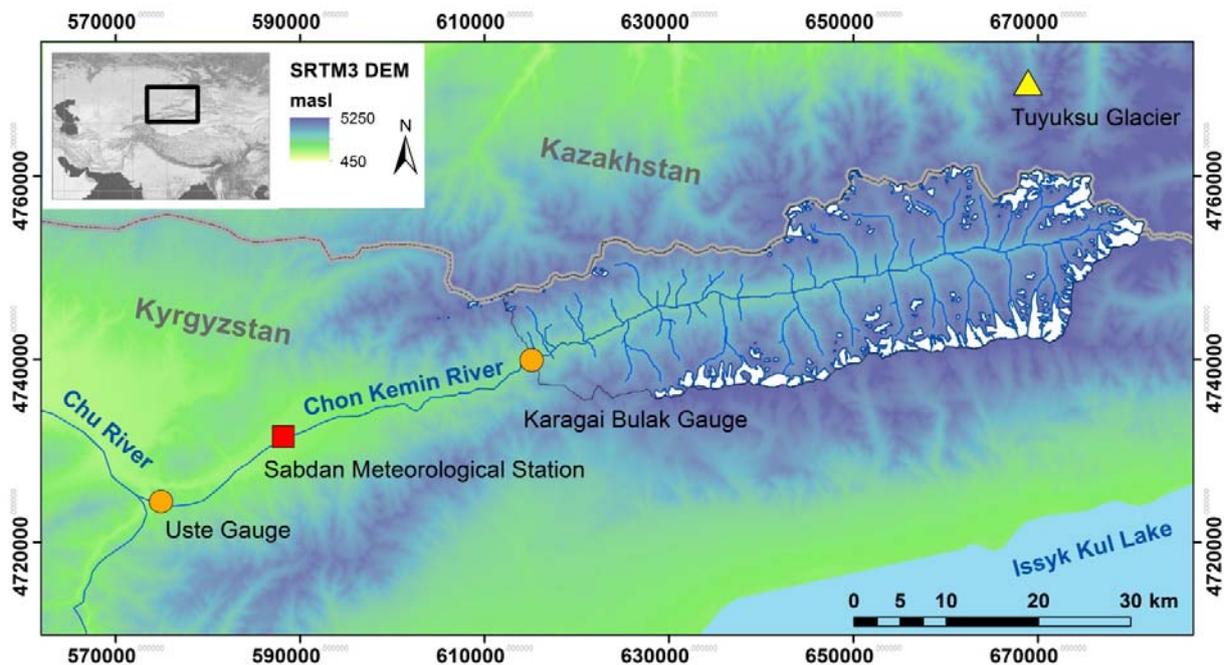
Figure 1
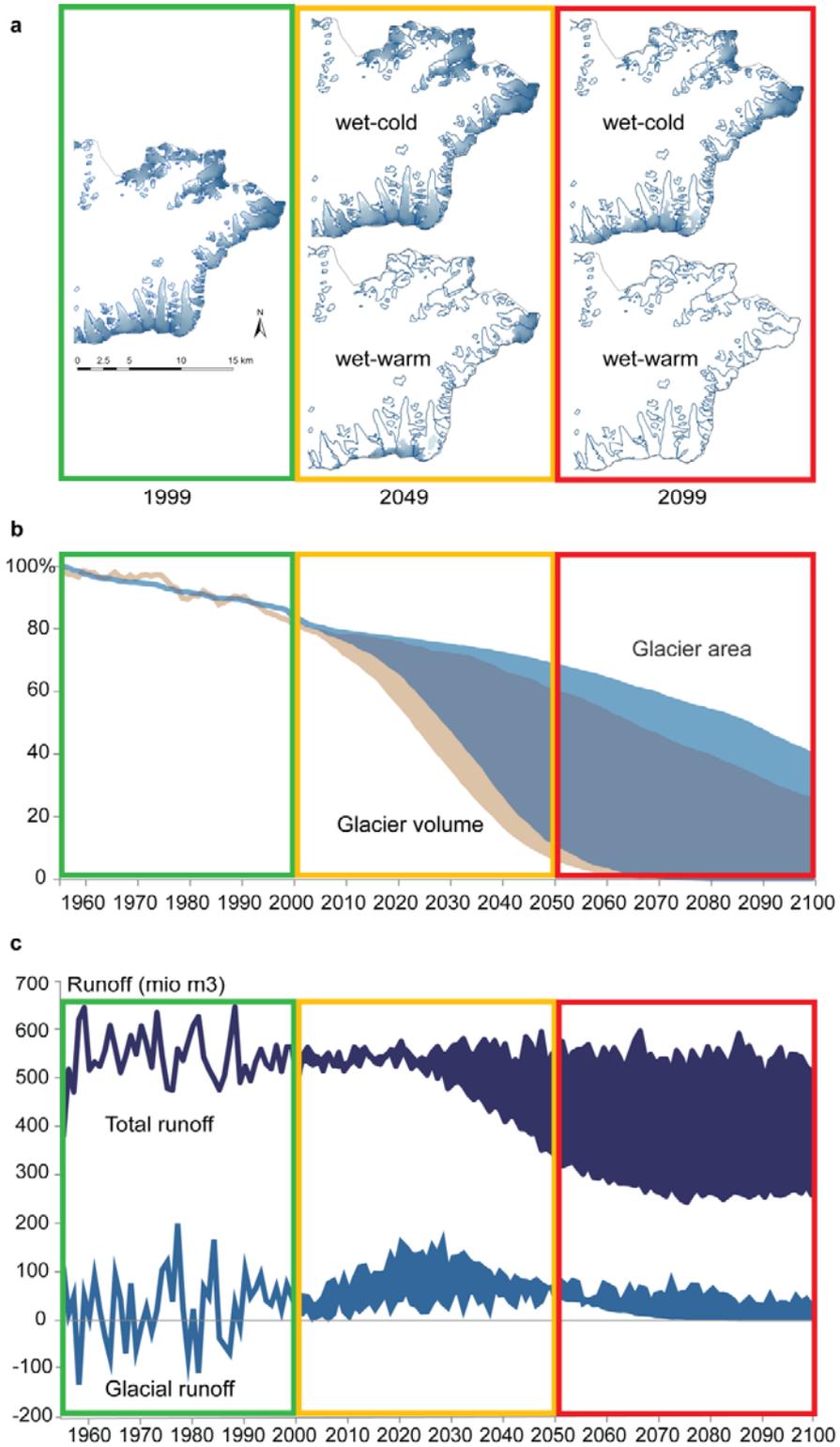
Figure 2
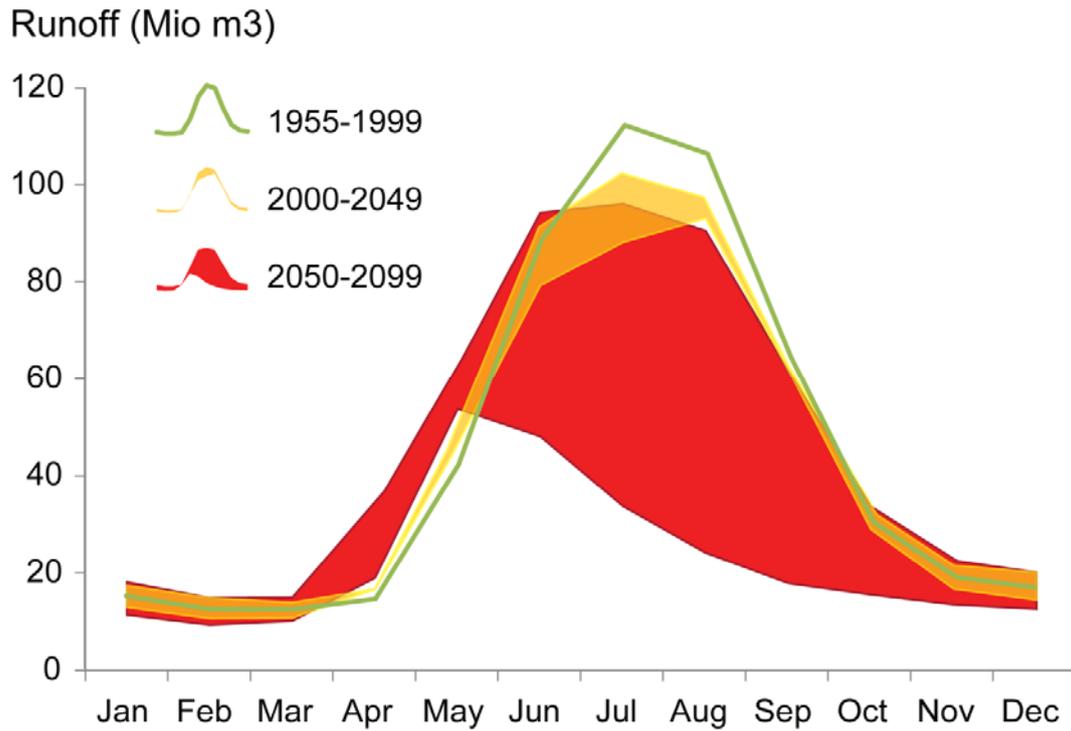
Figure 3

Tables

Table 1: Percental changes in glacier area, volume and runoff, as well as in total runoff and snow cover duration for all scenarios (dry-warm, wet-cold, wet-warm, dry-cold) relative to the past (1955-1999).

Table 1

All numbers are in percent	Present and near future (2000-2049)				Far future (2050-2099)			
Scenario	**Dw**	**Wc**	**Ww**	**Dc**	**Dw**	**Wc**	**Ww**	**Dc**
Area	-40	-19	-43	-19	-97	-41	-98	-48
Volume	-49	-23	-52	-24	-98	-56	-99	-64
Glacial runoff	+275	+17	+288	+36	-54	+62	-67	+93
Total runoff	-19	-1	-6	-4	-49	0	-37	-13
Total summer runoff (JJA)	-15	-4	-13	-9	-66	-9	-61	-22
Snow cover duration	-2	+5	-5	+5	-21	-1	-29	-2

The days of plenty might soon be over in glacierized Central Asian catchments

Supplementary Information

Annina Sorg*[1,2], Matthias Huss[3], Markus Stoffel[1,2] and Mario Rohrer[4]

[1] Institute for Environmental Sciences (ISE), University of Geneva, Route de Drize 7, 1227 Carouge, Switzerland

[2] dendrolab.ch, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1+3, 3000 Bern, Switzerland

[3] Department of Geosciences, University of Fribourg, 1700 Fribourg, Switzerland

[4] Meteodat GmbH, Technoparkstrasse 1, 8005 Zurich, Switzerland

1. Study area

The deeply incised Chon Kemin valley is located in the Kyrgyz part of the Tien Shan mountains, between the Zailiyskiy and Kungey Alatau ranges at the border to Kazakhstan. Running over 120 kilometers from west to east, the valley stretches from 1500 m above sea level to the highest peak Chok Tal at 4760 m above sea level, with an average elevation of 3170 m above sea level. The headwater catchment above Karagai Bulak gauge (42.8°N, 76.41°E) covers an area of 1'037 km^2, of which around 11% (112 km^2) have been covered by 217 glaciers in 1999 [1]. Eastern and Western Aksu Glaciers are the largest glaciers in the valley, covering 6.65 and 5.52 km^2, respectively.

The Chon Kemin river is the most important tributary (40% of total runoff) to the Chu river [2], providing Kyrgyzstan's capital Bishkek with fresh water before running further northwest to the Kazakh steppe. During summer, the Chon Kemin river contains almost exclusively melt water from glaciers.

The Zailiyskiy Alatau constitutes the first montane barrier for northern and western air masses travelling from Siberia and the Kazakh steppes to Central Asia [1,3]. Due to its west-east-orientation with high mountains at the valley end, the Chon Kemin valley is predominantly influenced by air masses coming from west [2]. Mean annual air temperature at Sabdan station (42.70°N, 76.10°E) is 4.9° C and mean annual precipitation is 445 mm (mean 1937-1998). Precipitation minima occur in winter as a result of the Siberian anticyclone, whereas most precipitation falls in early summer due to cyclonic activity and convective precipitation [4].

2. Data

We used exceptionally long data series of temperature, precipitation, discharge and glacier mass balance to run and calibrate a distributed glacio-hydrological runoff model (Fig. S1).
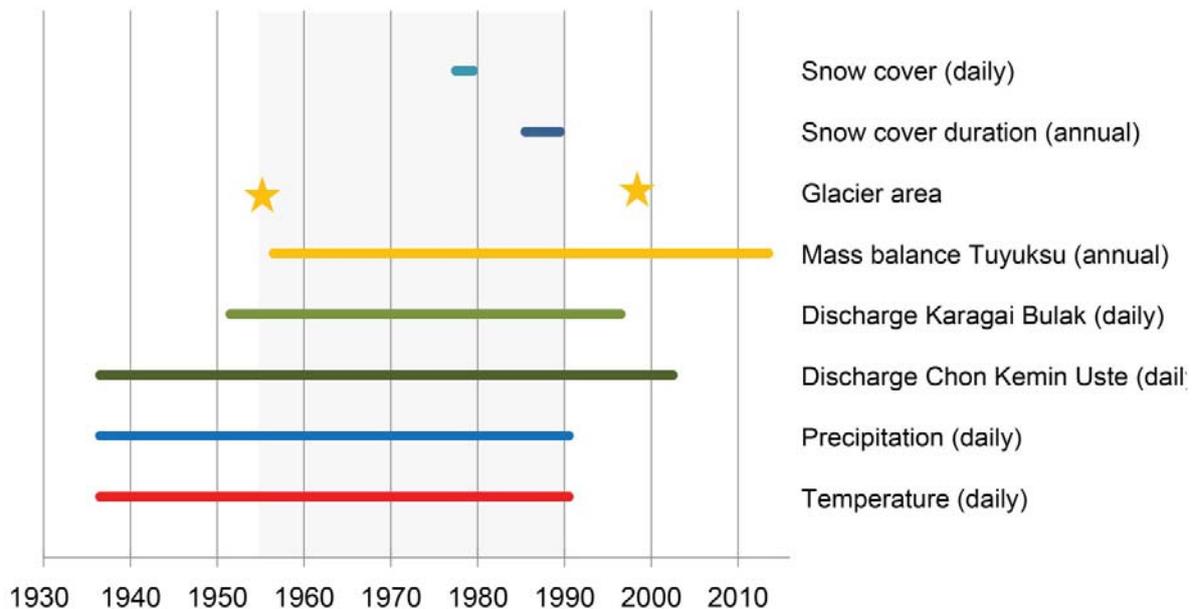
Fig. S1. Data coverage for model input and calibration, with calibration period (1955-1989) displayed in grey.

Temperature and **precipitation** time series from Sabdan station (42.70°N, 76.10°E, 1524 m asl, WMO N° 36921) were available in daily resolution for the time period 1937-1990. The data were downloaded from the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (http://climexp.knmi.nl).

The precipitation data series contained gaps (02/1955, 1966-1976, 10/1977, 04/1985, 06/1986, 04/07/12/1987), which we filled with daily data from the National Climatic Data Center NOAA (http://www1.ncdc.noaa.gov/pub/data/documentlibrary/tddoc/td9290c.pdf). As the quality of the NOAA data is likely to be lower than the quality of the KNMI data, we have excluded the period

1966-1976 for detailed calibration and used it only to approximate the transient glacier evolution in the past.

As the year 1999 marks the turning point between "past" and "future" in our model, we have extended the measured temperature and precipitation series with downscaled data from the most moderate scenario (dry-cold scenario, see Chapter 4 below) for the period 1990-1999 to allow continuous modeling from 1955 to 2099. The period 1990-1999 is, like 1966-1976, not analyzed in detail.

Discharge data for Chon Kemin Uste (42.67°N, 75.91°E, 1289 m asl) and Karagai Bulak (42.80°N, 76.41°E, 2078 m asl) gauges were available in daily resolution for the time periods 1936-2002 and 1951-1996, respectively. The data were provided by the Kyrgyz National Hydrometeorological Agency [5] and digitized by the authors of this study.

Mass balance and **equilibrium line altitude (ELA)** have been assessed since 1957 at Tuyuksu glacier, which makes them the longest series in Central Asia. We have received the data from the [6], the original author is P. A. Cherkasov.

Glacier outlines are from [1], who mapped the glacier coverage in the Chon Kemin and surrounding valleys using a snow-free Landsat ETM+ scene from 08/08/1999. A TM4/TM5 ratio image was used to delineate the glaciers and misclassified pixels of vegetated areas and lakes were eliminated using the Normalized Difference Vegetation Index (NDVI). We have also digitized glacier outlines reflecting the situation in the 1950s based on topographic maps [7] to calibrate the model.

Landuse classification for the three non-glacier surface types classified in GERM (forest, vegetation and bare surfaces) has been derived from a supervised classification in Erdas Imagine 8.4 of the same Landsat ETM+ scene as used for the glacier outlines.

Daily snow cover has been used for visual comparison from four Landsat scenes in 1977 (17/04, 23/05, 07/09 and 01/11) and two Landsat scenes in 1979 (30/03 and 12/05). All Landsat scenes were downloaded from http://earthexplorer.usgs.gov/.

Annual snow cover duration has been assessed from the Advanced Very High Resolution Radiometer (AVHRR) at a resolution of 1 km starting in 1986 [8]. The data were provided by Andreas Dietz.

The digital elevation model (DEM) and **catchment area delineation** are based on data from the Shuttle Radar Topography Mission SRTM3 [9]. The DEM was resampled from 90 meters to the model resolution of 200 meters. From the SRTM3 DEM, the catchment outline has been derived with ArcGIS Hydrotools. SRTM data were downloaded from
http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp.

3. Statistical trend analysis (Mann-Kendall trend test)

Trends in temperature, precipitation and runoff were analyzed with the 2-sided non-parametric Mann-Kendall trend test at the 80, 90 and 95% significance levels [10,11]. Serial correlation was removed using Sen's slope method [12] and Xuebin Zhang's pre-whitening approach [13]. With the help of moving time windows, the multiple trend tests were computed for all time windows of at least 30 years in length during the common 1937-1990 period. The trend matrices in Fig. S2 show the resulting trends (standardized test statistic Z_{MK}; tau) and significance levels (2-sided *p*-value) for key climate variables.

Next 2 pages:

Fig. S2. Summary of the Mann-Kendall (MK) trend test statistics. Trend significance is indicated by the 2-sided p-value and trends are indicated with the standardized test statistics tau.

Trend (Z_MK; tau)

[-0.3,-0.2)
[-0.2,-0.1)
[-0.1,-0.05)
[-0.05,-1e-06)
[1e-06,0.05)
[0.05,0.1)
[0.1,0.2)
[0.2,0.3)

Significance level (2-sided *p*-value)

[0.001,0.05)
[0.05,0.1)
[0.1,0.2)
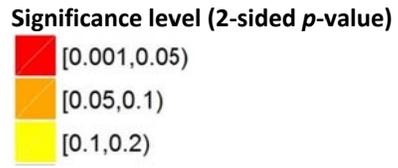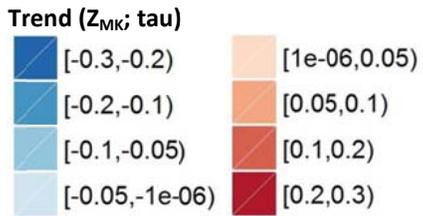
Mass balance Tuyuksu
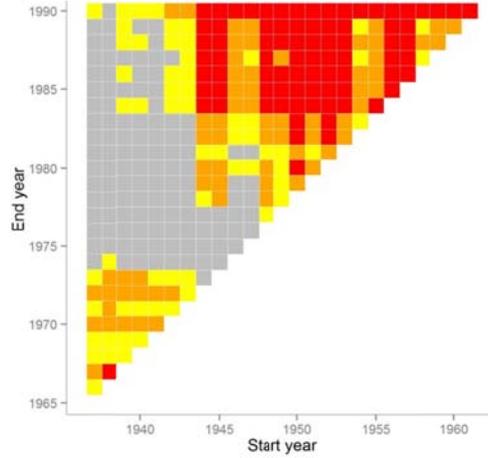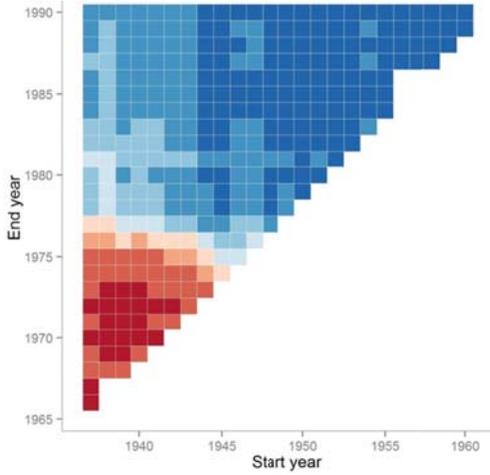
MAP
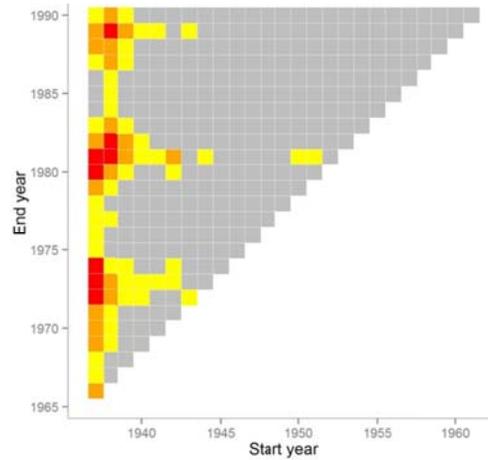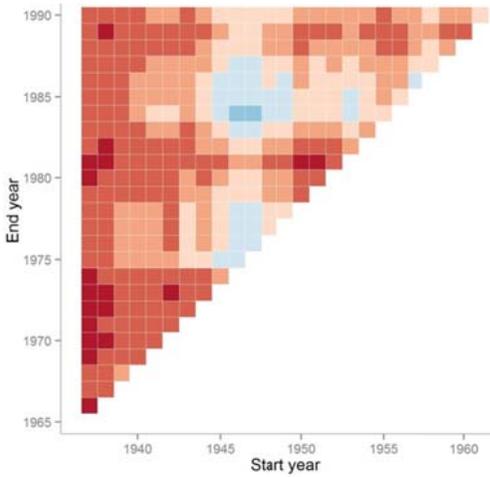
MAAT
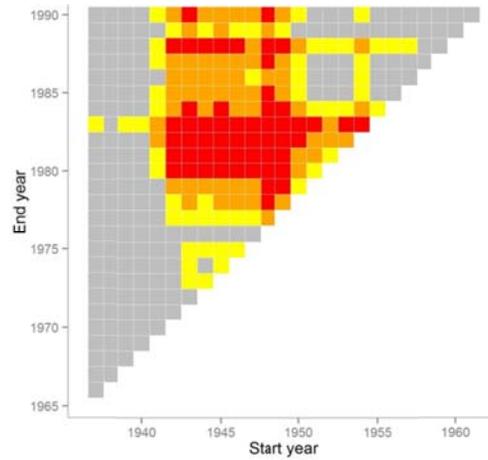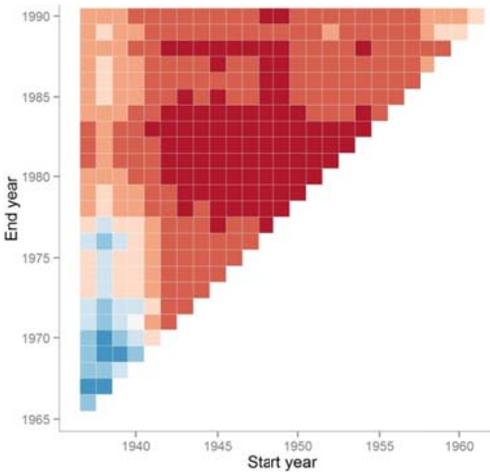
Summer temperature (JJA)
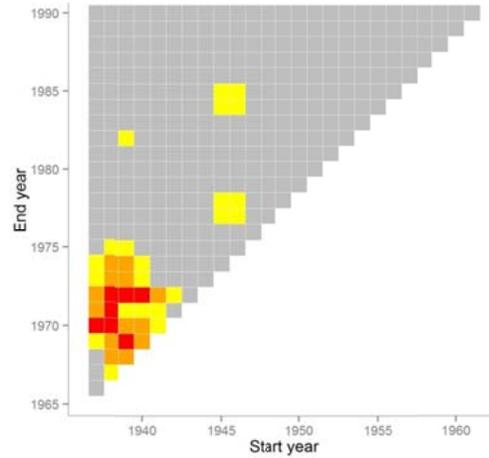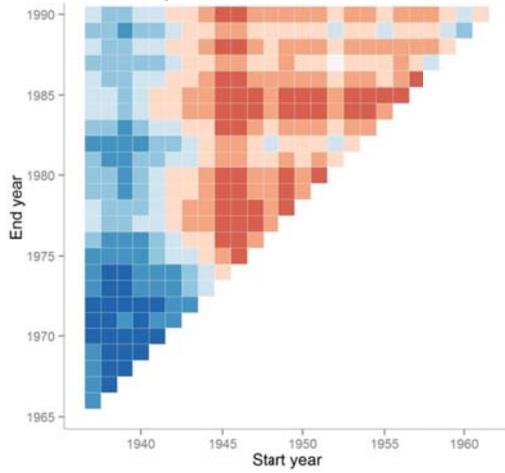
Total runoff Uste
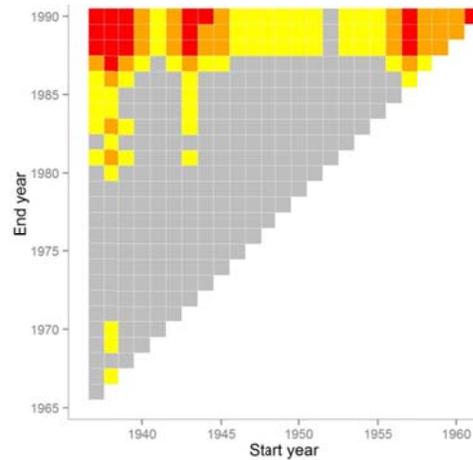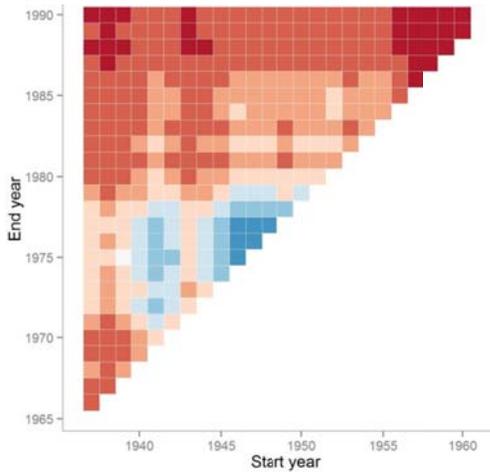
Summer runoff Uste (JJA)

70
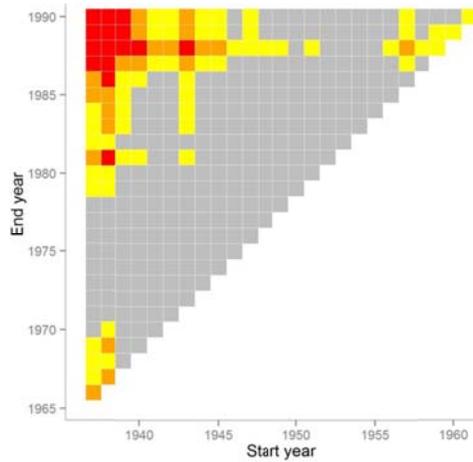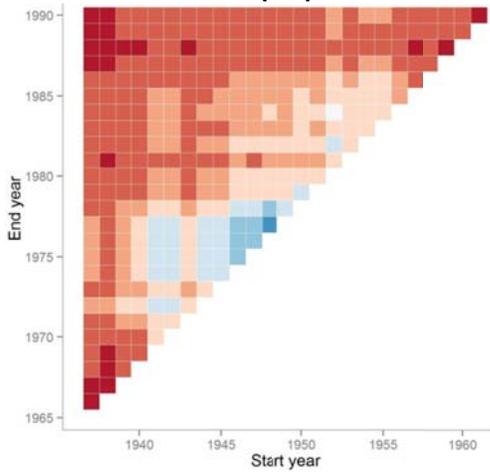
4. Climate data generation

We evaluated all available Global Circulation Model (GCM) runs for the two most extreme representative concentration pathways scenarios [14], RCPs 2.6 and 8.5, generated under the Climate Model Intercomparison Project CMIP5 [15] to cover the whole range of possible climatic changes [16]. Under the RCP 2.6 scenario, greenhouse gas emissions and emissions of air pollutants are reduced substantially over time. RCP 8.5 is characterized by increasing greenhouse gas emissions over time representative of scenarios leading to high greenhouse gas concentration levels. All GCM data were downloaded from http://cmip-pcmdi.llnl.gov/cmip5 (01/09/2013).

Downscaling of large-scale GCM output to a finer spatial resolution can be done either with dynamical or statistical approaches [17]. Whereas dynamical downscaling requires a higher resolution regional climate model (RCM) to be embedded within a GCM, statistical downscaling establishes empirical relationships between GCM-resolution climate variables and local climate.

We used the statistical "perturbation method" or "delta-change approach" [18-20], thus applying differences between the control and future GCM simulations to baseline observations by adding (temperature) or scaling (precipitation) the mean climatic change to each day. Following the method described in Huss et al. (2008), we use the daily variability of measured time series at Sabdan station and adapt their monthly means along the linear trend line between the standard WMO baseline period (1961-1990) and our future reference period (2081-2099). Using this technique, we obtain meteorological time series with the same resolution, characteristics and variance as in the past.

We then compared all RCP 2.6 and 8.5 GCM runs regarding changes in summer temperature and annual precipitation (mean 2081-2099 vs. 1961-1990; Fig. S3) and chose the four GCM runs which are closest to the 10th and 90th percentiles (Fig. S3), thus representing the range of dry-cold, dry-warm, wet-cold and wet-warm future climates [21,22].

Next page:

Fig. S3. Projected changes in climate at Sabdan station, Chon Kemin valley, according to RCPs 2.6 and 8.5 of the CMIP5 dataset. **a**, Changes in summer temperature and annual precipitation based on all GCM runs for 75-77.5°E and 40-45°N (baseline period 1961-1990 vs future period 2081-2099). The range between the 10th and 90th percentiles is shaded in grey. The four GCM runs closest to the percentiles have been chosen for runoff modeling. **b** and **c**, Time series of annual precipitation and summer temperature anomalies for Sabdan meteorological station relative to the 1961-1990 baseline period. The four scenarios represent the range of dry-cold, dry-warm, wet-cold and wet-warm future climates as displayed in Fig. 3a.
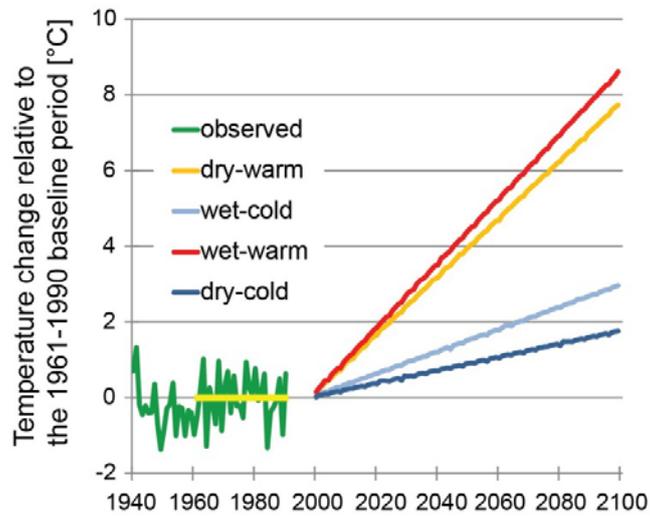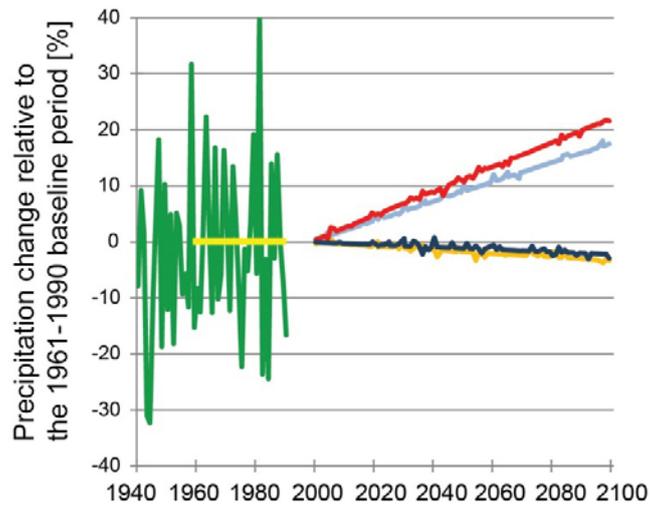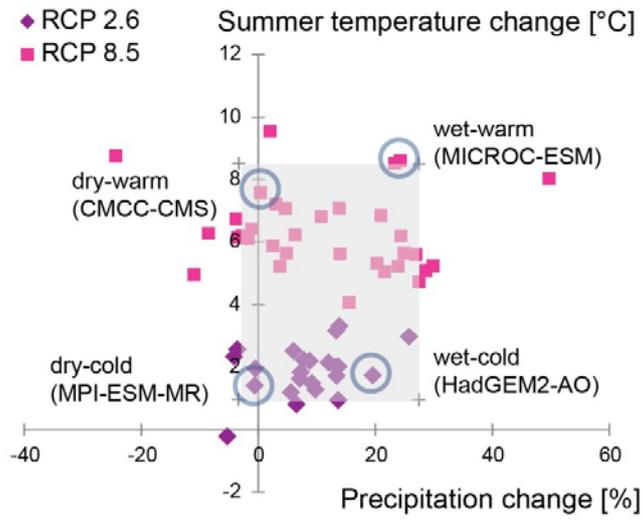
5. Glacier Evolution Runoff Model GERM

5.1 Calibration and validation procedure

Table S1. Multi-variable calibration of GERM developed for this study.

Parameter group	Criteria	Selection
Climate	Precipitation (4000 m asl)	values from Aizen et al. 2007 ± 10%
	Mean annual evaporation	
	Mean annual runoff	observed ± 10%
Melt	Daily snow cover	visual
	Annual snow cover	observed ± 10%
	Mass balance and ELA	
	Glacier area change	
Routing	Monthly runoff	NS > 0.8

Table S2. Key model parameters of GERM.

Description	Parameter	Value	Unit	Source / Calibrated
Climate parameters				
Precipitation gradient	dP/dz	4.3	%/100m	Bolch (2007)
Temperature gradient	dT/dz	-0.51	°C/100m	Bolch (2007)
Threshold snow / rain	T_{thres}	1.5	°C	Calibrated (range -1-2.5°C)
Actual / potential evaporation	F_{ET}	70-100	%	Calibrated
Snowdrift onto glacier	SD_{gl}	2	-	Calibrated
Melt parameters				
Physical parameter	C_0	-50	W m^{-2}	Calibrated
Physical parameter	C_1	10	W m^{-2}	Oerlemans (2001)
Albedo Ice	α_{ice}	0.35	-	Calibrated (range 0.3-0.5)
Albedo Firn	α_{firn}	0.55	-	Calibrated (range 0.5-0.6)
Albedo Snow	α_{snow}	0.75	-	Calibrated (range 0.7-0.9)
Routing parameters				
Retention slow reservoir	r_{slow}	350	days	Calibrated
Retention ice & firn	r_{ice}	15	days	Calibrated
Retention snow	r_{snow}	20	days	Calibrated
Retention rock	r_{rock}	25	days	Calibrated
Retention pasture	$r_{low\_vegetation}$	40	days	Calibrated
Retention forest	r_{forest}	55	days	Calibrated

Climate parameters

Precipitation was interpolated along a gradient of 4.3% per 100 meters, which corresponds to 31 mm per 100 meters as calculated by Bolch (2007). This gradient is in the range of other studies in the region [2,23]. Precipitation was assumed to increase gradually until the crestlines [2,24]. This results in interpolated precipitation of 934 mm a^{-1} at 4000 m above sea level, which corresponds well with the results of Aizen et al. (2007; ~950 mm a^{-1}). A threshold of 1.5°C with a linear transition range of ±1°C has been applied to distinguish between solid and liquid precipitation [25]. Similar to Kuhn (2003), we redistributed a constant fraction of snow fall (snowdist_gl = 2) within the basin from ice-free areas to areas covered by glaciers, as wind and avalanches tend to erode snow from ridges and steep slopes and deposit it in valleys and cirques [26,27]. This snowdrift leads to additional glacier accumulation and to reduced melting as a result of higher albedo for snow than ice.

Temperature was interpolated from Sabdan meteorological station using a gradient of -0.51% per 100 meters (Bolch 2007). This gradient is in the range of other studies in the region [24,28,29].

While potential evaporation can be much higher in arid Central Asia than in humid climates, actual evaporation is limited by the low water availability during dry summers [29]. An empirical evaporation model is implemented in GERM, which calculates daily potential evaporation based on air temperature and the saturation vapor pressure [19,30]. The model considers five surface types (snow, ice, rock, low vegetation and forest) and has an interception reservoir. Potential evaporation is reduced to actual evaporation for each surface type using a factor F_{ET} that includes a function accounting for the decrease of soil moisture. The parameters of the evaporation model are calibrated with the values given by Aizen et al. (2007) for the Chon Kemin valley. Modeled mean actual evaporation in the past (1955-1989) is 384 mm, which is in line with previous studies [31,32].

Melt parameters

Two melt models are implemented in GERM: an enhanced temperature-index melt model [33,34] and a simplified energy balance equation for net surface energy flux [19,35]. Latter approach is less sensitive to temperature changes [35,36], which renders it particularly adequate for modeling in arid regions like Central Asia and over long time periods with significant temperature increases. In the energy balance equation below, the first parenthetical expression represents the shortwave radiation balance and the second parenthetical expression represents long-wave radiation balance and turbulent exchanges:

$$\psi = \{ \tau \, (1\text{-}\alpha) \, Q_E \} + \{ c_0 + c_1 \, T \}$$

ψ daily mean surface energy flux (energy available for melting)

τ atmospheric transmission to solar irradiance (reduced incoming shortwave radiation due to cloudiness or haze)

α surface albedo for snow, ice and firn

Q_E clear-sky shortwave radiation (mean daily potential global radiation calculated from slope, aspect and topographic shading)

c_0 physical parameter ($10 \ W \ m^{-2}$, Oerlemans 2001)

c_1 physical parameter for parameter

The physical parameter c_1 was set to $10 \ W \ m^{-2} \ K^{-1}$ and c_0 was used as a tuning parameter [26,35,37]. Albedo had to be constrained for ice, firn and snow within the respective range of physical characteristics [38].

Routing parameters

The water available for runoff is determined daily at every grid cell by solving the water balance using the calculated quantities for liquid precipitation, melt and evaporation [19]. The runoff

routing model is based on the concept of linear storage, with an interception-, slow- and fast reservoir [19,39]. Liquid precipitation first enters the interception reservoir. When the surface-type dependent capacity is exceeded, it is routed into the slow reservoir, which represents subsurface runoff components. The water volume added to the slow reservoir depends on the filling level and on the maximum capacity of the slow reservoir [40]. When the maximum capacity of the slow reservoir is reached, water is routed into the fast reservoir, which represents direct and near-surface runoff components. All reservoirs are emptied at a reservoir-dependent retention constant.

5.2 Calibration and validation results

Annual discharge is well reproduced by the model (Fig. S4). Monthly simulated and observed discharge reach a Nash-Sutcliffe model efficiency coefficient of $E = 0.96$ [41], as shown in Fig. S5.
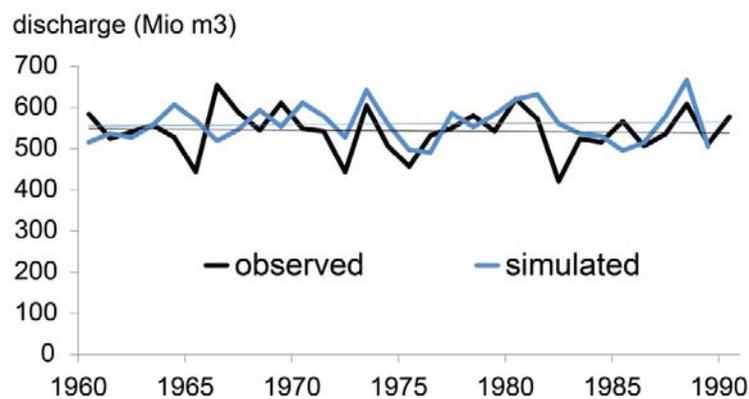
Fig. S4. Simulated and observed annual runoff at Karagai Bulak gauge (1959-1989).
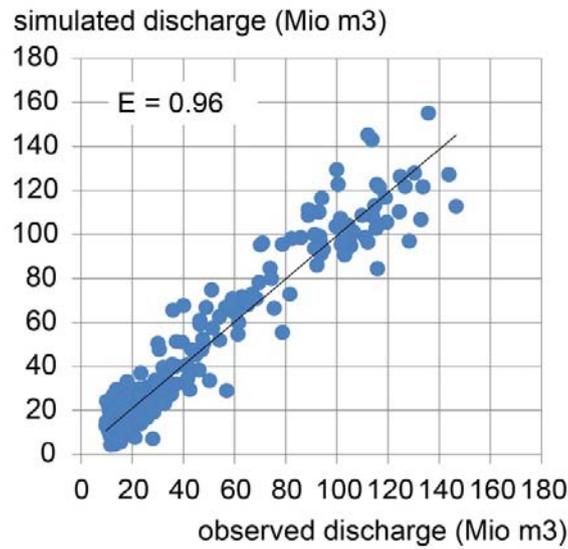
Fig. S5. Simulated and observed monthly runoff at Karagai Bulak gauge (1959-1989, with 1966-1977 excluded due to low quality of meteorological data). The Nash-Sutcliffe model efficiency criterion E is 0.96 [41].

Simulated daily snow cover also corresponds well to visible snow cover on six selected Landsat scenes in 1977 and 1979 (Fig. S6); seasonal accumulation and melting of snow are thus reproduced realistically by the model. Simulated snow cover is displayed with a threshold of 15 mm snow water equivalents, which corresponds to 50 mm snow depth at a snow density of 300 kg m^{-3}. The accumulation season at Tuyuksu Glacier typically starts at the end of August or beginning of September (21/08-22/09) and stops in middle June (02/06-24/06), which is well reproduced by the model [28,42,43].

	Simulated	Landsat
20.03.1979		
17.04.1977		
12.05.1979		
23.05.1977		
07.09.1977		

Snow water equivalent [mm]

	0 - 15		94 - 149
	16 - 20		150 - 204
	21 - 30		205 - 250
	31 - 45		251 - 300
	46 - 93		301 - 384
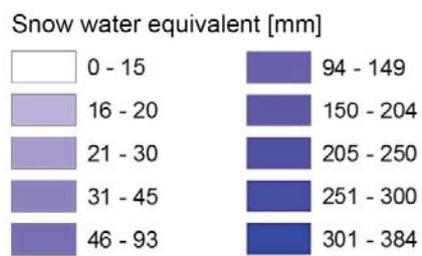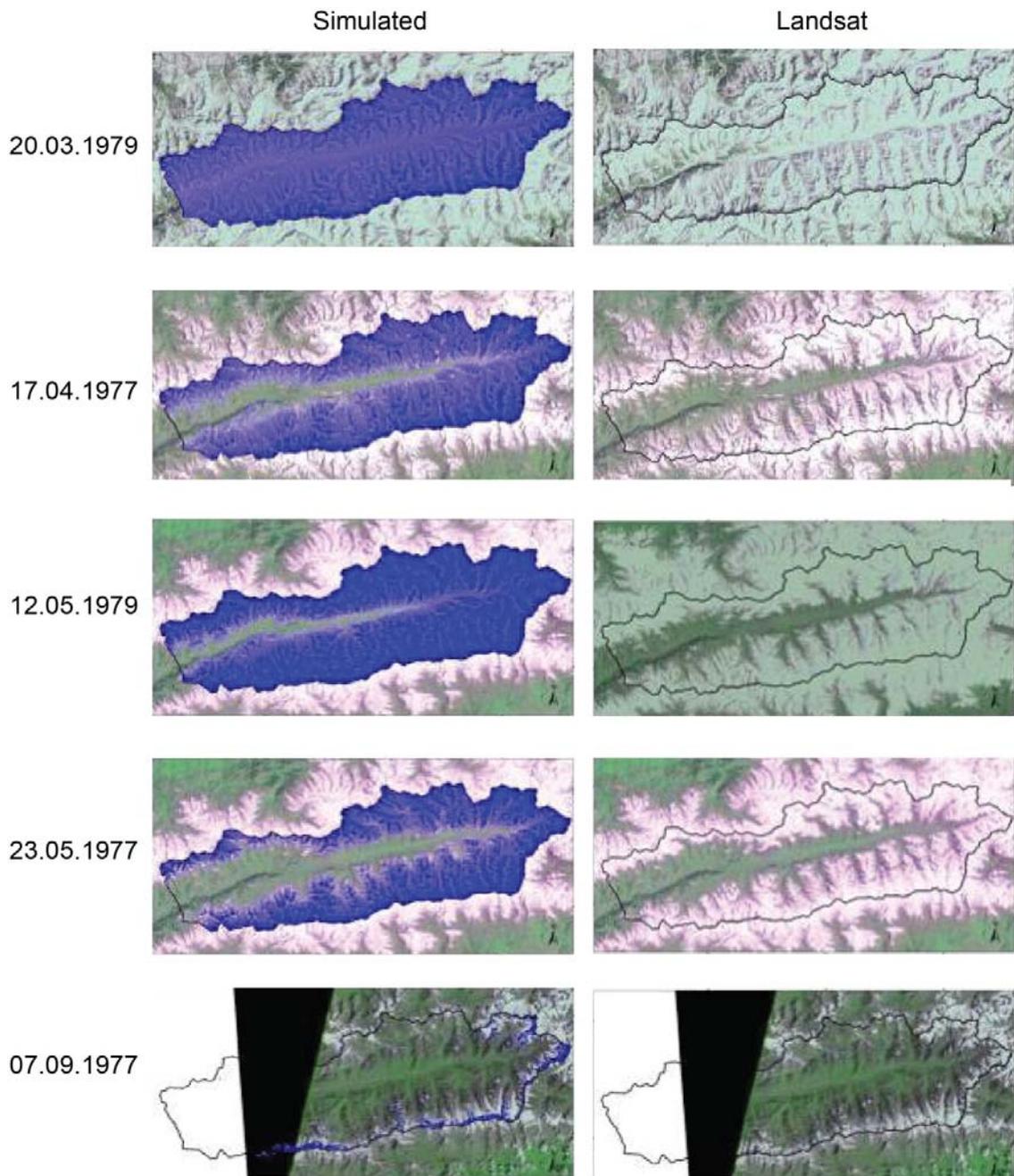
Fig. S6. Simulated and observed snow cover on six randomly chosen days in 1977 and 1979. Annual snow cover duration is simulated within a 10% range of observed values from AVHRR satellite image analysis (Table S3); snow-rich and snow-poor years are thus well distinguished and the altitudinal snow distribution is well reproduced by the model. Days with more than 91 mm simulated snow water equivalents have been counted for snow cover duration. This higher threshold for AVHRR satellite images as compared to Landsat satellite images is due to the different resolution of AVHRR images (1 km) and Landsat images (30 m). Altitudinal patterns are well represented by the model and years with long snow cover duration (e.g. 1986) are well distinguished from years with shorter snow cover duration (e.g. 1987). Simulated mean annual snow cover duration was always in the range of the observed value ± 10%, except in 1989, when snow cover duration was slightly overestimated.

Table S3. Simulated and observed annual snow cover duration in the Chon Kemin valley (1985-1989).

Snow cover duration [days]

Year	Observed mean	Observed ± 10%	Simulated mean
1985	186	168-205	189
1986	218	196-240	206
1987	166	149-182	181
1988	181	163-199	181
1989	179	161-197	149

Simulated mass balance and equilibrium line altitude (ELA) in the Chon Kemin valley show the same fluctuations at comparable levels as the series measured at Tuyuksu Glacier (Fig. S7). Simulated average ELA is 3875 m above sea level and thus corresponds to the previously assessed 3900 m above sea level in the Chon Kemin valley [42]. As a result of exposure to the North and the higher precipitation rate at Tuyuksu Glacier, ELA is slightly higher in the Chon Kemin valley than at Tuyuksu.
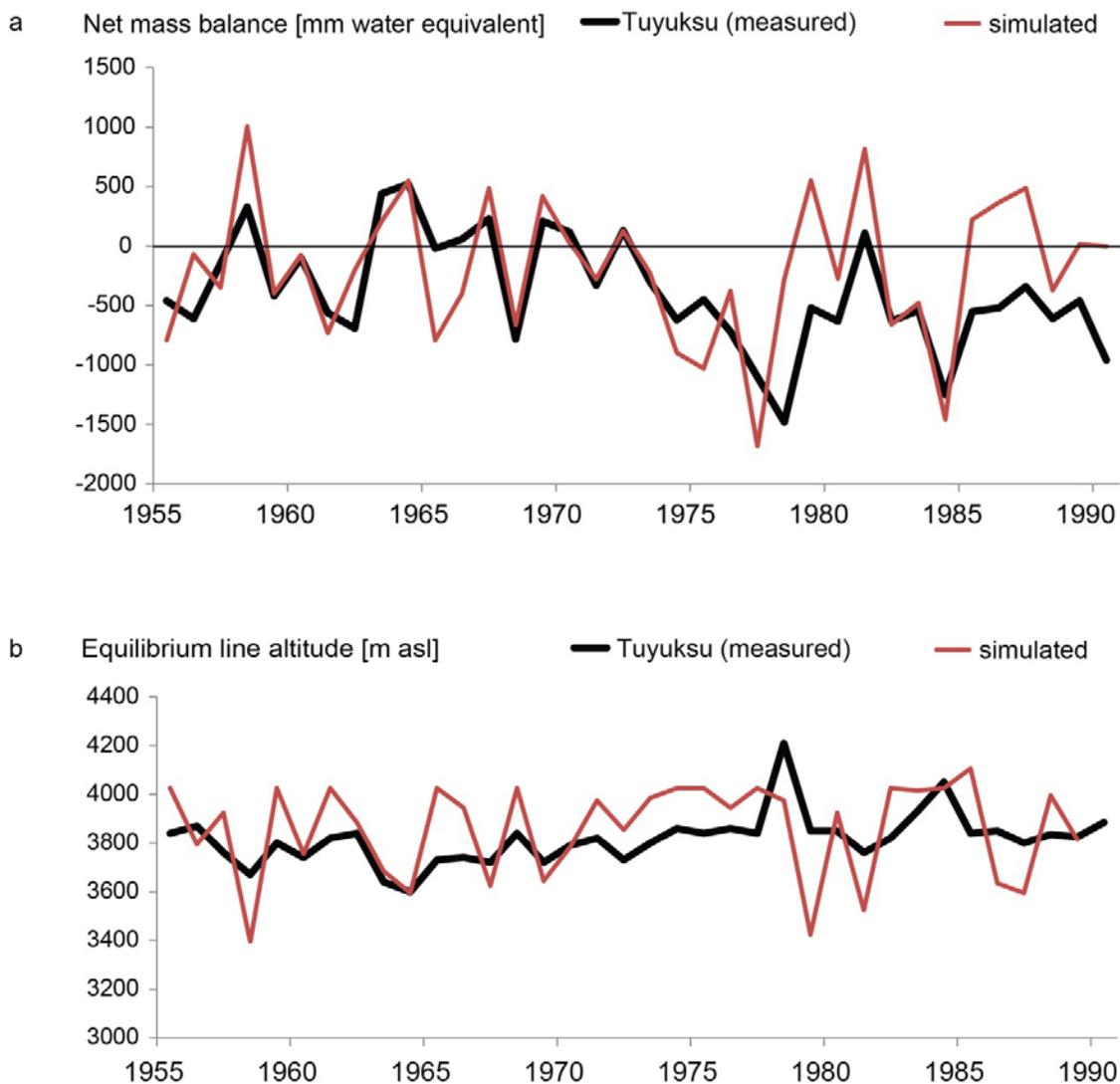
Fig. S7. Simulated and observed mass balance and equilibrium line altitude (ELA) between 1955 and 1990 in the Chon Kemin valley (simulated) and at Tuyuksu Glacier (measured).

The parameterization of glacier retreat is validated by comparing simulated with observed glacier shrinkage rates. The previously assessed annual shrinkage rate of 0.36% a^{-1} for the period 1955-1999 [1] is reproduced exactly by the model.

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Contrasting responses of Central Asian rock glaciers to global warming

Annina Sorg, Andreas Kääb, Andrea Roesch, Christof Bigler and Markus Stoffel

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Author affiliations

Annina Sorg*[1,2]

Andreas Kääb[3]

Andrea Roesch[2]

Christof Bigler[4]

Markus Stoffel[1,2,5]

[1] Climatic Change and Climate Impacts Group, Institute for Environmental Sciences (ISE), University of Geneva, Route de Drize 7, CH-1227 Carouge, Switzerland

[2] dendrolab.ch, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1+3, CH-3012 Berne, Switzerland

[3] Department of Geosciences, University of Oslo, P.O. Box 1047, N-0316 Oslo, Norway

[4] Institute of Terrestrial Ecosystems, Department of Environmental Systems Science, ETH Zurich, Universitätstrasse 16, CH-8092 Zürich, Switzerland

[5] Department of Earth Sciences, University of Geneva, Rue des Maraîchers 13, CH-1211 Geneva 4, Switzerland

* Corresponding author

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As glaciers in the arid Central Asian Tien Shan have experienced strong melting over the past decades[1,2], ice-rich permafrost bodies including over 1'000 rock glaciers[3] are receiving increased attention as potentially important freshwater resources. While the responses of Tien Shan glaciers, and glaciers elsewhere, to climatic changes are becoming increasingly well understood, this is not the case for permafrost in general and for rock glaciers in particular. We present here a novel approach 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 declassified and contemporary satellite imagery, we present the worldwide longest continuous record of rock glacier movements available today. We also demonstrate that the rock glaciers investigated exhibit synchronous periods of high and low activity at decadal timescales. Periods of enhanced activity coincide with warm summers, and the annual mass balance of the nearby Tuyuksu glacier fluctuates asynchronously with rock glacier activity. At multi-decadal timescales, however, the rock glaciers exhibit site-specific trends reflecting different stages of inactivation as a response to the strong increase in air temperature since the 1970s[4].

As a result of increasing air temperatures, glaciers in the arid Central Asian Tien Shan ranges have experienced strong melting over the past decades[1,2], with possible impacts on freshwater availability during the drier summer months. Ice-rich permafrost bodies could possibly compensate for the diminishing glacier waters, since they are assumed to store a similar amount of freshwater as the glaciers in the Tien Shan do[5,6]. A particularly important role in the regional hydrological cycle is hereby played by rock glaciers, frozen debris lobes that creep downslope

under gravity[7]. Rock glaciers typically contain between 20 and 80 vol% of ice[8] and are a widespread permafrost phenomenon in the Tien Shan; in northern Tien Shan alone (approximately 5'000 km^2), more than 1'000 rock glaciers have been inventoried[3].

Fragmental knowledge on long-term climatic impacts on rock glaciers

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 particular[3,5,8,9]. Geothermal observations have revealed a recent rise in permafrost temperature by 0.1 to 0.2°C a^{-1} and an active layer thickening of 0.77% a^{-1} (1974-2004, as measured at 3330 m asl at Zhusalykezen pass in Kazakhstan)[9]. Measurements of rock glacier front positions have started as early as 1923 in the Tien Shan[10] and exhibit high mean frontal advance rates of up to several meters per year, with an accelerating trend since the mid-1980s[3,5]. This trend is in line with observations of rock glaciers in the European Alps, which have significantly accelerated since the 1980s, probably in response to increasing permafrost temperatures[11]. Synchronicity of rock glacier activity as observed in the Alps[11], 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 temporal and spatial dimensions in the Tien Shan and in general, 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 aim

was to assess the response of rock glaciers to climate variability, and to test for regionally synchronous periods of high and low rock glacier activity in the Tien Shan.

The rock glaciers investigated are of (para-)glacial origin. As a peculiarity in regard to many other periglacial regions, rock glaciers in the Tien Shan tend to reach down below the tree line (**Fig. 1, Table S1**). All rock glacier fronts are located close to the zero-degree-isotherm of mean annual air temperature at around 2700 m asl[8], suggesting that the rock glacier bodies are only slightly below the freezing point, and thus of comparably low viscosity, fast moving and particularly sensitive even to minor changes in surface energy balance, such as induced by increasing temperatures[5,8]. The steep terminal fronts (>37°) with loose boulders and the "drunken trees" growing on the rock glaciers indirectly confirm the high activity of the investigated rock glaciers[7] (**Figs. S1-2**)

Novel dendrogeomorphic-photogrammetric approach

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 used the annual ratio between the number of reacting and the total number of sampled trees (I_t index[12]; **Figs. S4-7**) as a proxy of rock glacier activity. Effects of summer air temperature on rock glacier activity from 1895 to 2011 were quantified using distributed lag models[13]. The results were then complemented with displacement rates derived for each rock

glacier from four to five repeat aerial photographs from Soviet archives dating back to the year 1943, one declassified CORONA satellite image of around 1970, and one to three high-resolution, present-day satellite images (**Table S4**). Photogrammetric analyses were performed for a large set of visual features, including the location of sampled trees, and displacement rates were calculated over all periods using image cross-correlation[14,15] or manual identification where insufficient image quality prevented automatic matching.

Common signal of rock glacier responses to high summer temperatures

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 rock glacier movements implies that internal and topographic characteristics are superimposed by an external driver, decadal climate variations in the present case[16]. Increasing summer (JJA) air temperatures resulted in increasing rock glacier activity as shown by the high I_t indices at annual (**Fig. S9**) and decadal timescales (**Fig. 2).** The highest summer air temperatures (25.3°C) increased the likelihood of growth anomalies of trees growing on Ordzhonikidze rock glacier by 2.9 times (95% confidence interval: 1.5 to 5.7 times) and on Turgen Aksu rock glacier by 4.6 times (2.0 to 10.6 times) compared to the lowest summer air temperatures (19.4°C). Weaker effects were found at temperatures below 25.3°C and at lags of one year or more (**Fig. S9**). No significant effects were found for Karakorum and Kugalan Tash rock glaciers, probably as a result of the low sample sizes (**Tables S2 and S3**). A link between rock glacier activity and seasonal snow cover duration and -depth[17] or with seismic activity[18], as suggested by other authors, cannot be confirmed.

The rock glacier movements are also in line with annual mass balance data from the nearby Tuyuksu glacier, which fluctuates asynchronously with rock glacier activity (**Fig. 2**). In other words, when Tuyuksu glacier loses mass, rock glacier movements are on the rise, thus confirming indirectly the predominant role of summer air temperature on rock glacier activity in the Tien Shan. Ground ice temperatures have previously been shown to increase in periods with warm summers, thereby reducing ice viscosity and increasing water percolation and related heat advection[11,17]. At the same time, however, the link between glacier mass balance – as a proxy for summer temperature – and rock glacier activity has never before been assessed in such detail and on such a long timescale.

Long-term trends of rock glacier activity

At multi-decadal timescales, the rock glacier fronts under investigation exhibit contrasting trends (**Figs. 3 and S10**). The increase in air temperatures since the 1970s[4] has most likely triggered increasing movement rates at Karakorum rock glacier, as evidenced by tree-ring records and photogrammetric displacements (**Figs. 4 and S11**), but no clear increases in movement rates (**Figs. S12-14**) or growth anomalies (**Fig. S8**) at the other sites, except for the upper part of Ordzhonikidze rock glacier (**Fig. S13**). These long-term trends most likely reflect the different phases of rock glacier response to the strong increase in air temperature, and illustrate 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[16].

The first phase (or speed-up) applies to Karakorum rock glacier, as growth anomalies in trees have become increasingly frequent since the year 2000, with the highest activity assessed in 2007 (**Fig. S4**), and annual surface velocity rates are high. In the lowest part of the rock glacier,

movement rates have significantly increased from 2.8 ± 0.5 m a[-1] (1964-1971; mean values ± standard deviation) to 4.2 ± 0.5 m a[-1] (2001-2009; **Fig. S11**). The steep frontal slope and the rapidly changing surface geometry of the rock glacier snout from compression further confirm that the lower part and the frontal scarp of Karakorum rock glacier have been speeding up after a surface rupture in summer 1985[3].

The second phase (or inactivation) has most likely already started at Ordzhonikidze, Turgen Aksu and Kugalan Tash rock glaciers, where trees are recording decreasing amounts of growth anomalies (**Figs. S5-8**), in particular since the 1980s, and where horizontal velocity displacement rates in the lowest parts have shown no statistically significant change (**Figs. S12-14**). Velocity rates are considerably lower than at Karakorum rock glacier, with 0.8 ± 0.4 m a[-1] on Ordzhonikidze (1966-2013), 0.4 ± 0.2 m a[-1] on Turgen Aksu (1943-2012) and 1.4 ± 0.3 m a[-1] on Kugalan Tash (1956-2012), respectively. The decreasing activity rates as from tree rings, or constantly low displacement rates as from image analysis, seem to be a combined effect of topographic inactivation – all investigated rock glaciers have reached the valley bottom –, of dynamic inactivation from insufficient debris supply, and of a shrinking ice core in the lower areas of the rock glaciers, where the lower limit of sporadic permafrost is reached[8].

Conclusion

The decadal-scale activity of the four observed rock glaciers shows a synchronous and direct reaction to variations in summer air temperature. This 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[11].

On multi-decadal scales, the different trends of surface velocities among and within the rock glaciers reflect different site-specific conditions. The different phases of rock glacier reaction to the rise in atmospheric warming are best illustrated on Ordzhonikidze rock glacier (**Fig. S13**), where surface velocity has been steadily increasing since the 1950s in the uppermost – and thus coldest – part of the rock glacier. This is probably a result of enhanced viscosity due to increasing ice temperatures and water percolation. In the middle part of Ordzhonikidze rock glacier, surface velocity has increased between the 1950s and the 1980s and is since then decreasing, probably as a result of the shrinking ice core and a consequently thickening active layer, which reduces the sensitivity to short-term variations in surface 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 established a while ago.

Outlook

Permafrost bodies and glaciers in the Tien Shan likely store a comparable amount of freshwater[5,6] and exhibit similar seasonal and diurnal discharge patterns, although runoff from rock glaciers is generally lower and fluctuates less due to the insulating debris layer[19,20]. Nevertheless, rock glaciers can contribute significantly to overall freshwater availability during dry summers and can exacerbate extreme flood peaks during thunderstorms when warm rain infiltrates into the frozen debris layer[19]. 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 Zhasyk 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 potential from degrading rock glaciers such as slope instability and debris flows[20-22].

Methods

Dendrogeomorphology

More than 40 years ago, the principles of dendrochronology were further developed to include the dating of geomorphic events, thus establishing the principles of dendrogeomorphology[23]. While the dendrogeomorphic approach has been widely applied in the field of natural hazards[24], the lack of trees at high elevations, namely in permafrost regions, has so far limited its application in rock glacier research to a few studies[12,21,25,26].

The principal idea behind the dendrogeomorphic approach in a periglacial context is that trees growing on rock glaciers will react to unstable growing conditions from pronounced rock glacier activity with the formation of growth anomalies. Horizontal forces in the shallow root zone can result in tree tilting ("drunken forest"[25]) and thus initiate the formation of compression wood, but also lead to the (partial) destruction of the root plate and thus induce a strong growth reduction. The burial of the tree stem base may lead to abrupt growth suppression as well. All these reactions can be dated with annual or even seasonal resolution.

We followed standard dendrogeomorphic field methods[27] to collect and prepare increment cores and cross-sections from 30 junipers (*Juniperus* sp.) and 250 Tien Shan spruces (*Picea*

shrenkiana (Fish. & 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[28] 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. S8**) 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_t index[12] as the ratio between the number of trees showing a reaction (R_t) and the total number of sampled trees (A_t) on a rock glacier in any given year (t):

$$I_t = \frac{R_t}{A_t} \times 100\% \tag{1}$$

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 assessed from above- and below-average values of the 5-year running mean of the I_t indices[25,26].

Effects of summer (JJA) air temperature on rock glacier activity from 1895 to 2011 were quantified using distributed lag models[13]. 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:

$$f(A_t; R_t; p_t) = \binom{A_t}{R_t} \times p_t^{R_t} \times (1 - p_t)^{A_t - R_t} \tag{2}$$

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

$$ln\left(\frac{p_t}{1-p_t}\right) = \text{intercept} + \sum_{k=0}^{5} ns(st_{t-k}; 2 \text{ df}) + ns(\text{year}; 7 \text{ df}) \tag{3}$$

where ln is the natural logarithm and $\frac{p_t}{1-p_t}$ 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 (st) 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"[29] (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.

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[30]. With the help of moving time windows, the multiple trend tests were computed for the I_t indices 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.

Photogrammetry

Contemporary high-resolution satellite images with spatial resolutions between 0.5 – 1m for all four sites were co-registered, if more than one was available for a site, and orthorectified using the ASTER Global DEM (tests with Shuttle Radar Topography Mission DEM have also been performed) and UTM projection. Based on these master orthoimages, the Soviet era airphotos and the 1970s Corona declassified satellite photos were oriented and rectified using rational function models based on 40-50 control points each. The resulting orthoimages have spatial resolutions of 0.5 to 2 m. 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[14,15], 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 ASTER GDEM inaccuracies. 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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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 and paper writing process.

Competing Financial Interests statement

The authors declare no competing financial interests.

Figures

Fig. 1 ¦ Overview of the study sites and sampled trees. a. Location of Karakorum, Kugalan Tash, Ordzhonikidze and Turgen Aksu rock glaciers in the Kyrgyz and Kazakh parts of the Tien Shan. **b.** Forested terminus of Ordzhonikidze rock glacier. **c.** Disturbed tree on the frontal slope of Ordzhonikidze rock glacier.

Fig. 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_t 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.

Fig. 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 (τ) and significance levels (two-sided p-values) for different start and end years and a minimum period of 30 years.

Fig. 4 ¦ Activity of Karakorum rock glacier (1964-2009). 5-year-running-mean of I_t Index from dendrogeomorphic analysis (red) and average velocities in the lower part of the rock glacier from photogrammetric analysis (blue; 1σ confidence interval in grey).
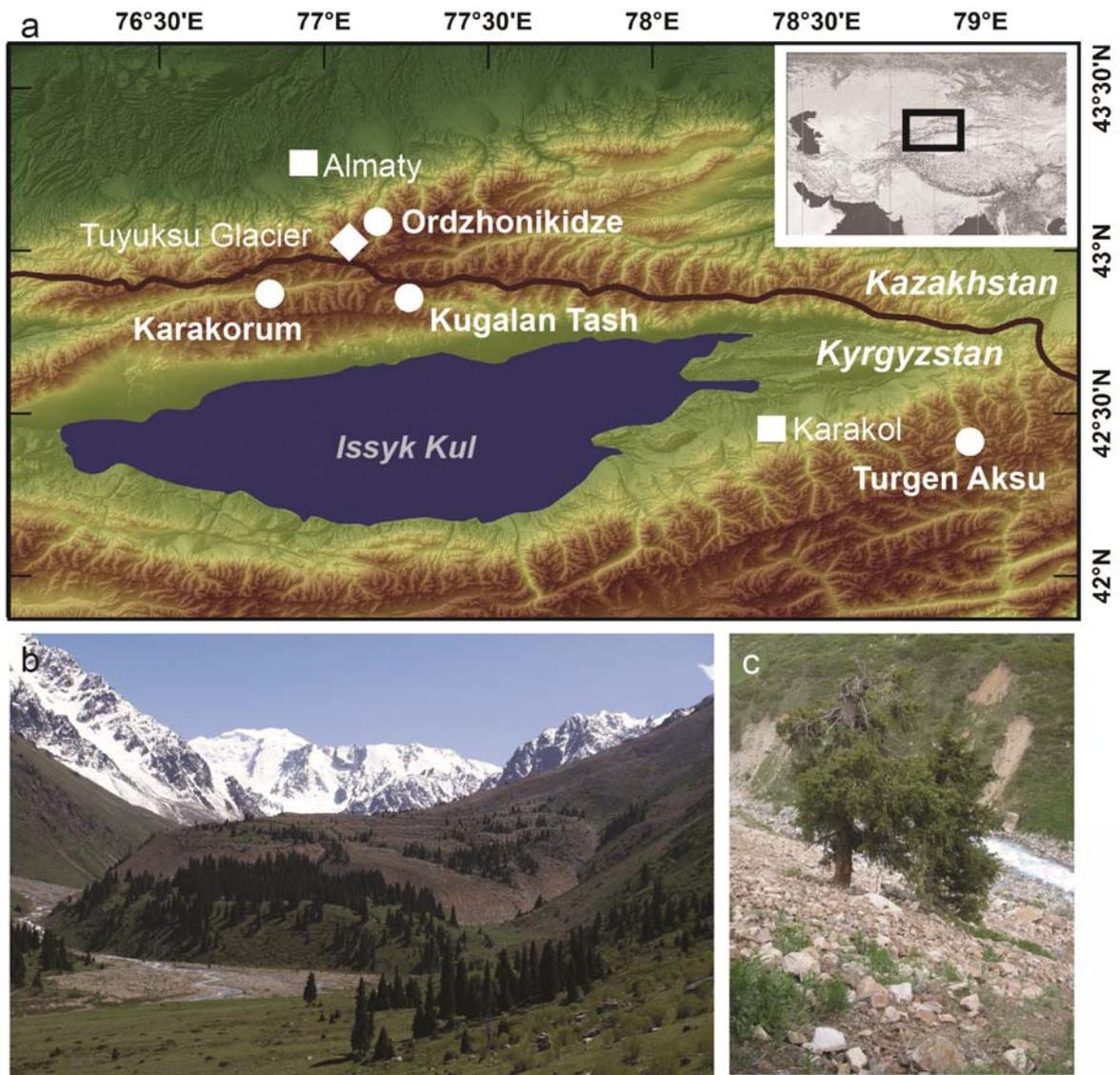
Figure 1
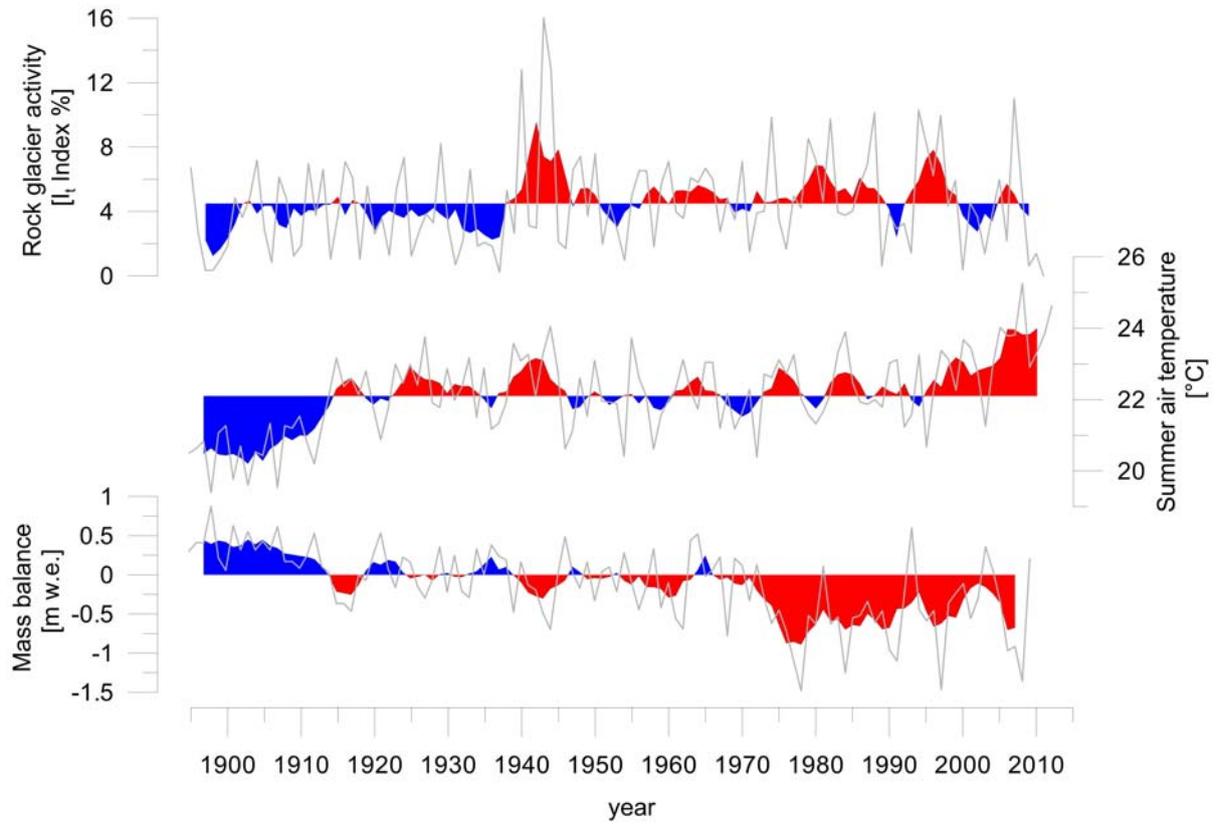
Figure 2
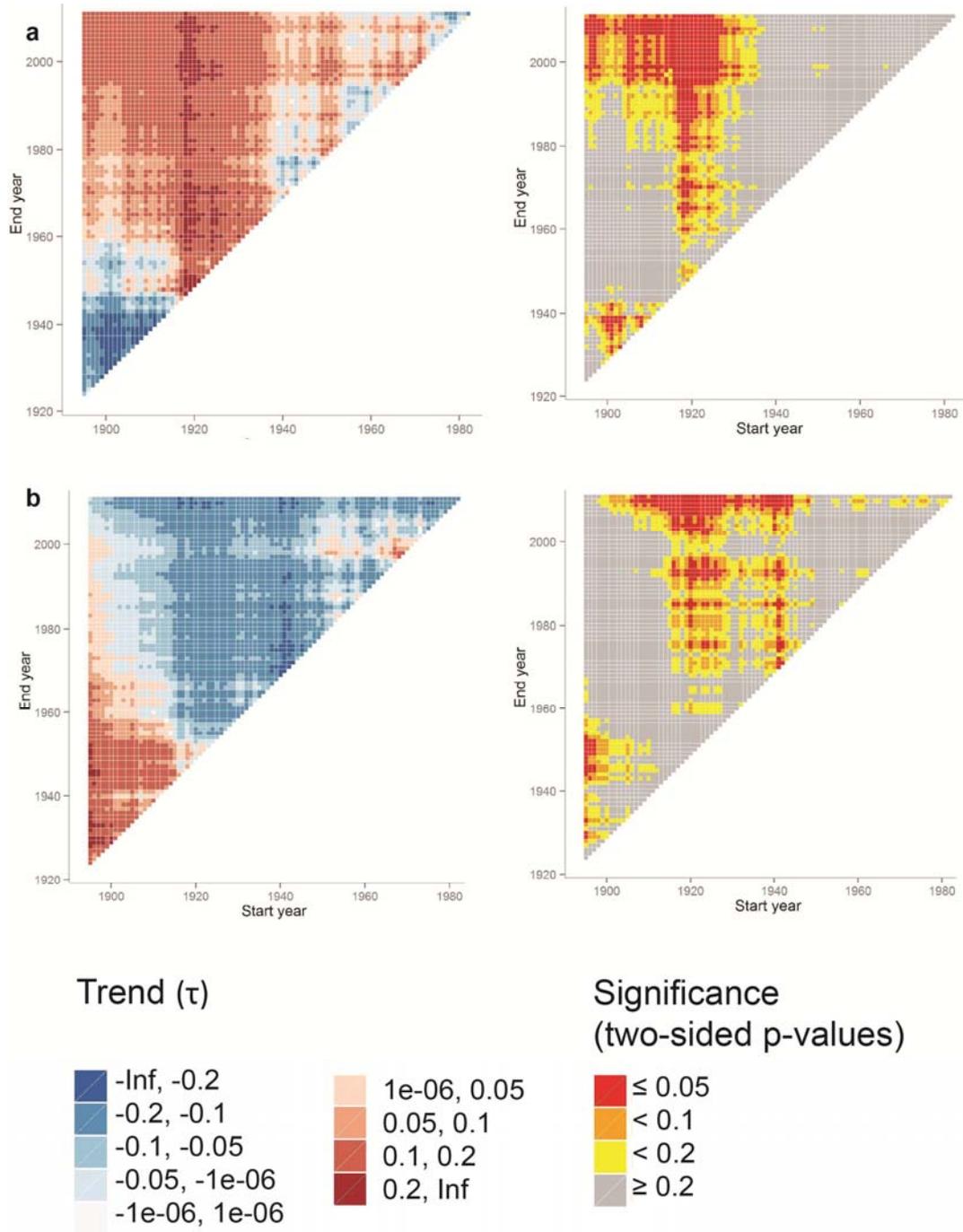
Figure 3
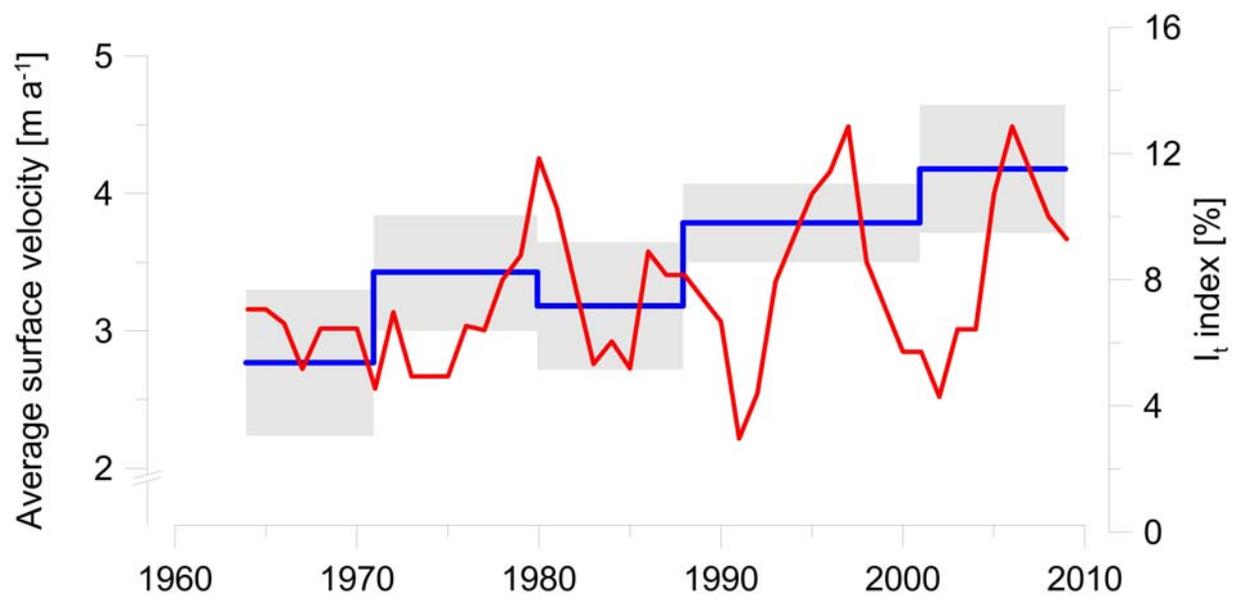
Figure 4

Contrasting responses of Central Asian rock glaciers to global warming

Supplementary Information

Annina Sorg*[1,2], Andreas Kääb[3], Andrea Roesch[2], Christof Bigler[4] and Markus Stoffel[1,2,5]

[1] Climatic Change and Climate Impacts Group, Institute for Environmental Sciences (ISE), University of Geneva, Route de Drize 7, CH-1227 Carouge, Switzerland

[2] dendrolab.ch, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1+3, CH-3012 Berne, Switzerland

[3] Department of Geosciences, University of Oslo, P.O. Box 1047, N-0316 Oslo, Norway

[4] Institute of Terrestrial Ecosystems, Department of Environmental Systems Science, ETH Zurich, Universitätstrasse 16, CH-8092 Zürich, Switzerland

[5] Department of Earth Sciences, University of Geneva, Rue des Maraîchers 13, CH-1211 Geneva 4, Switzerland

1. Study sites

Many rock glaciers in the Tien Shan have developed during the Holocene; their formation is likely to be associated with high rates of debris accumulation during phases of glacier retreat[1]. All investigated rock glaciers emanate from cirques with small residual glaciers at altitudes between 3300 and 3800 m asl (Table S1), where they have been overwhelmed and depressed during Little Ice Age glacier advances[2]. The steep cirque walls and lateral slopes supply the debris for the rock glaciers[3], which consist mainly of weathering-prone coarse-crystalline granite, schists and, in the case of Karakorum rock glacier, Cambrian gneisses[1,3,4]. The steep terminal fronts (>38°; Fig. S1) with loose boulders and the "drunken trees" (Fig. S2) growing on the rock glaciers indicate that the investigated rock glaciers are highly active[4-6]:

2. Data

Climate data

Time series of temperature, precipitation and snow depth were available in daily resolution from Almaty station (43.23°N, 76.93°E, 851m asl, ECA station code 3289; Fig. 1) for the time period 1891-2011 (temperature and precipitation) and 1924-1995 (snow depth). The data were downloaded from the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (http://climexp.knmi.nl).

Mass balance

Mass balance has been assessed since 1957 at Tuyuksu glacier, which makes this data set the longest mass balance series in Central Asia. The mass balance data were made available through the World Glacier Monitoring Service[7], the original author is P. A. Cherkasov. For the period 1895-1957, we relied on reconstructed mass balance of Tuyuksu glacier[8-10].

Earthquakes

We analysed all documented earthquakes with a magnitude higher than 5 and with an epicenter within a 200 km radius around 43°N / 77°E since 1895. The data were downloaded from the U.S. Geological survey earthquake data base (www.earthquake.usgs.gov: Significant Earthquakes World Wide (NOAA) and Historical & Preliminary Data (PDE) catalogs).

Aerial photographs and satellite imagery

All aerial photographs used in this study were provided by the Institute of Geology of the National Academy of Sciences of the Kyrgyz Republic and the State Mapping and Geodetic Service of the Kyrgyz Republic. The Corona declassified satellite photos were obtained from the US Geological Survey (www.earthexplorer.usgs.gov). The contemporary commercial high-resolution satellite images stem from DigitalGlobe and their sensors Ikonos, Quickbird, GeoEye, WorldView-1 and WorldView-2. The availability of aerial photographs and satellite imagery is shown in Table S4.

4. Supplementary tables

Table S1 ¦ Characteristics of the investigated rock glaciers.

	Coordinates	Elevation (m asl)	Area (km^2)	Aspect
Karakorum	42°52´N / 76°50´E	2650-3500	1.4	N
Kugalan Tash	47°46´N / 78°49´E	2970-3800	1.5	S
Ordzhonikidze	43°04´N / 77°09´E	2720-3500	2.9	NE
Turgen Aksu	42°25´N / 78°57´E	2800-3300	0.3	N

Table S2 ¦ Number of sampled Tien Shan spruces (*Picea shrenkiana* (Fish. & C.A. Mey.) subsp. *tianshanica* (Rupr.)) and junipers (*Juniperus* sp.) and dates of innermost tree ring of oldest trees on the investigated rock glaciers.

Rock glacier	*Picea shrenkiana*	*Juniperus sp.*	Innermost year of oldest tree
Karakorum	28	-	1856
Kugalan Tash	-	16	1687
Ordzhonikidze	180	-	1577
Turgen Aksu	73	4	1581

Table S3 ¦ Number of of growth anomalies on the investigated rock glaciers (percentages in brackets). trd: traumatic resin ducts; cw: compression wood; gs: growth suppression; gr: growth release; i: injury; ct: callous tissue.

Rock glacier	trd	cw	gs	gr	i	ct	total
Karakorum	9 (7)	14 (11)	78 (58)	31 (23)	-	1 (1)	133
Kugalan Tash	-	-	14 (45)	17 (55)	-	-	31
Ordzhonikidze	225 (25)	159 (18)	229 (27)	142 (16)	18 (2)	110 (12)	883
Turgen Aksu	32 (8)	11 (3)	208 (50)	151 (37)	2 (-)	8 (2)	412

Table S4 ¦ Aerial and satellite images of the investigated rock glaciers used for this study.
A: aerial photograph, C: Corona satellite photo, S: contemporary satellite image.

Year	Karakorum	Kugalan Tash	Ordzhonikidze	Turgen Aksu
1943				A
1953			A	
1956		A		
1964	A			
1966			A	
1968				C
1971	C	C	C	
1973		A		
1976				A
1977	A			
1980	A	A		
1981				A
1985	A		A	
1988	A	A		
2001	S			S
2004		A		A
2008	S			
2009	S		S	
2012		S		S
2013			S	

5. Supplementary figures
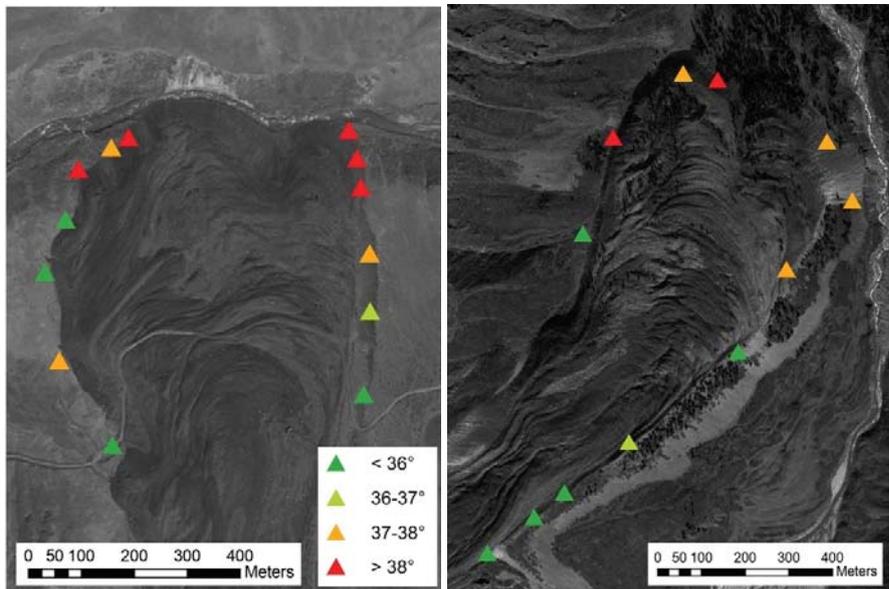
Fig. S1 ¦ Frontal slopes of Karakorum (left) and Ordzhonikidze rock glaciers (right).
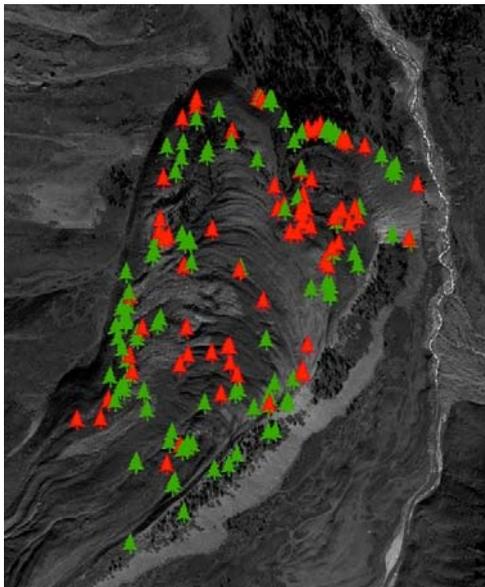
Fig. S2 ¦ Tilting direction of "drunken trees" on Ordzhonikidze rock glacier. Trees growing in the center of the rock glacier tend to be tilted backwards (upslope; red), whereas trees at the edge tend to bend away from the rock glacier (downslope; green).
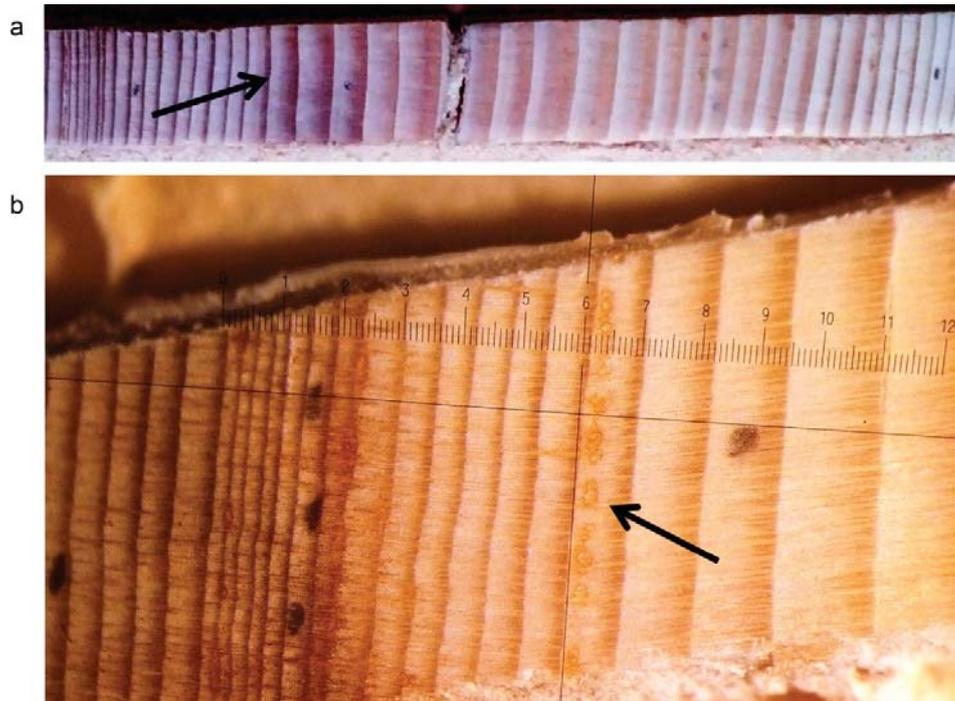
Fig. S3 ¦ Two typical reactions of disturbed trees on rock glaciers as observed on Ordzhonikidze rock glacier. **a**. Onset of compression wood after tilting of the tree. **b**. Formation of traumatic resin ducts after an injury from rockfall.
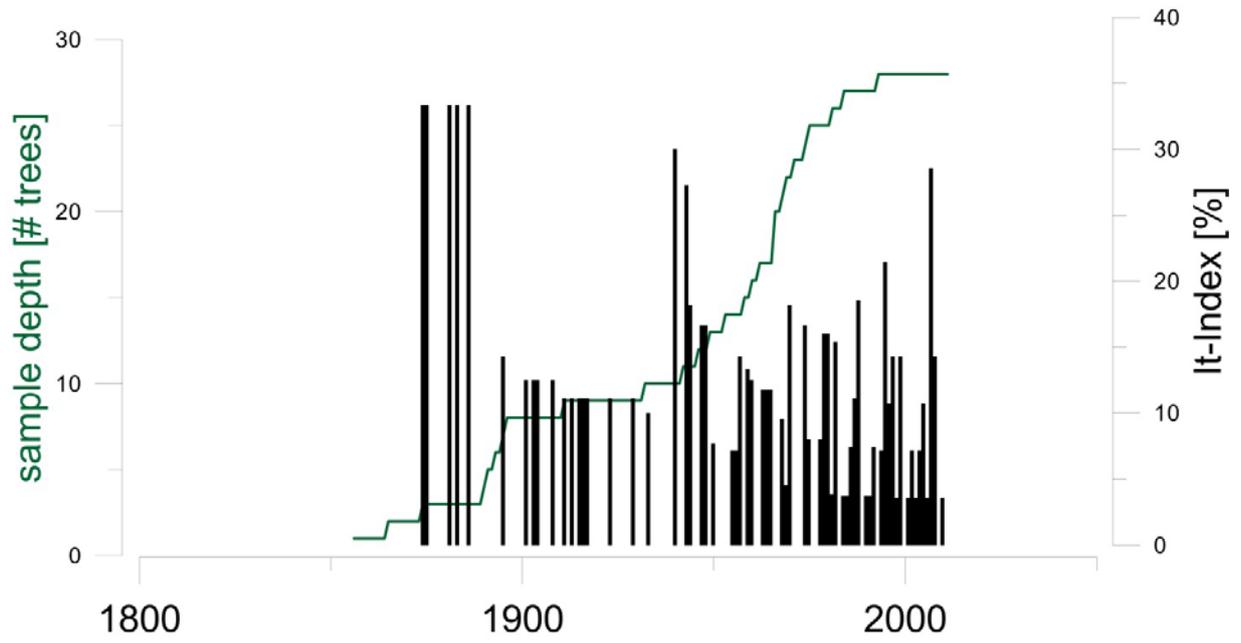
Fig. S4 ¦ Sample depth and I_t index for Karakorum rock glacier.
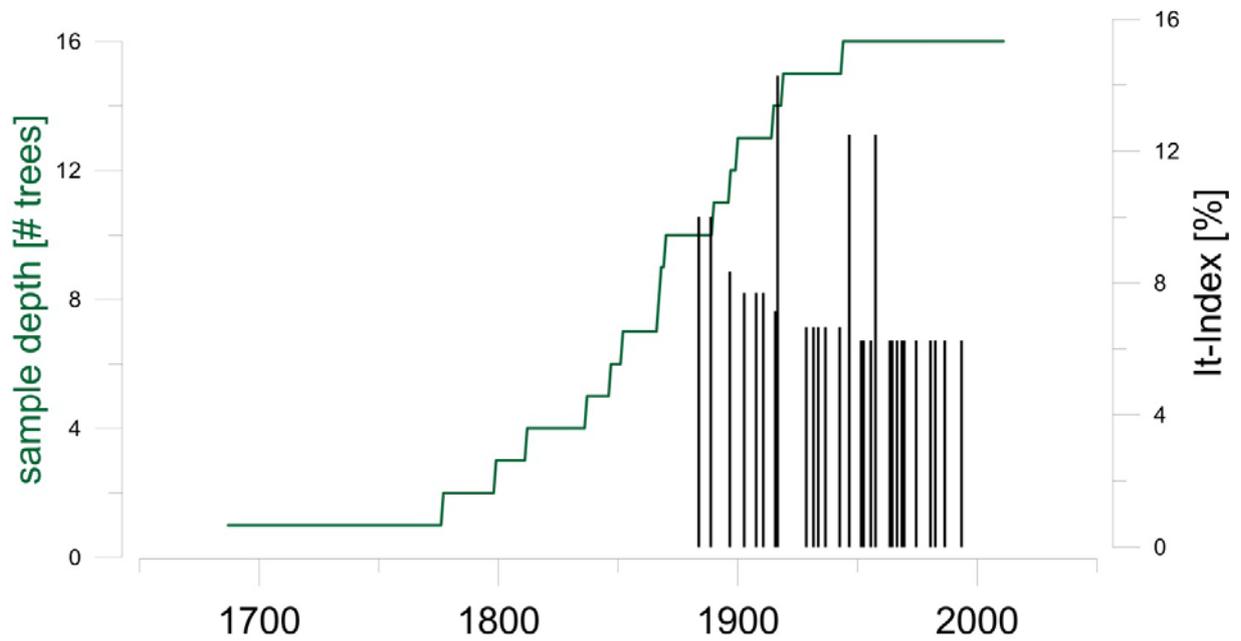
**Fig. S5** ¦ Sample depth and I_t index for Kugalan Tash rock glacier.

118
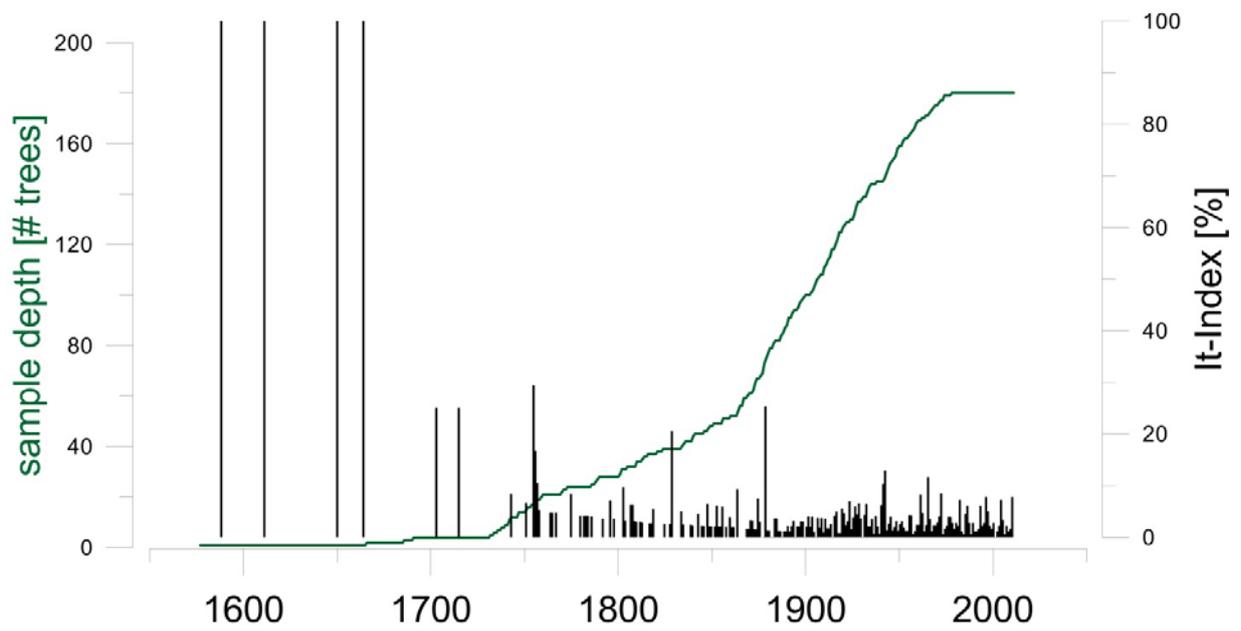
Fig. S6 ¦ Sample depth and I_t index for Ordzhonikidze rock glacier.
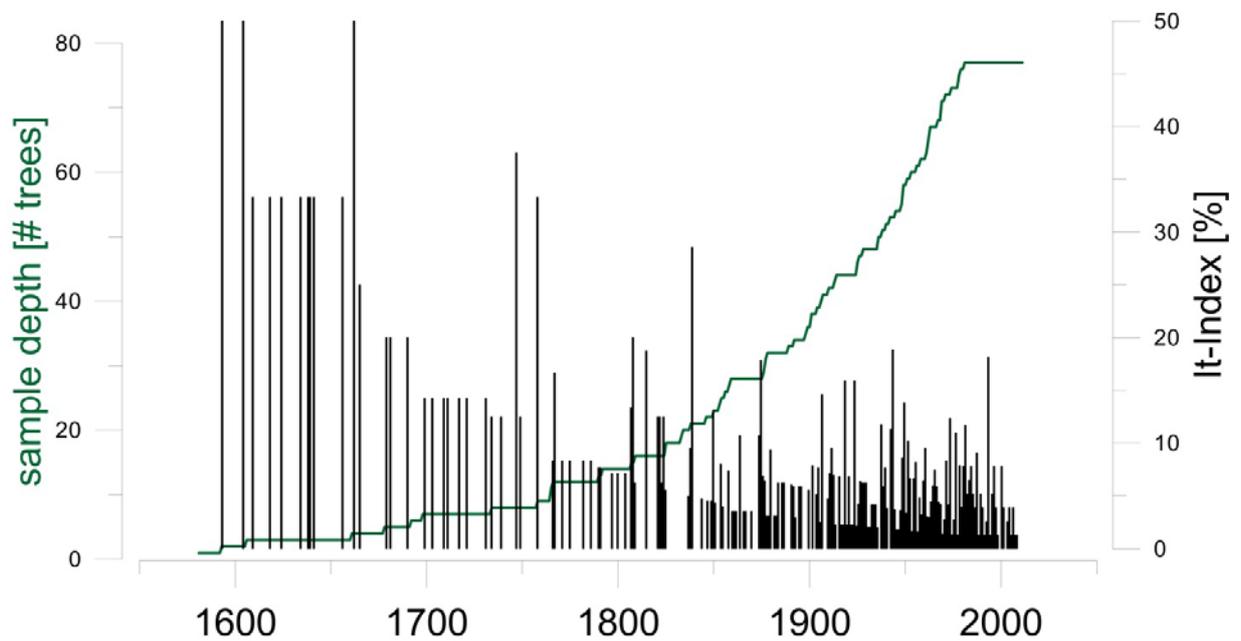
Fig. S7 ¦ Sample depth and I_t index for Turgen Aksu rock glacier.
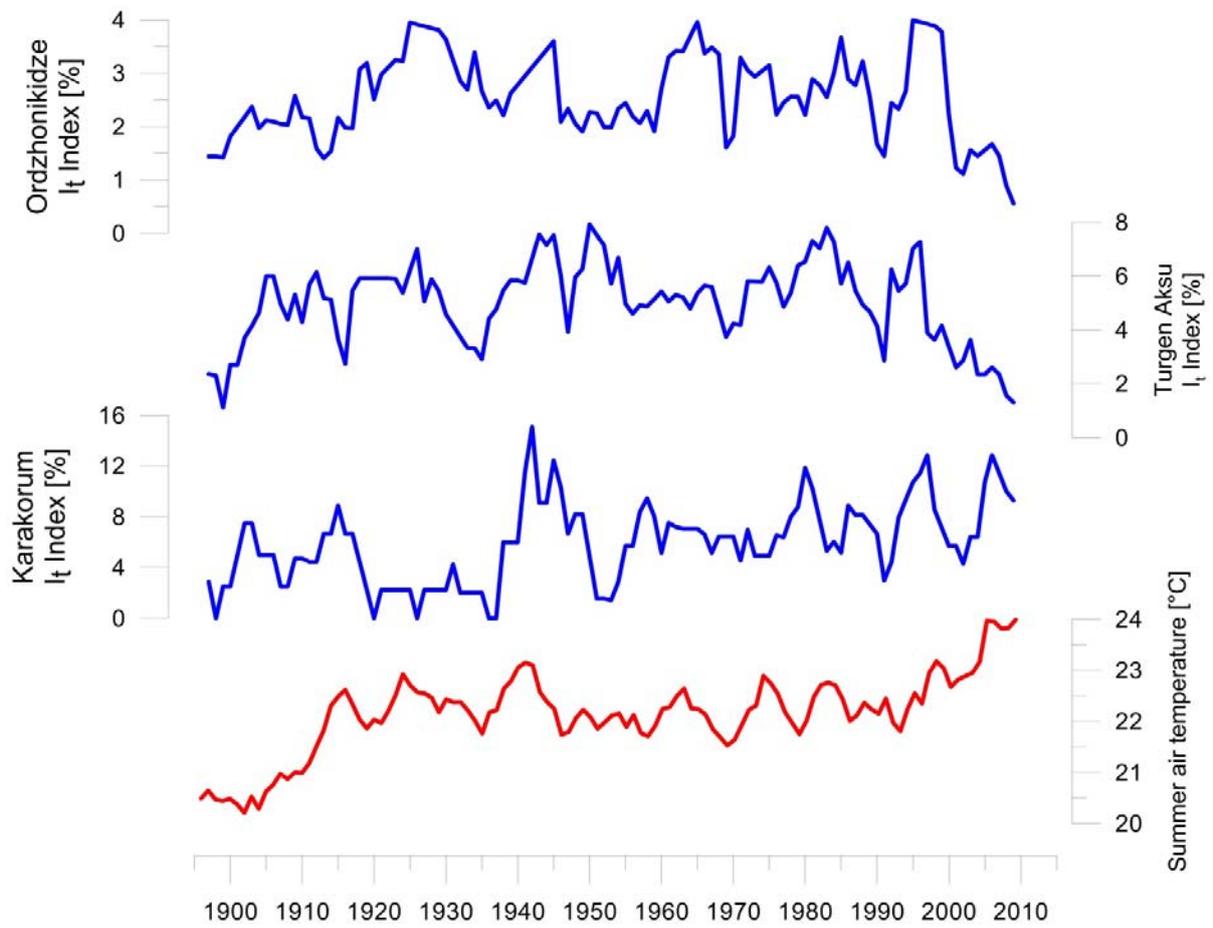
Fig. S8 ¦ I$_t$ indices of, Ordzhonikidze, Turgen Aksu and Karakorum rock glaciers and summer air temperatures (JJA) in Almaty (1895-2011; 5-year-running-means). Kugalan rock glacier is not shown due to the limited sample size.
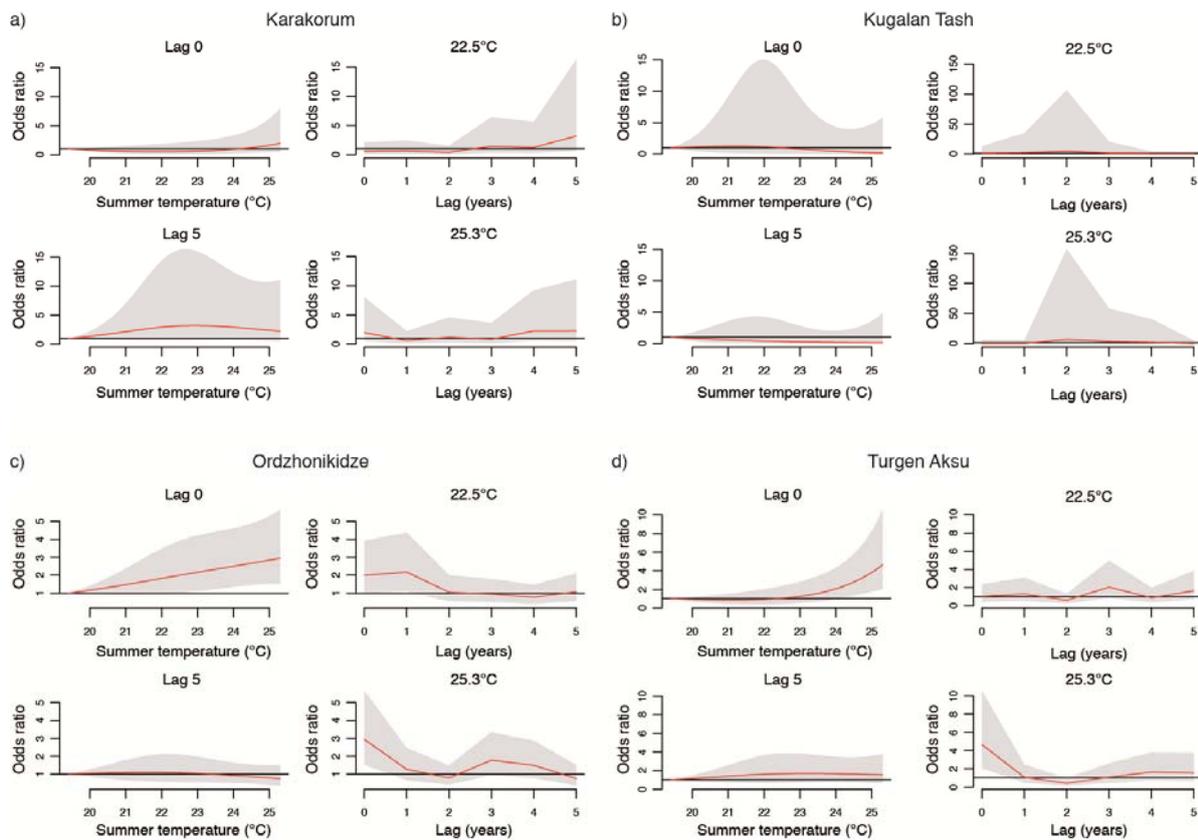
Fig. S9 ¦ Effects of summer temperature on rock glacier activity (1895-2011) shown for a) Karakorum; b) Kugalan Tash; c) Ordzhonikidze; and d) Turgen Aksu rock glaciers. On the left, odds ratios from the distributed lag models (equation 3; expected value: red line; 95% confidence interval: gray shading) are shown at fixed lags (0 and 5 years) and for varying summer temperatures. On the right, odds ratios for fixed summer temperatures (22.5°C and 25.3°C) and varying lags are shown. Odds ratios were calculated in comparison to the lowest summer temperature (19.4°C) observed in the series. Note the different scales of the y axes.
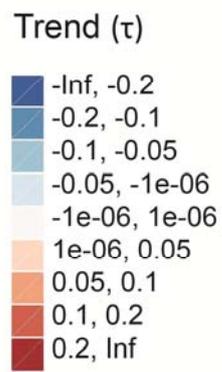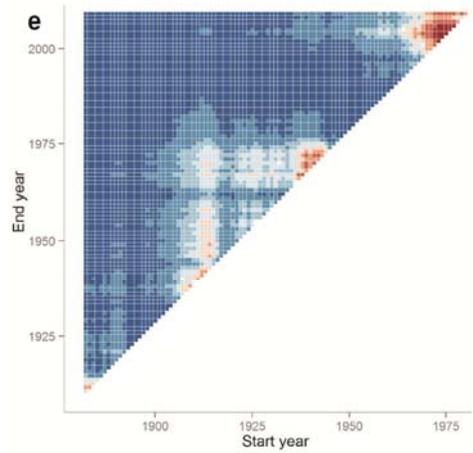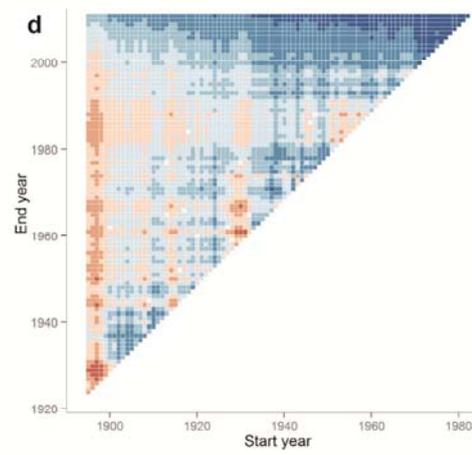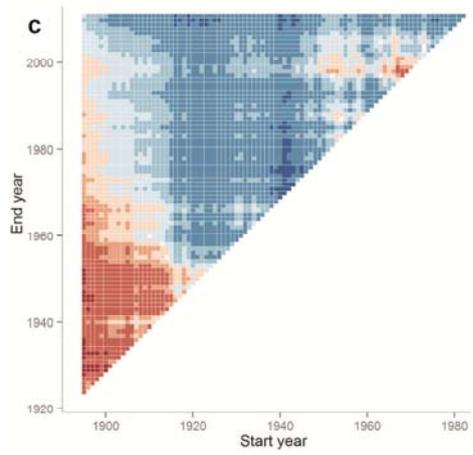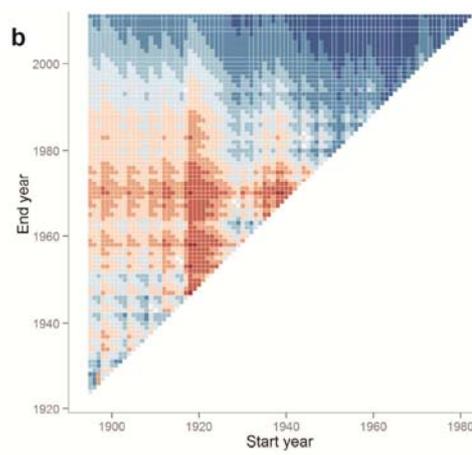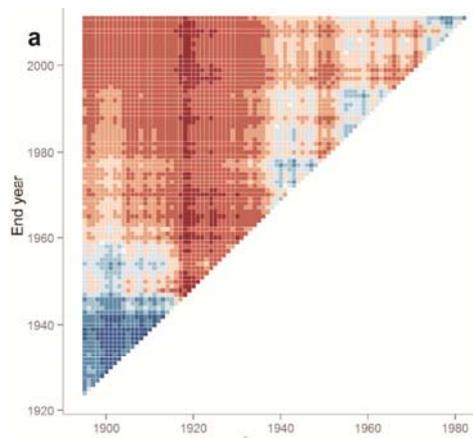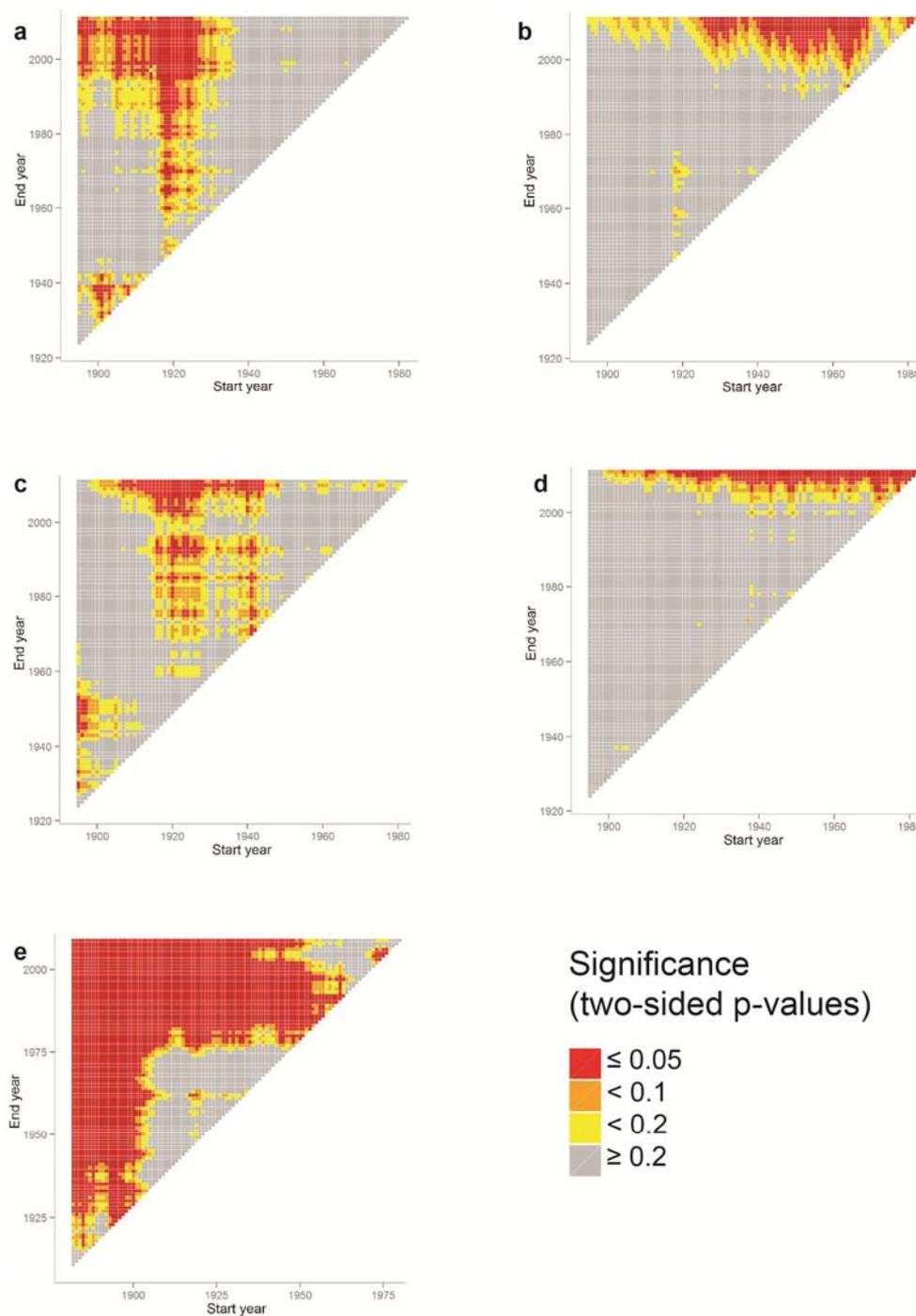
Fig. S10 ¦ Mann Kendall trend matrices of rock glacier- and glacier activity with the standardized test statistic (τ; above) and significance levels (two-sided p-values; below) for different start and end years and a minimum period of 30 years (1895-2011). **a.** I_t index Karakorum rock glacier. **b.** I_t index Kugalan Tash rock glacier. **c.** I_t index Ordzhonikidze rock glacier. **d.** I_t index Turgen Aksu rock glacier. **e.** Mass balance Tuyuksu glacier.
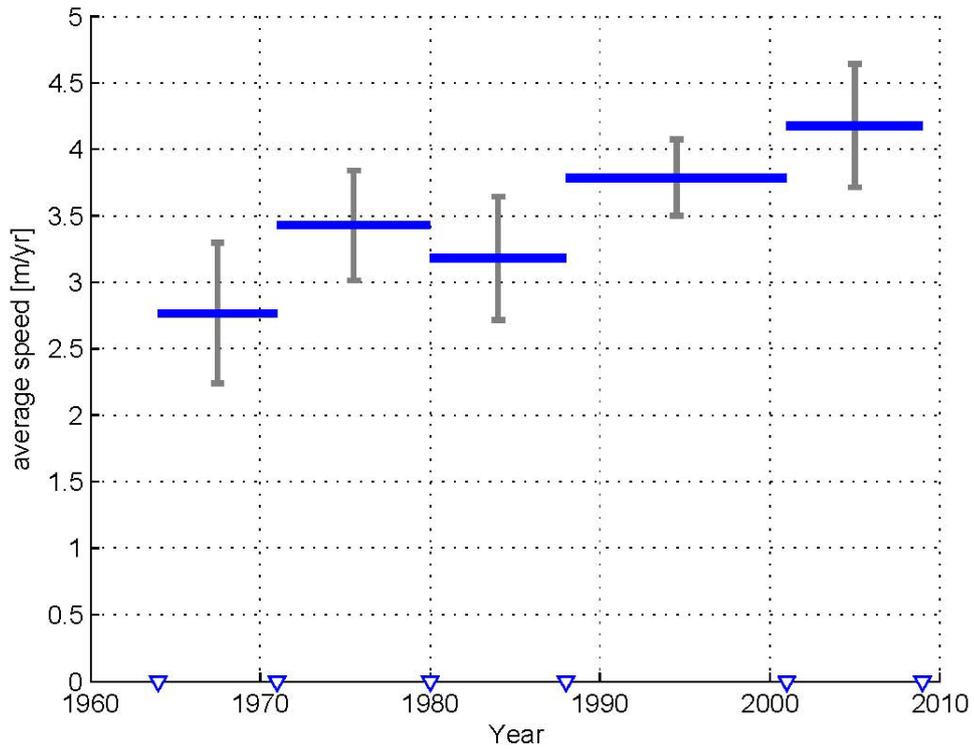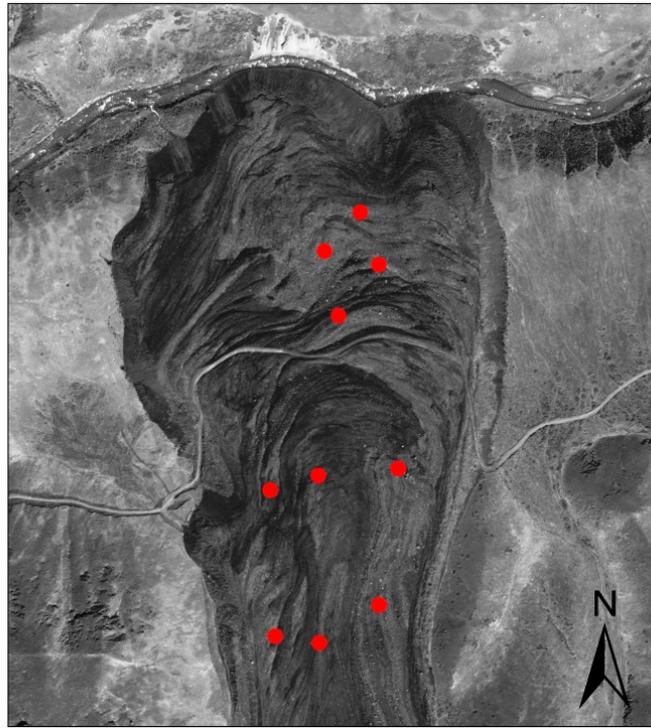
Fig. S11 | Location of clusters used for photogrammetric analysis (above) and average speed with 1σ confidence interval (below) at Karakorum rock glacier.
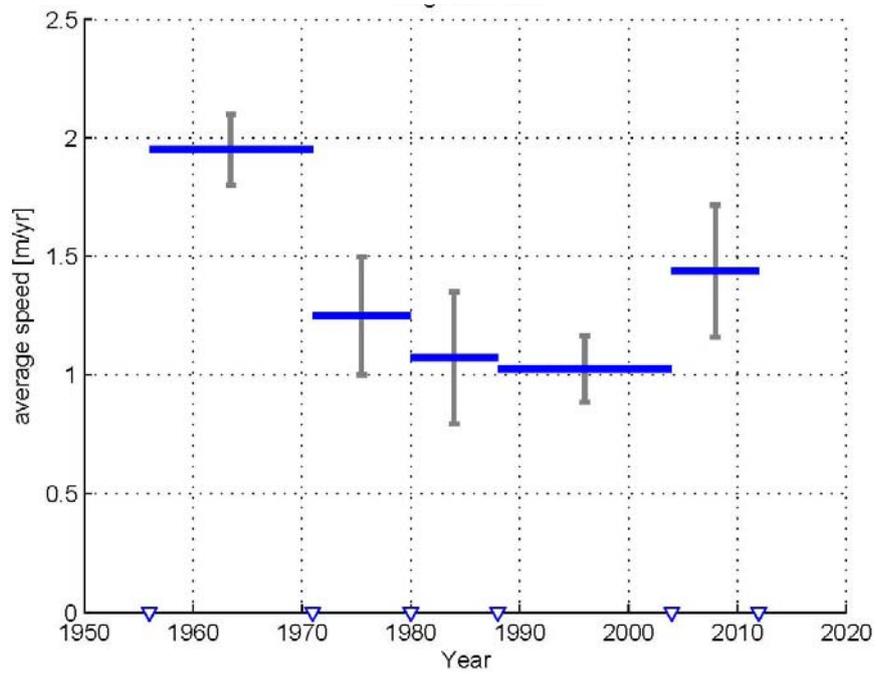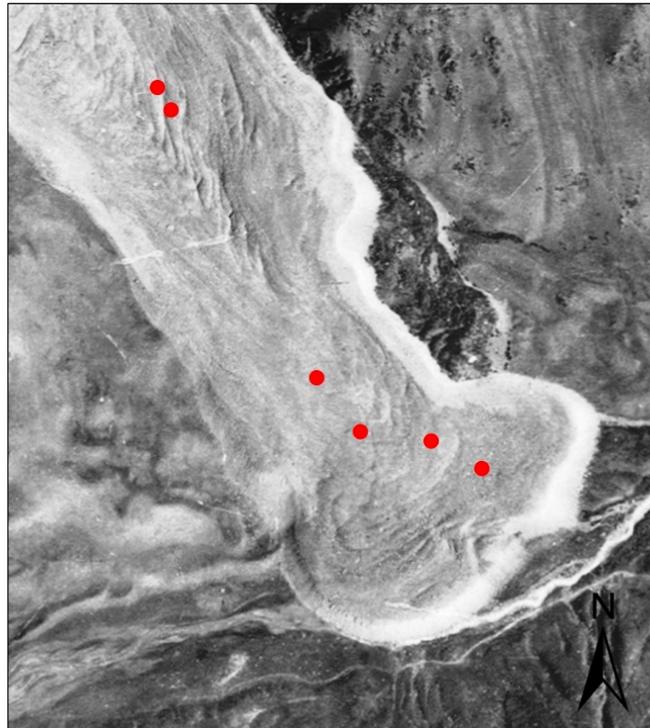
Fig. S12 ⦙ Location of clusters used for photogrammetric analysis (above) and average speed with 1σ confidence interval (below) at Kugalan Tash rock glacier.
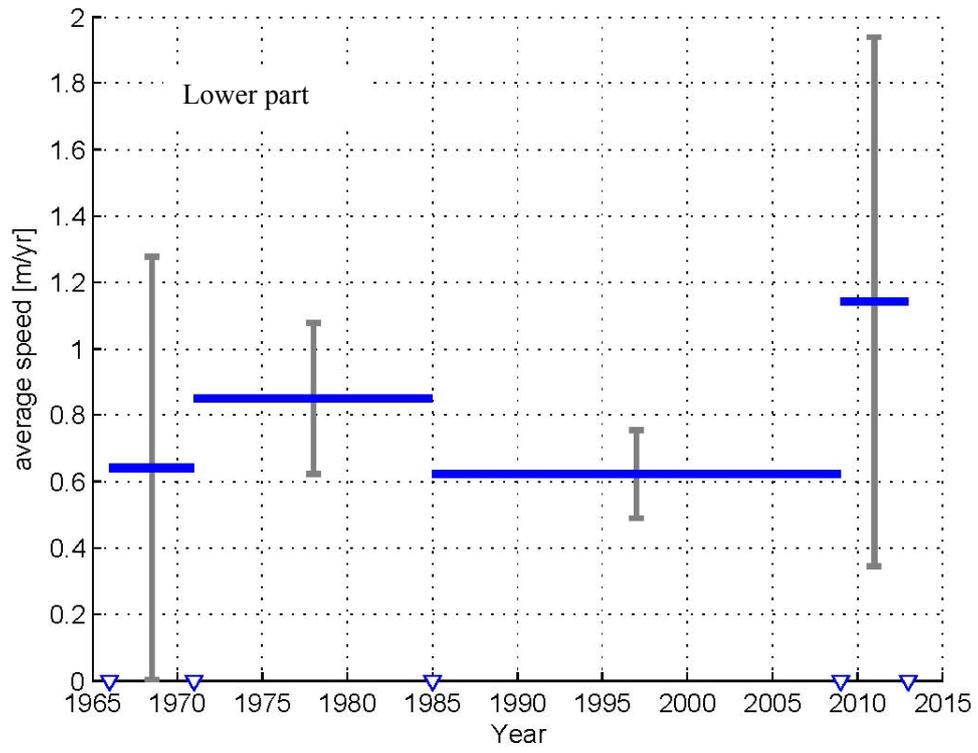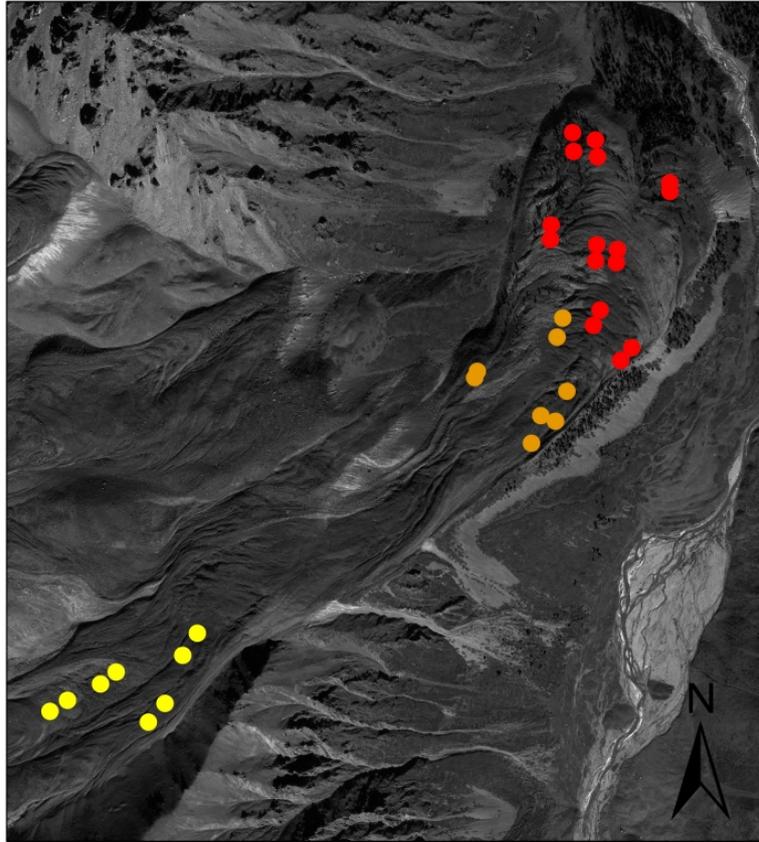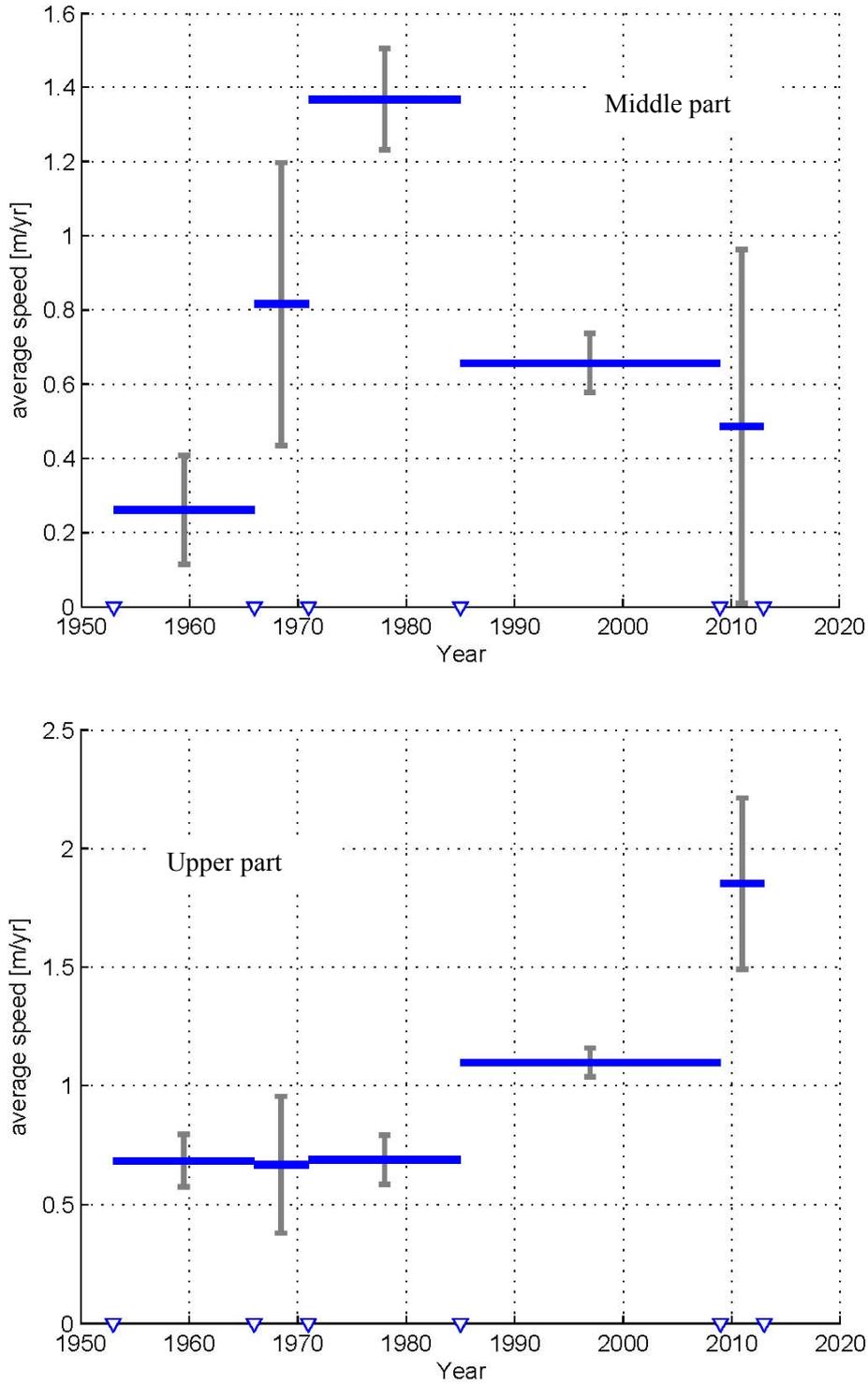
Fig. S13 ⊦ Location of clusters used for photogrammetric analysis (above) and average speed with 1σ confidence interval (below) at Ordzhonikidze rock glacier. Three regions have been differentiated on the rock glacier: lower part (red), middle part (orange) and upper part (yellow).
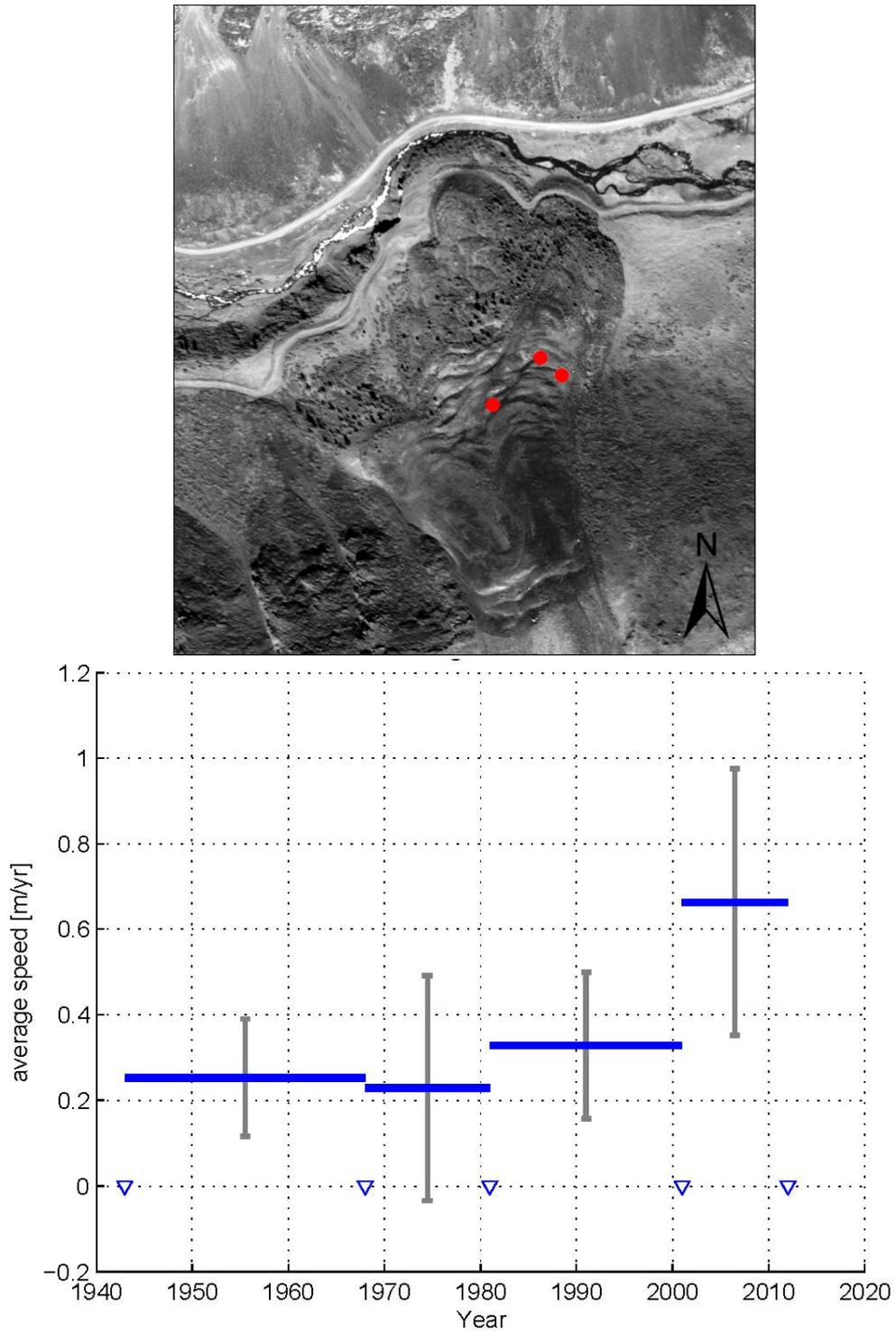
Fig. S14 ¦ Location of clusters used for photogrammetric analysis (above) and average speed with 1σ confidence interval (below) at Turgen Aksu rock glacier. Average speed is much lower than for the other rock glaciers and uncertainty is high due to bad image quality.

Supplementary animation
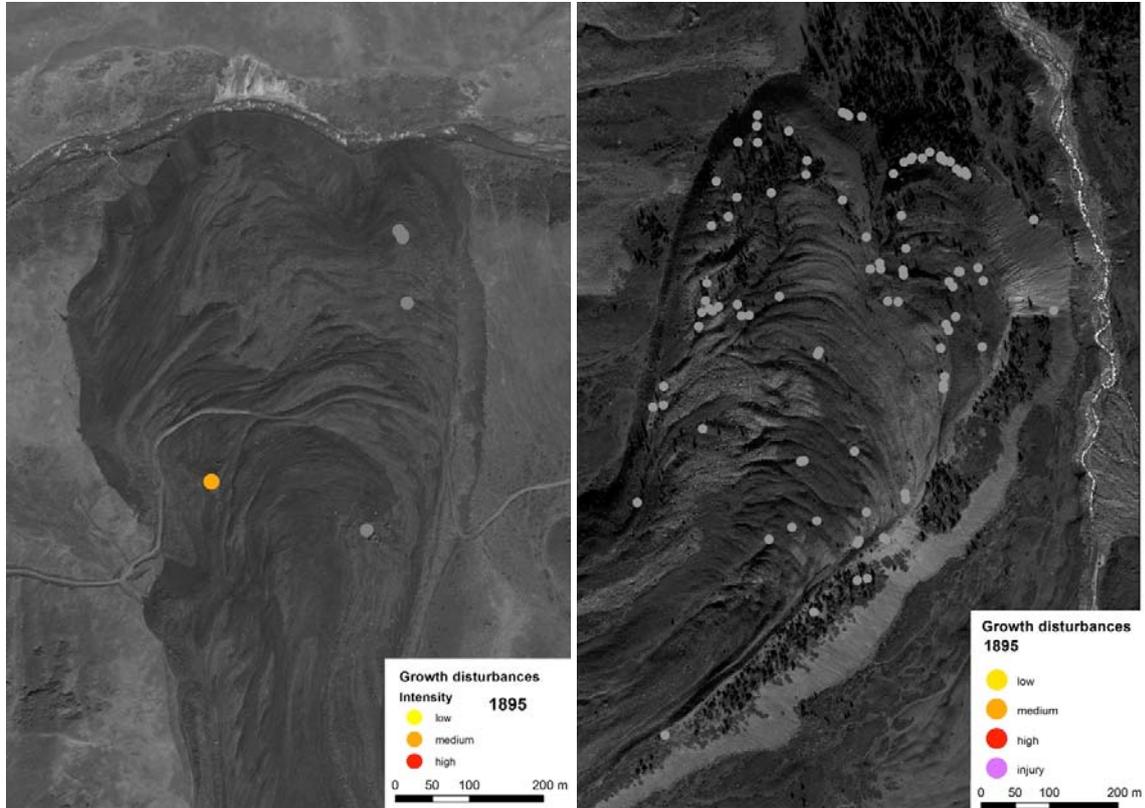
Animation S1 ¦ Animation of trees showing growth disturbances on Karakorum (left) and on Ordzhonikidze rock glacier (right) during the period 1895-2011 (separate .avi-files).

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D

Coping with changing water resources:

The case of the Syr Darya river basin in Central Asia

Annina Sorg, Beatrice Mosello, Gulnara Shalpykova, Andrew Allan, Margot Hill Clarvis and Markus Stoffel

Coping with changing water resources: The case of the Syr Darya river basin in Central Asia

A. Sorg [a,*], B. Mosello [b], G. Shalpykova [c], A. Allan [d], M. Hill Clarvis [a], M. Stoffel [a]

[a] Institute for Environmental Sciences (ISE), University of Geneva, Site de Battelle/D, 7 route de Drize, 1227 Carouge, Switzerland
[b] Water Policy Programme, Overseas Development Institute, 203 Blackfriars Road, London SE1 8NJ, United Kingdom
[c] School of Politics and International Relations, The University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom
[d] Centre for Water Law, Policy and Science (under the auspices of UNESCO), Peters Building, University of Dundee, DD1 4HN Scotland, United Kingdom

ARTICLE INFO

ABSTRACT

This paper discusses how climatic-hydrological and socio-political developments will affect water allocation in the Syr Darya river basin and which adaptation measures will be needed to cope with changing water resources. In view of the geo-political complexity, climate-driven changes in water availability are of particular importance in this region. Water shortages during summer will become more frequent as precipitation is expected to further decrease and glacial meltwater releases will decrease in the long-term due to reduced glacier volume. Being the main valve to the entire Syr Darya river system, the Toktogul reservoir in Kyrgyzstan could take over, at least partly, the role of glaciers as seasonal water redistributors, thus allowing the generation of energy in winter – benefiting upstream countries – and irrigation for large-scale agriculture in summer – benefiting downstream countries. To date, however, there is no regional consensus on a balanced reservoir management, which currently favours irrigation according to past Soviet priorities. Moreover, the perception of water as a 'national concern' in Central Asia discourages efforts towards cooperation between states at the regional level. So far, climate change adaptation has focused on technical rather than institutional solutions. We suggest that policy-relevant adaptation measures should include consistent data collection and dissemination, cross-sectoral collaboration, promotion of national responsibility and initiative, and agreeing on a regional strategy.

1. Introduction

1.1. Geographical, hydrological and climatic setting

Water takes on special importance in Central Asia: covering more than four million square kilometres, the post-Soviet states of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan make up an area that is larger in size than India, Pakistan, and Bangladesh combined, and is home to roughly 60 million people. The majority of water feeding the two main rivers of the region, the Amu Darya and the Syr Darya, is formed from glacier- and snowmelt in the high Pamir and Tien Shan ranges in Kyrgyzstan and Tajikistan (Fig. 1). The

Syr Darya river is formed by two tributaries originating in Kyrgyzstan, the Naryn River and the Kara Darya river. As it flows towards the Aral Sea, the Syr Darya river provides freshwater and water for irrigation to Uzbekistan, Tajikistan and Kazakhstan (Barnett et al., 2005; Immerzeel et al., 2010; Kaser et al., 2010).

In view of its high complexity and interdependence, climate-driven changes in water availability are of particular importance for the Syr Darya basin. Substantial changes are expected to occur in the amount and seasonality of precipitation, with a likely increase in winter and decrease in summer (IPCC, 2007). This will put even more importance on the buffering effect of glaciers, which release additional water during dry summers and thus compensate for rain shortfalls. In the future, however, this buffering of glaciers will likely undergo a substantial change and reduced glacier volume will eventually result in a decrease of glacier-fed summer runoff (Braun and Hagg, 2009; Sorg et al., 2012). Water shortages during summer are thus likely to be caused by two exacerbating factors – less precipitation and less glacial meltwater. Implications are also expected for runoff from snowmelt, as snowcover duration is probably continuing to decrease (Aizen et al., 1997) and snowmelt will occur earlier in the year (Khalsa and Aizen, 2008). These expected changes call for appropriate adaptation measures (EDB, 2009; Perelet, 2010).

1.2. Complexities of the geo-political context

Historical legacies and the regional political context are of particular relevance in the Syr Darya basin. Agriculture was initially made possible by the Soviet administration in the early 20th century in Central Asia through the development of intensive irrigation systems to fuel larger-scale cotton cultivation. By the 1960s, the traditional belief in inexhaustible Central Asian water resources had diminished as river flows and ground water reserves were depleted and water and soil quality degraded (Klötzli, 1997).

In order for the Soviet Union to become self-sufficient, priority for water allocation was given to the cotton production in the Uzbek Soviet Socialist Republic (SSR) and to rice production in the Kazakh SSR, with the Kyrgyz SSR designated as water supplier. Major investments were made in the construction of dams, reservoirs, irrigation canals and other structures to promote and manage the transfer of water from its source in the Kyrgyz mountains to the main growing areas in the Uzbek and Kazakh SSRs. The administrative borders of the Central Asian Republics did not match the natural hydrological borders of the Syr Darya basin and were disregarded in the construction process of irrigation canals and dams. The costs of water management within the upstream SSRs were paid for or subsidised from Soviet central funds and the upstream republics received benefits such as the provision of cheap fuel, electricity and food supplies (Kemelova and Zhalkubaev, 2003; Klötzli, 1997; Hodgson, 2010; ICG, 2002).

The demise of the USSR in 1991 brought about dramatic geopolitical changes in Central Asia; both Syr Darya and Amu Darya became international river basins covering territories of newly independent states. It also caused a sudden power vacuum and the breakdown of the state-controlled subsidised provision system. The most difficult Soviet legacy, however, was the mismatch between the regional water management systems and the newly established political borders. At the same time, the cotton-oriented economic development of Soviet planners had produced environmental depletion and degradation (Klötzli, 1997), which now needed to be resolved by independent
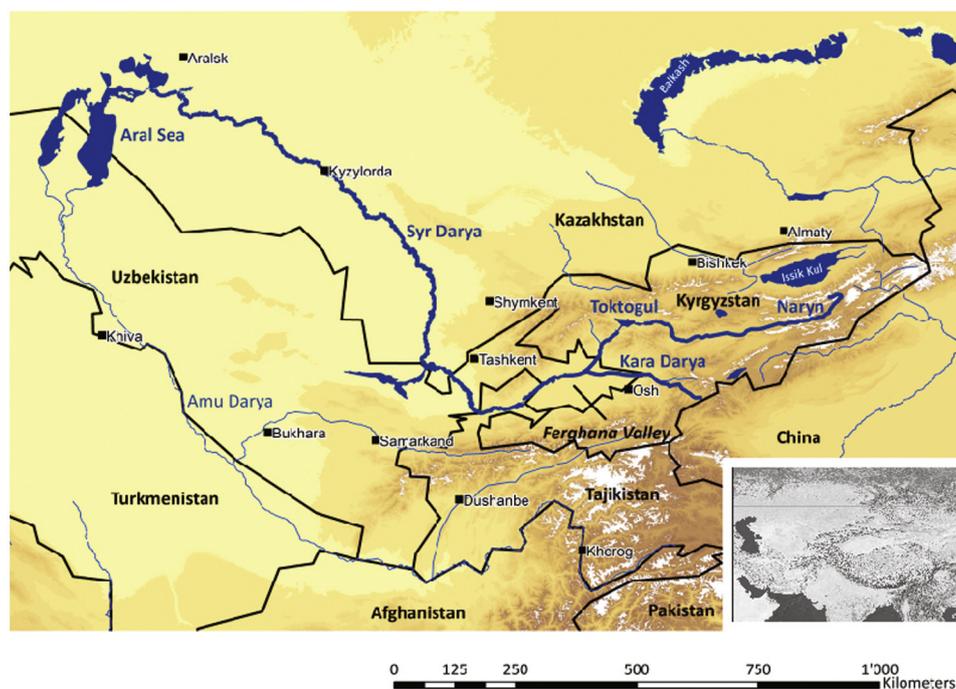

Fig. 1 – Hydro-political map of Central Asia.

countries. Furthermore, the introduction of private land holding, and the decentralisation of water allocation, led to a multiplication of water users and responsibilities concerning water allocation and infrastructure maintenance (Bichsel et al., 2009). This situation was further complicated as each riparian state declared state ownership over natural resources (Sehring, 2009).

The combination of Soviet central planning and fractious Central Asian states after the collapse of the Soviet Union has therefore created numerous challenges (Mosello, 2008). The distribution of water in the Syr Darya basin continues to be aimed at increasing the output of water-intensive cotton and rice production (ICG, 2002; World Bank, 2011a). The recipients of the benefits have become the newly independent downstream states, which makes them in favour of maintaining the status quo and transforms any development of water resources management in upstream countries into a situation with a high conflict potential (Allouche, 2004; Shalpykova, 2002).

1.3. Aims and objectives of this study

Changing water availability in mountain regions has a strong impact on water-dependent economic sectors such as energy and agriculture. The Syr Darya river basin figured as a non-European case study within the EU-FP7 ACQWA project (www.acqwa.ch), which aimed at identifying how climate change might impact rivalries among these sectors in mountain environments and adjacent lowlands (Beniston et al., 2011).

So far, most studies on water related challenges in Central Asia have focused either on climato-hydrological or on socio-political aspects. In this paper, we bring these two perspectives together for the case of the Syr Darya river basin in order to identify issues which are likely to be exacerbated by both climatic-hydrological and socio-political developments. The goal of this paper is thus to present the impact of future climatic trends on the water regime (chapter 2), to assess current challenges of water governance (chapter 3), and to discuss adaptation challenges and options for water governance and management in the Syr Darya river basin (chapter 4).

2. Future water availability and -demand in the context of climate change

2.1. Climatic trends

Central Asia is characterised by a continental and semi-arid to arid climate with hot summers and cold winters. Precipitation rates are low, especially during summer, when precipitation occurs almost exclusively in the mountainous regions. Over the past decades, temperatures have increased in all parts of Central Asia, whereas precipitation rates have increased at low altitudes and decreased at higher elevations (IPCC, 2007; Giese et al., 2007; Sorg et al., 2012). In the future, substantial climatic changes are expected to occur in the amount and seasonality of precipitation and in a continuous increase of temperatures, which exerts feedback mechanisms on the hydrological cycle: Precipitation is likely to increase in winter (4–8% by 2050), whereas summer precipitation is expected to

decrease by an equal amount (4–7%).[1] This will probably result in more extreme events such as drought-prone summers and flooding in winter and spring. Temperatures are likely to further increase in all seasons: summer and winter air temperatures are expected to increase by +3.1 to +4.4 °C and by +2.6 to +3.9 °C until 2050, respectively. Although these projections reflect the current state of knowledge, changes in precipitation and snow remain highly uncertain, and the level of temperature increase, especially at high altitudes and during summer, suffers from considerable disagreement between existing data (Sorg et al., 2012).

As a result of higher temperatures and a prolonged melting season, glaciers in the Tien Shan mountains have already lost much of their volume in the past decades–probably around 0.9% per year (Dikikh, 2004; Vilesov and Uvarov, 2001). The estimated glacier volume in the Syr Darya catchment has been reduced from approximately 121 km^3 in the 1960s/1970s to 101 km^3 in 2000 (UNDP, 2009). However, these numbers have to be treated with caution, as they are only rough estimates. Gravimetric measurements (GRACE) revealed a glacier mass loss for the entire Tien Shan of around 5 ± 6 Gt (0.32 ± 0.39 m water equivalent) per year in the period 2003–2010 (Jacob et al., 2012). Snowcover is also affected by climate change, as increasing temperatures reduce the proportion of solid precipitation and lead to earlier and more intense snowmelt. Thus, snowcover duration is likely to decrease further (Aizen et al., 1997) and snowmelt will occur earlier in the year (Khalsa and Aizen, 2008).

2.2. Impacts on water availability

These changes will put even more importance on the buffering effect of glaciers, which release additional water during dry summers and thus compensate for rain shortfalls. In the future, however, this buffering of glaciers will likely undergo a substantial change and reduced glacier volume will eventually result in a decrease of glacier-fed summer runoff (Fig. 2; Braun and Hagg, 2009; Sorg et al., 2012). At first, shrinking glaciers supply ample quantities of water in the form of increased glacial runoff (phase 1), thus providing surface runoff surpluses over a number of decades that might seem to represent a potential opportunity to develop hydropower infrastructure and produce more energy (Beniston et al., 2011). However, this water supply is far from sustainable and inevitably results in a tipping point ("peak water", Baraer et al., 2012; Gleick and Palaniappan, 2010), as glacial contributions diminish. Thus, reduced glacier volume will eventually result in a decrease of summer runoff (phase 2), if no other sources can offset water deficiency from reduced glacier melt (Braun and Hagg, 2009). The volume of summer-time glacier meltwater may then no longer be sufficient to feed water into river catchments at a time of the year when precipitation amounts are low and the snowpack has already melted (Beniston et al., 2011). Moreover, the year-to-year variability of surface runoff tends to increase when glaciers lose some of their buffering capacity and runoff will thus

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[1] Numbers are based on the lower and higher bound IPCC SRES B1 and A1F1 (IPCC, 2007).
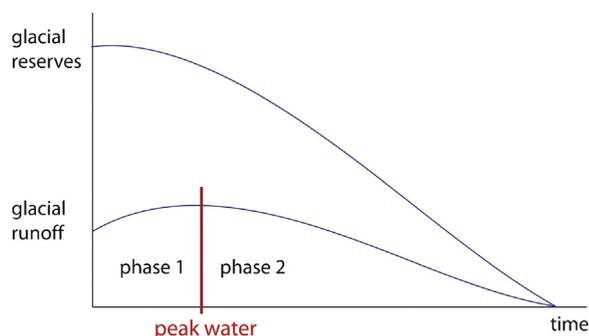
Fig. 2 – Tipping point ("peak water") in glacial runoff.

respond more directly to inter-annually variable precipitation (Braun and Hagg, 2009).

It remains uncertain as to when the Syr Darya or its tributaries will cross this tipping point, though some of them may even have already done so. It appears that catchments with a higher fraction of glacierised area showed mainly increasing runoff trends in the past, while river basins with less or no glacierisation exhibited large variations in the observed runoff changes (Unger-Shayesteh et al., 2013). The increase in long-term average annual runoff of Syr Darya at the confluence of Naryn and Kara Darya from 29.1 km^3 (average 1947–1972) to 30.4 km^3 (average 1973–2000; Mamat-kanov et al., 2006; Yakimov and Kostenko, 2003) could be a result of increased glacier melting, but could have also been caused by increasing precipitation amounts. Numerical modelling of runoff components in the headwater catchment of Syr Darya is needed to shed light on past and future changes in glacial runoff and on dating the tipping point. Considerable uncertainties regarding the future evolution of precipitation amounts and impact on water availability, however, will remain.

2.3. Growing demand for water

The Central Asian economies are dominated by irrigated agriculture practices (Granit et al., 2010) and water consumption has been mounting to unsustainable levels (ICG, 2002). More than 90% of water in the region goes to irrigated agriculture, which produces about 30% of the regional GDP and provides employment for more than 60% of the region's population (ICG, 2002; Rakhimov, 2009). Agriculture in the region is dominated by cotton production with an increasing shift towards wheat. Uzbekistan, for instance, is currently the second largest exporter of cotton in the world, selling over 800,000 metric tonnes every year (Granit et al., 2010). In Tajikistan, two-thirds of agricultural production is irrigated, but many farmers still have to make a living from rain-fed land, which is even more vulnerable to drought and climate change (Oxfam, 2010). In addition to climate change impacts, the potential for conflict in the region is exacerbated by the current high population growth rate of between 2.5% and 3.4% per year (Lutz, 2010). As living standards improve and demand for resources increase, pressures on scarce water resources heighten.

3. Current governance challenges in the Syr Darya river basin

3.1. International aspects of water governance

In view of the geo-political complexity, water governance is particularly challenging in the Syr Darya river basin. Customary international law allows riparian states an equal right to the equitable and reasonable share of international watercourses (McCaffrey, 1991, 2007; Rieu-Clarke, 2005). The Syr Darya downstream states have acceded to the *Helsinki Convention* (UNECE, 1992), but as of today, neither Kyrgyzstan nor Tajikistan have done so. Of the riparian countries, only Uzbekistan has ratified the *Convention on the non-navigational uses of international watercourses* (UN, 1997). Both of these instruments actively require cooperation by states over shared waters to ensure that the standards required by international law are upheld. While Kazakhstan and Kyrgyzstan have acceded to the *Espoo Convention* (UNECE, 1991) – though not to the strategic environmental assessment protocol – Uzbekistan, potentially a beneficiary under the convention, has not. The *Aarhus Convention* (UNECE, 1998) is in force in the Syr Darya basin, again with the exception of Uzbekistan. Uzbekistan also has yet to sign the *Framework Convention for the Protection of the environment for sustainable development in Central Asia* (UNEP, 2006).

The patchy application of relevant international agreements is exacerbated by implementation challenges related to transposing international law to national frameworks. Thus, Uzbekistan has yet to put a Water Code in place and Kyrgyzstan has not yet implemented its own 2005 Water Code (Djayloobaev et al., 2009) or the practical aspects of the *Aarhus Convention* (UNECE, 2010a,b). In addition, the lack of financial capacity, difficulties in enforcement and compliance, and sparse data gathering and monitoring networks render the application of international law difficult.

3.2. The dilemma of water allocation at the regional and basin level

A fundamental driver of tensions in the Syr Darya basin derives from the operating regime of the basin's largest reservoir, the Toktogul (Antipova et al., 2002). With a total volume of 19 billion m^3, Toktogul is the main valve to the entire river system and accounts for 91% of electricity production in Kyrgyzstan (World Bank, 2004). Whereas downstream Uzbekistan requires water discharges in summer to irrigate its cotton fields, upstream Kyrgyzstan prefers water discharge in winter when demands for electricity are highest. Although the series of dams that form the Toktogul cascade were intended to be dual purpose, thus for both irrigation and hydropower generation, most of the water was conveyed by canals to the downstream republics to irrigate their fields (Hodgson, 2010). The failure of downstream republics to deliver required agricultural and energy supplies (ICG, 2002) has "led the upstream republics to withhold irrigation water during summer months for release in winter in order to meet internal needs for electricity" (UNDP, 2003).

Interestingly, downstream countries are seen to have greater material and non-material power than upstream countries, thus producing asymmetrical power relationships (Votrin, 2003; Zeitoun and Warner, 2006). Water is perceived as a 'national concern' in Central Asia and the five republics have brought it into their national security agenda (ICG, 2002; Mosello, 2008). This securitisation of the water discourse discourages efforts towards cooperation between states at the regional level, despite a number of attempts that have been made in this direction (Mosello, 2008). For example, the *Almaty Treaty on Cooperation in the Field of Joint Water Resources Management and Conservation of Interstate Sources* (1992) reaffirmed the Soviet-era water sharing provisions that were set in 1984 and are still in force today (*Scheme for Complex Use and Protection of Water Resources of the Syrdarya River Basin*, 1984; Table 1). The 1992 *Almaty Treaty* sets offtake limits for each riparian country with respect to surface and groundwater, and in relation to irrigation and non-irrigation uses. It also led to the establishment of the *Inter-state Commission for Water Coordination* (ICWC), which was charged with the allocation of water in respect of canals and structures controlled by the Soviet-era *Basin Valley Organisations* (BVOs), which are still in place today (Allouche, 2007). Other regional agreements have followed, with the goal of establishing a common coordinated policy for energy and water resources (*Agreement on the Use of Water and Energy Resources in the Syr Darya Basin*, 1996) and to provide for compensation of upstream countries with coal, gas or money for energy loss when releasing water in winter, and for the implementation of joint hydropower projects (*Agreement on the Use of the Syr Darya Water Resources*, 1997, and *Agreement over the use of the Naryn – Syr Darya Cascade*, 1998; Allouche, 2007; Hodgson, 2010). The abstention of Uzbekistan from recent agreements has, however, greatly undermined this approach (Hodgson, 2010; Libert et al., 2008).

In general, therefore, non-cooperation tends to prevail as a consequence of a number of reasons. First of all, existing agreements do neither incorporate adequate provisions for data exchange nor notification of planned measures at the regional level, which increases mistrust amongst the Central Asian governments as far as water resources are concerned. In each country, water, agriculture and energy decision-making continue to occur in a separate way, which renders the governance structure for water resources management

sectorial, fragmented and confused – a situation that is further complicated by the presence and action of international organisations. If integration does not occur at the national level, it is unlikely to happen at the regional level either. Therefore, the political, economic and social context of water resources management has resulted in the Central Asian states perceiving water resources as a zero-sum game, one in which one's gain is achieved at the expense of another's loss (Mosello, 2008).

While the BVOs as well as the ICWC are still operational, they cease to play significant roles in terms of water allocation (Hodgson, 2010). The rights claimed by upstream countries to be compensated for storage and supply of irrigation water as well as for the operation and maintenance of the water infrastructure have been persistently opposed by downstream governments (Hodgson, 2010; Slay, 2011) stating their entitlement to the free use of naturally flowing water (Shalpykova, 2002). Tensions started surfacing particularly from 2001 onwards, when the Kyrgyz government made an attempt to introduce water-pricing by supplying water to downstream countries only on a 'paid' basis and operation and maintenance costs of the water infrastructure should be shared (*Law On Interstate Use of Water Units, Water Resources and Water Facilities of the Kyrgyz Republic*, 2001; Tarlock and Wouters, 2007; Votrin, 2003). The 2001 law was based on principle 4 of the *Dublin Statement on Water and Sustainable Development* (1992), according to which ''*water has an economic value in all its competing uses and should be recognised as an economic good*''. Given that the largest part of water usage of the Syr Darya waters is not for drinking, sanitation or subsistence agriculture, but for cash crops such as cotton (Khamrayev, 2009), a monetary compensation for Kyrgyzstan's energy losses and costs for the maintenance of water infrastructure would have only seemed reasonable. However, the 2001 law was severely criticised in Kazakhstan and Uzbekistan. The Kazakh leader, Nazarbaev, claimed that the law ''does not have any legal foundation [...] it is impossible to set a price for irrigation water [...] it contradicts international standards [...] it is unacceptable for Kazakhstan'' (Usubaliev, 2002). Uzbekistan's President Karimov supported his colleague by saying ''Water belongs to God'' (Uzbekistan National News Agency, 2001). As of today, Kyrgyzstan's Ministry of Foreign Affairs has not yet implemented the 2001 law (UNDP, 2003).

Table 1 – Water offtake quotas in the Syr Darya river basin according to Resolution No. 413 (07.02.1984).

Republic	Offtake Quotas (km^3)				
	Total	Including		Including for irrigation	
		Surface sources	Underground and return waters[a]	Total	Underground and return waters
Uzbekistan	25.49	19.69	5.80	21.36	4.21
Kazakhstan	15.29	12.29	3.00	10.40	2.26
Kyrgyzstan	4.88	4.03	0.85	4.38	0.51
Tajikistan	3.66	2.46	1.20	3.17	0.75
Total	49.32	38.47	10.85	39.31	7.73

[a] Return flows from irrigation drainage canals – i.e. water that has gone into canals and not leaked, evaporated or been used consumptively by crop uptake.

4.   Implications for adaptation

4.1.   Equitable water allocation

The agreements currently framing water governance and management in the Syr Darya basin do not address the question of equitable water allocation at the basin level, which still favours irrigation according to past Soviet priorities. Furthermore, the system suffers from considerable technical losses, because the infrastructure dates from before independence and little or no investments have been made since then (Murphy et al., 2011) as a consequence of commercial losses (OECD, 2011) and corruption. These dual governance issues are exacerbated by climate change impacts such as water shortages during summer, when water is pivotal for irrigation. Thus, the Central Asian states face at the same time significant challenges and impetus to develop coherent and effective strategies to guarantee an equitable and sustainable allocation of water resources. Currently, water resources management in the region focuses on infrastructural projects (e.g., dams, canal repairs, groundwater wells, irrigation), and pays less attention to increasing the adaptiveness of governance processes. Accordingly, infrastructure improvements are the most common adaptation measure prioritised by the Central Asian States' National Communications to the United Nations Framework Convention on Climate Change (CAREC, 2011, 38). However, while relatively adequate attention is also posed upon the development of effective regulatory transboundary water agreements and the implementation of Integrated Water Resources Management (IWRM), none of these efforts explicitly target adaptation to climate change, mostly as a result of lacking national adaptation policy frameworks (CAREC, 2011, 38).

4.2.   Infrastructure and technology

Despite the uncertainty over the extent of the changes induced by climate, projections suggest that the Syr Darya basin will experience reduced summer runoff and seasonal water shortages. For upstream countries, technical and infrastructural adaptation measures could include the construction and maintenance of hydropower dams that replicate glaciers by storing water resources in the winter season and releasing them during summer. Just as glaciers have in the past and at present acted as intra- and inter-annual buffers in the hydrological cycle, hydropower dams might have to take over this role of seasonal redistributors in the upper Syr Darya catchment. If the proposed construction of the Verkhnenarynsky hydropower cascade upstream of Toktogul reservoir will be realised,[2] Kyrgyzstan will be able to generate sufficient electricity in winter, and to run the Toktogul reservoir in

irrigation mode (Abbink et al., 2010). This development underscores the need for mutually accepted rules on releases and compensations between upstream and downstream stakeholders. To prevent any misuse, minimum runoff has to assured in summer and flooding releases have to be prevented in winter. In return, downstream users will have to compensate for shortfalls in hydropower generation when upstream countries release water upon request during summer.

For downstream countries, adaptation of the irrigation system will require efficiency improvements and changes in crop choice. This is particularly complex in the context of planned economies like Uzbekistan and in local processing monopolies (OECD, 2011), and the interpretation of ''vegetation'' and ''non-vegetation'' seasons in the 1998 Agreement makes irrigation scheduling more appropriate for some crops than others. Downstream countries are also likely to invest in additional backup-reservoirs, which change the seasonal distribution of water availability for any given release by the upstream country (Abbink et al., 2010). Such reservoirs have already been constructed in Uzbekistan (e.g. Arnasai, Kenkulsai, Rezaksai reservoirs) and in Kazakhstan (e.g. Koksarai reservoir; CAWATER, 2013).

4.3.   Governance and policy

More comprehensive approaches are also required to direct investments from being focused on infrastructure only to also taking into account environmental sustainability, capacity building and participatory management. Adaptive governance will need to involve ''the evolution of new governance institutions capable of generating long-term, sustainable policy solutions to wicked problems through coordinated efforts involving previously independent systems of users, knowledge, authorities, and organised interests'' (Scholz and Stiftel, 2005). Thus, policy-relevant adaptation measures should include consistent data collection and dissemination, cross-sectoral collaboration, promotion of national responsibility and initiative, and agreeing on a regional strategy. For Central Asia, this will mean that, in order to respond to climate-induced and socio-economic challenges to water resources management, the following issues need to be addressed:

(a) Consistent data collection and dissemination: Existing agreements do not provide adequately for data exchange or notification of planned measures. Although this is not mandatory under the current *1992 Almaty Treaty*, managing compliance with international agreements will be impossible without monitoring networks. In particular, a need exists to expand data collection and processing on surface and groundwater, to monitor climate change impacts on water, agriculture and energy and to enhance the quality and scope of climate change vulnerability assessments, including economic assessments. Monitoring networks and cadastre development are critical for both short- and long-term planning and management of resources, but financial limitations have thus far fatally compromised these elements (Djayloobaev et al., 2009; UNECE, 2009, 2010a,b; World Bank, 2009, 2011b) with financial corruption further eroding implementation in some cases (EBL, 2011).

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[2] In September 2012, the Russian state-controlled hydropower company RusHydro and Kyrgyzstan's Electric Stations have set up a joint venture for the construction of the Verkhnenarynsky hydropower cascade. Kyrgyzstan will manage water resources and set tariffs for power export (Uznews, 2012), while Russia will take on the role of mediator in Kyrgyzstan's dispute with downstream countries (HydroWorld, 2012).

Table 2 – Suggested policy measures to address climate change impacts in the Syr Darya basin.		
Governance and policy barriers to adaptation		**Suggested policy measure**
a	No adequate provisions for data exchange or notification of planned measures	- Intensified data collection, processing and sharing on surface and groundwater - Monitoring of climate change, including the continuation and re-establishment of hydro-meteorological measurements and in situ measurements of snow and glaciers - Monitoring of impacts on agriculture and energy - Enhanced quality and scope of climate change vulnerability assessments, including economic assessments
b	Sectoral separation of water from agriculture and energy, as well as from disaster risk and land management	- Integrated water resources management with improved communication between competent decision-making authorities across sectors to allow a balanced operational regime of hydropower dams and to assure the flexibility to react to future water supply and demand - Improved connections between economic actors in the river basin - Identification of solutions to invest in hard and natural infrastructure
c	Risk that national authorities do not assume responsibility and initiative	- Development of national adaptation plans to improve water use efficiency and agricultural crop diversification
d	Lack of regional cooperation	- Enhanced data communication and trainings on climate change impacts and adaptation options on various levels

(b) Cross-sectoral collaboration: In all Central Asian countries, the separation of water from agriculture and energy decision-making, as well as disaster risk and land management is a critical issue. One prominent example in this sense is the state-owned power company Electric Stations operating the Toktogul reservoir, which is instructed by both the Ministry of Energy and the State Committee for Water Resources. The former requires water discharges to produce sufficient electricity for domestic demand and exports, while the latter aims at satisfying irrigation demands and attends the negotiations of the ICWC. These instructions are frequently conflicting and certainly do not help Kyrgyzstan's negotiating position vis-à-vis its neighbours. Incentivising better connections between economic actors in the river basin might also open the doors for identifying solutions to invest in both hard and natural infrastructure, which in turn would increase the adaptive capacity of water systems in the Central Asian region.

(c) Promotion of national responsibility and initiative: So far, most of the adaptation actions in the region have been funded and encouraged by external donors and international organisations (e.g. World Bank, International Monetary Fund, international NGOs). While their interventions can be considered as positive first steps, the risk is that national authorities do not step in and leave the responsibility to the international community only (O'Hara, 2004). Central Asian countries should therefore develop national adaptation plans that are free from the economic interest of increasing productivity at all costs, and focus instead on improving water use efficiency and agricultural crop diversification.

(d) Regional strategy: For all Central Asian countries, their capacity to adapt to the prospected impacts of climate change would be greatly enhanced by improving the diplomatic relations with their neighbours. Given the interconnected nature of the hydrological system and legacy management system in place, institutions can only become and remain adaptive if a mutually-agreed and shared regional strategy is

in place. There is a recognised need to enhance data communication and educational systems and trainings on climate change impacts and adaptation options on various levels, for example by developing a comprehensive and freely accessible water web-portal for Central Asia (Table 2).[3]

5. Conclusion

The post-Soviet history of Central Asia has introduced immense social, political and economic changes. This article has discussed how current challenges in the water operating regime are likely to be exacerbated by climate change impacts. Substantial changes are expected for precipitation, with a likely increase in winter and a decrease in summer, and for glacial meltwater releases, with a short-term increase and a long-term decrease. The difficulty for the Central Asian states is to apply the principles of equitable and reasonable use by revising the Syr Darya water allocation scheme as well as to agree on a balanced reservoir management, which would allow the generation of energy in winter – benefiting upstream countries – and irrigation for large-scale agriculture in summer – benefiting downstream countries.

To date, climate change adaptation has focused on technical rather than institutional solutions. We present adaptation options relating to both these significant areas of adaptation. Technical and infrastructural adaptation measures include a reconsideration of operating regimes as hydropower dams will have to take over the role of glaciers as seasonal redistributors in the upper Syr Darya catchment. To prevent any misuse, mutually accepted rules have to be

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[3] Existing web-portals such as CAREWIB (CAWater-Info, www.cawater-info.net) or CAWSCI (Central Asia Water Sector Coordination Initiative, http://waterwiki.net/index.php/CAWSCI; not regularly updated) seem to be predominantly used by international actors and less by regional and local decision-makers.

effectuated to assure minimum runoff in summer and to prevent flooding releases in winter. In return, downstream users will have to share operation and maintenance costs and compensate for shortfalls in hydropower generation when upstream countries release water upon request during summer. The core challenge related to the governance of regional water resources will be to agree on how much water should be discharged, at what time and for which purpose. While the new role of reservoirs both in upstream and downstream countries will play a crucial role in adaptation to climate changes, our analysis suggests that the following governance related adaptation measures are key: ensuring consistent data collection and dissemination, fostering cross-sectoral collaboration, promoting national responsibility and initiative, and agreeing on a regional strategy. Given the interconnected nature of the hydrological system, as well as the Soviet legacy in the definition of a common water management paradigm, institutions can only become and remain adaptive if a mutually agreed and shared regional strategy is in place.

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Annina Sorg holds a MSc degree in Environmental Sciences from the Swiss Federal Institute of Technology (ETH Zurich). She is currently doing a PhD at the Universities of Geneva and Berne in the field of glaciology, hydrology and dendrogeomorphology. Annina has spent almost one year in Kyrgyzstan and is the first author of a review article in Nature Climate Change. Further outcomes of her PhD will be the application of a distributed runoff model (GERM) to a glacierised catchment in Northern Tien Shan and the reconstruction of rock glacier activity in the Central and Northern Tien Shan mountains. Methods include hydrologic modelling, dendrogeomorphology and analysis of historic aerial photographs (remote sensing). Annina is a member of the EU-FP7 ACQWA project coordination team.

B. Mosello completed her PhD at the Graduate Institute of International and Development Studies in Geneva in 2013, focusing on issues related to institutional adaptation to climate change in the water sector. After obtaining a BA degree in Development Studies at the University of Pavia (Italy), she continued her academic career with a MSc in Political Science at the Graduate Institute in 2008. From 2006 to 2008, she was a research assistant at the Geneva Centre for the Democratic Control of Armed Forces (DCAF) in the Gender and Security programme. From 2008 to 2012, Beatrice worked at the Graduate Institute of International Studies as a researcher, participating in the EU-FP7 ACQWA project. Beatrice spent extensive time working in Central Asia, where she held a Fellowship at the American University of Central Asia in Bishkek, Kyrgyzstan. Currently, Beatrice is a project officer for the Climate and Development Knowledge Network based at the Overseas Development Institute in London.

G. Shalpykova is a Doctorate Researcher at the School of Politics and International Relations of the University of Nottingham (UK) and a Senior Scientific Fellow at the Institute of Water Problems and Hydropower under the National Academy of Sciences of the Kyrgyz Republic. Gulnara obtained her MSc degree in International Relations from the International University of Japan, where she received the Asian Development Bank Scholarship and wrote her MSc thesis on water disputes in the Syr Darya river basin (IUJ, 2002). Currently, Gulnara is doing research on the problem of cooperation, when geographically adjacent states, in the absence of a central authority and shared interests, decide if, how and why to cooperate with each other on topics related to natural resource use, development or management.

A. Allan is a Senior Lecturer at the Centre for Water Law, Policy and Science at the University of Dundee. His research focuses on the legal frameworks affecting water resource management around the world. He has a particular interest in the problems associated with policy and legal implementation at the national level. Andrew obtained his LLB (Hons) and Diploma in Legal Practice at the University of Edinburgh, completing his LLM at the University of Dundee.

M. Hill Clarvis did her PhD in the Research Group on Climate Change and Climate Impacts at the University of Geneva in 2008. Her research is part of the EU-FP7 ACQWA project and focuses on better understanding the adaptive capacity of water governance systems of Switzerland and Chile. After completing a BA Hons Classics degree at the University of Cambridge, she worked in the commercial sector for 3 years at Xchanging, in London and Frankfurt. She then went to Imperial College, London to gain a MSc in Environmental Technology. Since starting her masters and then PhD, she has continued to work part time in the field of sustainable finance, for the Life Incubator, Asset4 and now for UNEP-Finance Initiative.

M. Stoffel director of the EU-FP7 ACQWA project, is a physical geographer by formation and currently works as an Assistant Professor at the Institute for Environmental Sciences (ISE) and the Department of Earth and Environmental Sciences, University of Geneva, and as a Senior Lecturer at the Institute of Geological Sciences at the University of Berne, where he runs the dendrolab.ch. Markus has (co-) authored more than 120 peer-reviewed papers on hydrological, periglacial, and geomorphic processes in mountain and hillslope environments and the impact of climate change on their occurrence, as well as on integrated water resources management.

3. Synthesis

"Science never solves a problem without creating ten more."

George Bernard Shaw

3.1 Key findings

The four articles composing this thesis provide a broad perspective of the various impacts of climate change on glaciers, rock glaciers and water availability in the Tien Shan.

Chapter A – Climate change impacts on glaciers and runoff in Tien Shan (Central Asia) – represents the first comprehensive compilation and regional synopsis of relevant studies addressing past and future changes of Central Asian glaciers and runoff. As virtually all data until 1991 have been published in Russian only and numerous research activities are still documented exclusively in Russian, access to scientific literature is rendered difficult particularly for non-Russian-speakers. This review paper provides a coherent basis for future research and puts the finger on open research questions. The three key findings are:

- Glacier shrinkage is more severe in the low-lying outer Tien Shan ranges than in the continental, high-altitude inner ranges.
- Over the past decades, increasing runoff has been observed in several headwater catchments and rivers draining from the inner Tien Shan ranges (e.g. Tarim river), whereas runoff has remained relatively stable in the outer ranges (e.g. Chu and Talas rivers).

- Water shortages during summer will become more frequent as precipitation is expected to further decrease and glacial meltwater will decrease in the long-term due to reduced glacier volume.

Chapter B – The days of plenty might soon be over in glacierized Central Asian catchments – addresses a major gap detected in Chapter A: "To establish sound conclusions related to changes in future glaciation and runoff, modelling efforts need to integrate […] a representative multi-model ensemble of downscaled climate models." Thus, for the first time in the Tien Shan region, a downscaled ensemble of the latest climate model intercomparison project CMIP5 (Taylor et al. 2012) is used to force the distributed glacio-hydrological model GERM (Huss et al. 2008). A multi-variable calibration allowing a realistic reproduction of each runoff component is then successfully applied and further developed to reduce the problem of equifinality (Konz et al. 2010). The model has been run for the Chon Kemin catchment, but the following three key findings similarly apply to the whole headwater catchment of the Chu river providing water to Bishkek, the capital of Kyrgyzstan:

- Glaciers in the Chon Kemin valley might in a worst-case scenario disappear completely by the end of the 21st century. Even in the most glacier-friendly scenario, glaciers will lose up to two thirds of their 1955 extent by the end of the 21st century.

- The range of climate scenarios translates into different changes of overall water availability, from peak water in the 2020s (warm scenarios) over a gradual decrease (dry-cold scenario) to status quo of total runoff until the end of the 21st century (wet-cold scenario).

- Even in the most optimistic scenarios, summer runoff will decrease in the future (-9%; worst case: -66%, average 2050-2099 as compared to 1955-1999).

Chapter C – Contrasting responses of Central Asian rock glaciers to global warming – sheds light on the climatic response of rock glaciers, which are likely to gain importance for freshwater supply in the context of shrinking glaciers. This study presents the first tree-ring based rock glacier activity reconstruction in Central Asia and can be seen as a major step forward in the field of dendrogeomorphic investigation of the cryosphere. Complemented by the analysis of aerial photographs from the Soviet era, the research setting presented here is unique not only for Central Asia, but worldwide, and allows for the following three key findings:

- On a decadal timescale, the investigated rock glaciers exhibit a common signal of high and low activity.

- Periods of enhanced activity coincide with warm summers and the annual mass balance of the nearby Tuyuksu Glacier fluctuates asynchronously with rock glacier activity.

- On the multi-decadal timescale, the investigated rock glaciers exhibit site-specific trends reflecting different stages of inactivation as a response to the strong air temperature increase since the 1970s.

Chapter D – Coping with changing water resources: The case of the Syr Darya river basin in Central Asia – addresses the impacts of altering water resources on the Central Asian region. So far, most studies on water-related challenges in Central Asia have focused either on climatic-hydrological or on socio-political aspects. In this study, both perspectives are brought together so as to identify the major challenges in the Syr Darya river basin. The three key findings are:

- Reservoirs could take over the role of glaciers as seasonal water redistributors, thus allowing the generation of energy in winter – benefiting upstream countries –, and irrigation for large-scale agriculture in summer – benefiting downstream countries.

- The perception of water as a 'national concern' in Central Asia discourages efforts towards cooperation between states at the regional level.

- Policy-relevant adaptation measures should include consistent data collection and dissemination, cross-sectoral collaboration, promotion of national responsibility and initiative, and agreeing on a regional strategy.

3.2 Overall discussion and outlook

By assessing the impacts of climate change on glaciers, rock glaciers and water availability in the Tien Shan, this thesis addresses a hot topic in a region that has until recently been largely neglected by the international scientific community. The abundant treasures of long-term measurement series and aerial photographs reaching back to the 1940s have so far remained largely unreported beyond the borders of the former Soviet Union, although an increasing number of projects has been initiated in the past few years to investigate climate-driven impacts on the cryosphere and hydrology in the Tien Shan (e.g. CAWa, SuMaRiO, Aksu-Tarim). Hence, this thesis counts among the few works in English language using firsthand information and making it known to the wider public.

The multi-variable calibration of the glacio-hydrological model GERM (Huss et al. 2008) as applied and further developed in this thesis capitalizes this broad data basis and holds much potential for application and further refinement in other catchments of the Tien Shan and elsewhere. Future research should build upon a modelling approach as presented in this thesis to shed light on differences in the response sensitivity among watersheds in different climatic and altitudinal regions of the Tien Shan. Further studies should also continue to improve the extended multi-variable calibration. Particularly the use of satellite images for information on the snow cover duration holds a great potential. Here, snow density measurements in the field could improve the conversion of 2D snow cover information into snow water equivalents. Future modelling attempts should also pay close attention to uncertainties in climate and glacio-hydrological models (Lutz et al. 2013, Huss et al. 2014) – particularly regarding changes in precipitation and evaporation, which present the largest uncertainties in this study. Climate model uncertainty also translates into uncertainty regarding future temperature-precipitation feedbacks, especially in relatively low-lying regions like the Chon Kemin valley. For instance, increased winter precipitation could lead to increased snowpack, higher albedo and thus to reduced glacier melting, or, in contrast, a greater fraction of precipitation could fall as rain if winters become warmer, thus resulting in a declining snowpack (Stewart 2009). Although GERM accounts for these feedback mechanisms, they are highly sensitive, as slightly deviating input data can lead to large differences in the projections.

The dendrogeomorphic reconstruction of rock glacier activity as presented in this thesis remains unprecedented in regard to its large sampling depth, regional perspective and analysis of potential drivers. While comparable dendrogeomorphic studies have been initiated almost 40 years ago in other regions of the world, e.g. in Canada (Zoltai 1975, Bachrach et al. 2004) and in the USA (Shroder 1978, Giardino et al. 1984, Daanen et al. 2012), these studies have been limited to single rock glaciers with low sampling depths. The work presented here mainly focused on the links between climate and rock glacier activity and future investigations should address open questions regarding the time-lag of tree reactions to rock glacier activity. Complementary studies using other methods on the investigated rock glaciers would add value to the results presented in this thesis. For instance, geophysical methods (Maurer and Hauck 2007) could shed light on differing internal structures of the investigated rock glaciers, particularly regarding the depth of the active layer and the ice distribution within the rock glaciers. Borehole temperatures would further give evidence for differing temperatures among the investigated rock glaciers. Finally, the current study could be extended to other forested rock glaciers, e.g. in the Enylchek region in Kyrgyzstan or on California Peak Rock Glacier and Doris Rock Glacier in Colorado and on Sourdough Rock Glacier in Alaska, USA. Such an extension of study sites would pave the way to retrieve a global signal of decadal rock glacier activity. Further research should envisage a combined modelling approach to quantify the contribution of glaciers and rock glaciers to overall water availability in the Tien Shan. A permafrost module is already implemented in GERM, but without detailed field data for calibration and validation, this extension is subject to large uncertainties.

The findings of this thesis call for immediate mitigation measures to assure long-term water security in Central Asia and to avoid an exacerbation of geo-political conflicts. The difficulty for the Central Asian states is and will be to apply the principles of equitable water allocation and to agree on a balanced reservoir management, which would allow the generation of energy in winter – benefiting upstream countries – and irrigation for large-scale agriculture in summer – benefiting downstream countries. While science can provide background information and identify the time horizon for tipping points, action needs to be taken by the regional authorities. In view of the complex geo-political situation in Central Asia, such socio-political aspects greatly amplify the uncertainty stemming from climatic-hydrological projections.

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Acknowledgements

Curriculum vitae

Annina Sorg

Citizenship: Swiss
Date of birth: 01.06.1984 (Lindau ZH)

Work experience

02/2014	Impuls AG Thun, Switzerland Project collaborator natural hazards group
10/2010 – 01/2014	Universities of Geneva and Berne, Switzerland PhD within the EU 7th framework project ACQWA Project secretary of the EU 7th framework project ACQWA Teaching assistant in photogrammetry and dendrogeomorphology Assistant to the SDC-DST Joint Working Group (JWG) and Indian JWG Members Mission to Switzerland Collaboration in the Scientific & Technological Cooperation Programme Switzerland-Russia, Field Research Course on Lahars, Kamchatka
08/2008 – 09/2010	Forest office of the Canton of Berne, Switzerland Scientific collaborator
2005-2008	Internships for the Swiss federal forest authorities' eligibility: Forest office in Sarnen, Switzerland (4 months) Forest office in St-Ursanne, Switzerland (3 months) Intercooperation in Jalalabad, Kyrgyzstan (6 months)
2007	Weissgrund Kommunikation AG Zurich, Switzerland Project assistant

| 2004 - 2008 | Waldschule Winterthur, Switzerland |
| | Guide, accountant and secretary |

| 2001 - 2008 | Feelancer for newspapers „Der Landbote" (Winterthur) and „Kiebitz" (Illnau-Effretikon) |

Studies

| 2002 - 2007 | Diploma / MSc degree in Environmental Sciences at the Swiss Federal Institute of Technology (ETH Zurich) with specialization on natural hazards. |

| 2000 - 2001 | High School Year with Graduation in Manteca, USA |

| 1996 - 2002 | Gymnasium Rychenberg in Winterthur, Switzerland |

Languages

German, English, French, Russian

Publications (peer-reviewed)

Sorg, A., Mosello, B., Shalpykova, G., Allan, A., Hill Clarvis, M., Stoffel, M. (2013): Coping with changing water resources: The case of the Syr Darya river basin in Central Asia. *Environ. Sci. Policy*, doi:10.1016/j.envsci.2013.11.003.

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