***NATURE CLIMATE CHANGE* | REVIEW**

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

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Abstract

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.

Subject terms: Adaptation Agriculture Cryospheric science Geography Hydrology Impacts Mitigation

Introduction

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, 2, 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, 7, 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, 15, 16] but also add to political instability in Central Asia[17].

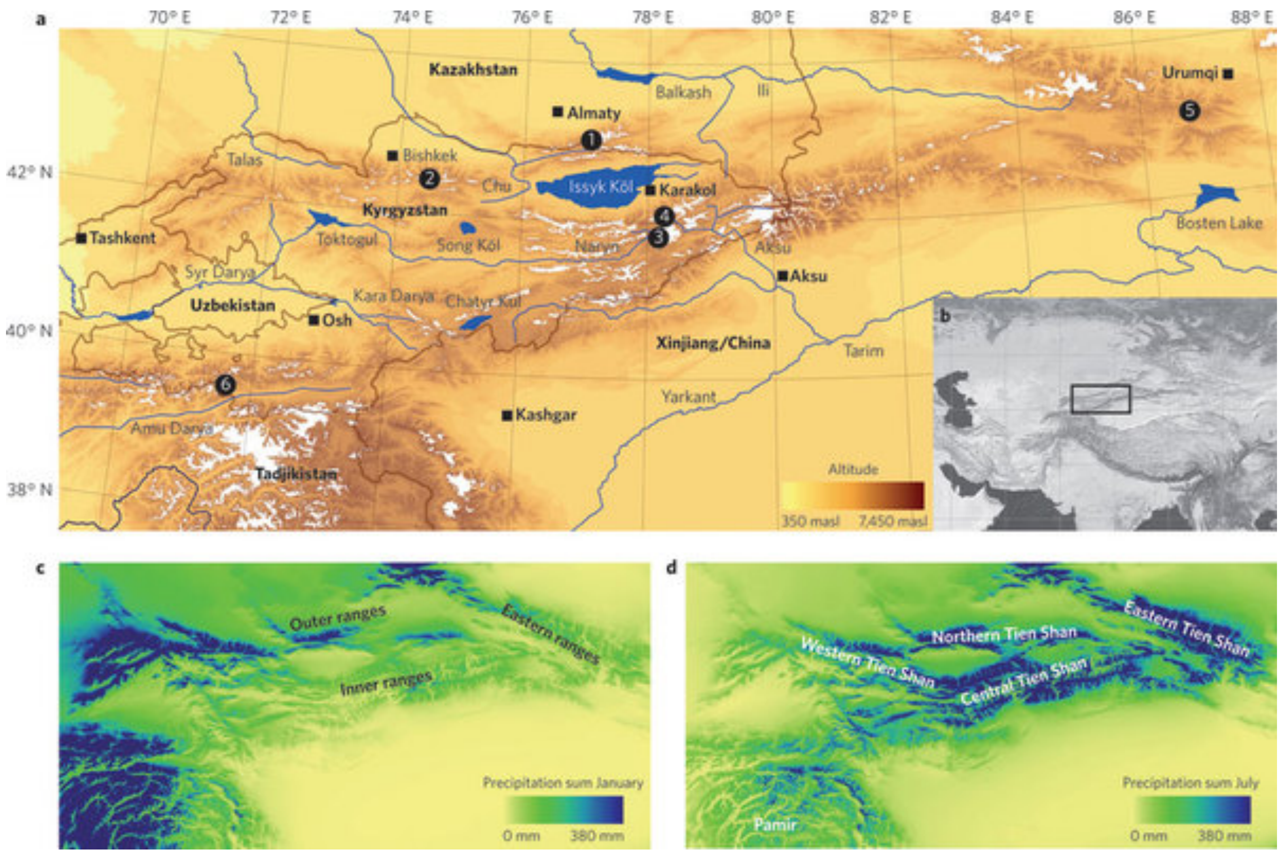
Only a limited number of studies currently address the timing and evolution of expected glacier shrinkage[18, 19] and related changes in runoff[20, 21]. In this Review, we explore the range of changes in glaciation and related discharge in different climatic regions of the Tien Shan. Based on existing 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.

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).

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 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].

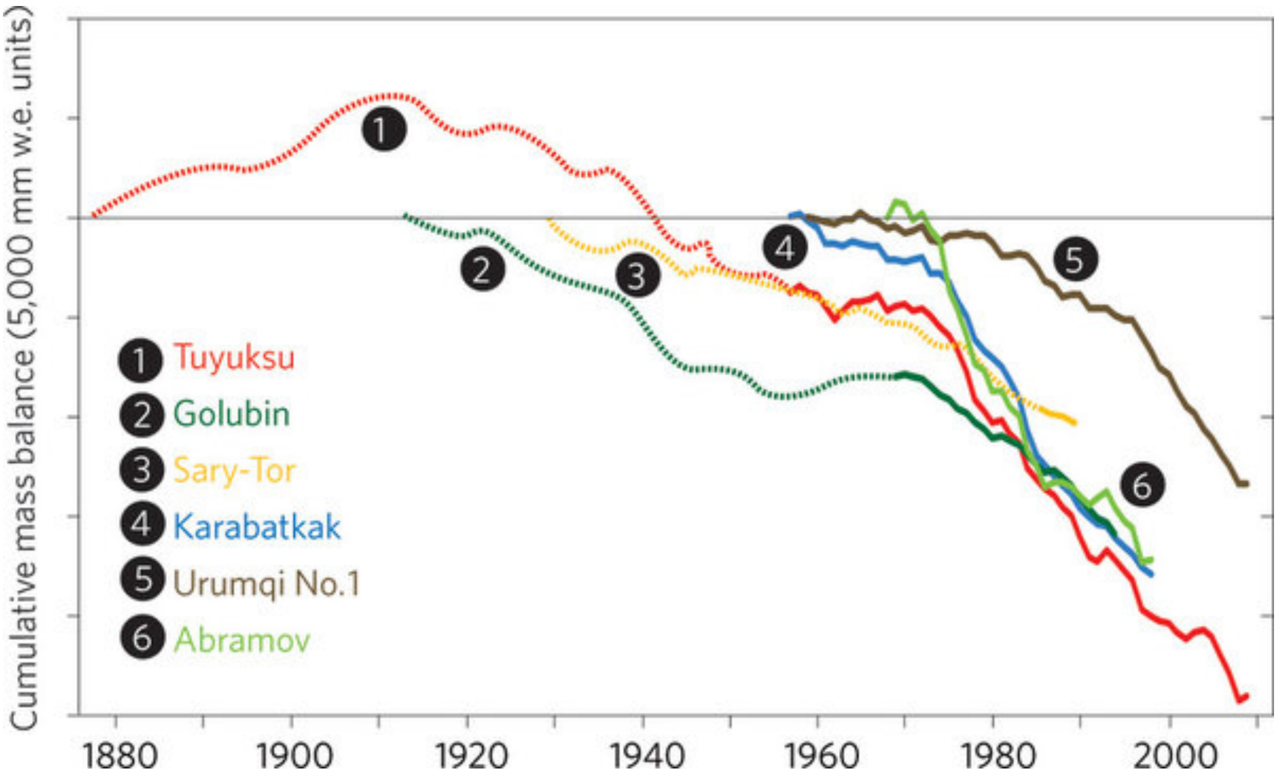
Glacier shrinkage

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 including 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 inventory 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 provide 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, 7, 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].

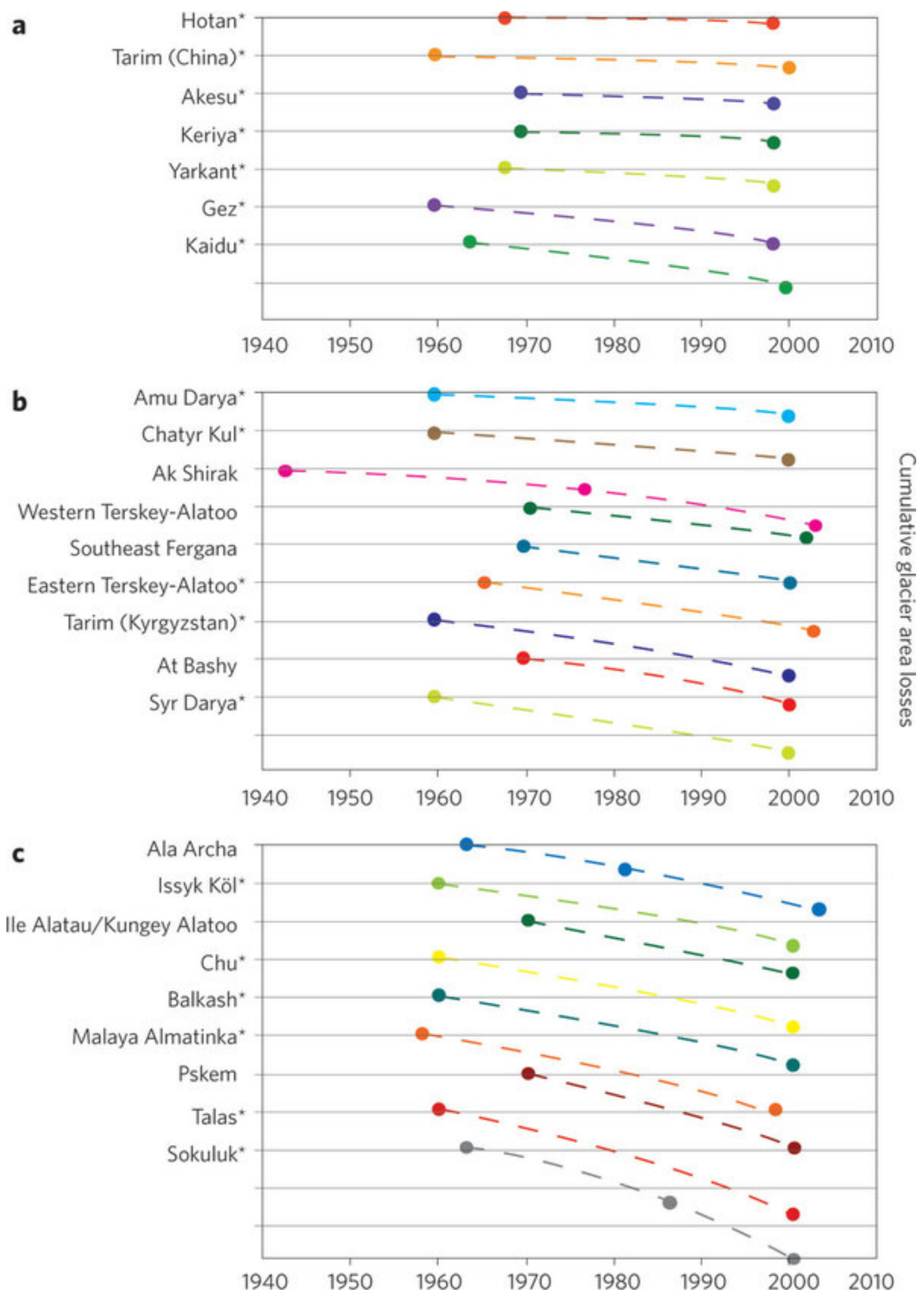
The majority of Tien Shan glaciers were quasi-stable from the late 1950s to the early 1970s[51]. In the mid-1970s, glacier wasting accelerated in the outer[10, 25, 52], inner[9, 19, 53] and eastern[54, 55] ranges. Long-term *in situ* measurements of mass balance on five glaciers in the Tien Shan mountains and on one glacier in the Alay range reflect this acceleration in the loss of ice (Fig. 2 and Supplementary Table S3)[23, 56, 57, 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 equivalent) 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 counterbalanced by smaller losses in the inner ranges (where no recent mass budget measurements exist). Indirect data from remote sensing corroborate the mass balance data, thus revealing striking regional variations[7, 60] (Fig. 3 and Supplementary Table S4). The strongest annual area shrinkage rates since the middle of the twentieth century were 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 represent the southern margin of the Asian high mountains complex (0.1 to 0.7% a^{-1})[61].

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.

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.

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 accumulation and thus mass turnover of the mainly cold glaciers are relatively 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 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].

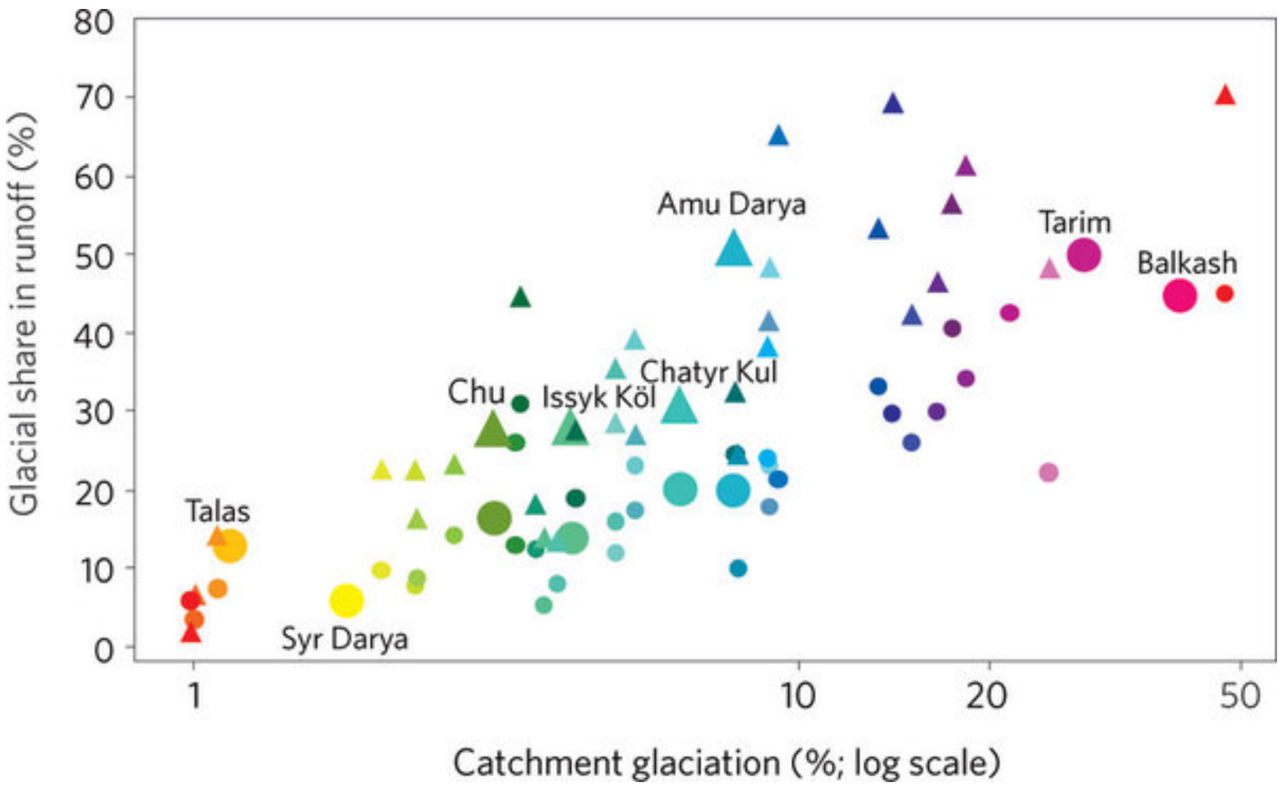
Limitations in glacier change assessments

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 overestimated 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 misinterpreted fresh snowcover and the neglect of debris cover on glaciers 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 balance 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 measurements 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 climate 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 even be 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.

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.

Long-term average annual runoff in Kyrgyzstan has increased from 47.1 km^3 (~1947–1972) to 50 km^3 (1973–2000)[26]. In past decades, increasing runoff has also been measured in several headwater catchments and rivers draining from the inner ranges[26] (for example 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 decreasing, 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 meltwater 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 continue. 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 subject to great uncertainty, in terms of both future climate projections 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 km^2) and the approximations used: current glaciation was estimated from correlation analysis between the Soviet Glacier Inventory and subsequently monitored individual glaciers, 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 irrespective of the approaches used, all currently existing studies anticipate comparable short- and long-term impacts of climate and glacier change on runoff in the main Tien Shan rivers. The current level of total runoff (50 km^3, 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 km^3)[81]. Within the range of the IPCC SRES B1 and A1F1 scenarios, runoff is expected to decline to between 38 and 44 km^3 by 2050 and to 32–41 km^3 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, 87, 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.

References

1. Immerzeel, W. W., van Beek, L. P. H. & Bierkens, M. F. P. Climate change will affect the Asian water towers. *Science* **328**, 1382–1385 (2010).
2. Barnett, T. P., Adam, J. C. & Lettenmaier, D. P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**, 303–309 (2005).
3. Kaser, G., Grosshauser, M. & Marzeion, B. Contribution potential of glaciers to water

availability in different climate regimes. *Proc. Natl Acad. Sci.* **107**, 20223–20227 (2010).

4. Dikikh, A. N., Sokalskaya, A. M., Dyurgerov, M. B., Razek, I. V. & Sinoan, Y. in *Glaciers of Tien Shan* (eds Dyurgerov, M. B., Chaohai, L. & Zichu, C.) 131–167 (VINITI, 1995).
5. Hagg, W., Braun, L. N., Weber, M. & Brecht, M. Runoff modelling in glacierized Central Asian catchments for present-day and future climate. *Nord. Hydrol.* **37**, 1–13 (2006).
6. Solomina, O., Barry, R. & Bodnya, M. The retreat of Tien Shan glaciers (Kyrgyzstan) since the Little Ice Age estimated from aerial photographs, lichenometric and historical data. *Geogr. Ann. A* **86**, 205–215 (2004).
7. Liu, C. & Han, T. Relation between recent glacier variations and climate in the Tien Shan mountains, Central Asia. *Ann. Glaciol.* **16**, 11–16 (1992).
8. Mikhalenko, V. N. *et al*. Glacier recession in the Tien Shan between the 19th and the beginning of the 21st century: results of ice-core drilling and borehole temperature measurements. *Data Glaciol. Stud.* **98**, 175–182 (2005) [in Russian].
9. Narama, C., Kääb, A., Duishonakunov, M. & Abdrakhmatov, K. Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (~1970), Landsat (~2000), and ALOS (~2007) satellite data. *Global Planet. Change* **71**, 42–54 (2010).
10. Bolch, T. & Marchenko, S. Significance of glaciers, rockglaciers and ice-rich permafrost in the Northern Tien Shan as water towers under climate change conditions. *Assess. Snow Glacier Water Resources Asia* **8**, 132–144 (2009).
11. Konovalov, V. G. in *Hydrology in a Changing Environment* (eds Wheater, H. & Kirby, C.) 141–146 (British Hydrological Society, 1998).
12. Hagg, W., Braun, L. N., Kuhn, M. & Nesgaard, T. I. Modelling of hydrological response to climate change in glacierized Central Asian catchments. *J. Hydrol.* **332**, 40–53 (2007).
13. Braun, L. N. & Hagg, W. Present and future impact of snow cover and glaciers on runoff from mountain regions - comparison between Alps and Tien Shan. *Assess. Snow Glacier Water Resources Asia* **8**, 36–43 (2009).
14. Berg, L. S. Is Central Asia drying out? *Proc. Russ. Geogr. Soc.* **41**, 507–521 (1905) [in Russian].
15. Micklin, P. P. Desiccation of the Aral Sea: a water management disaster in the Soviet Union. *Science* **241**, 1170–1176 (1988).
16. Fairless, D. Northern Aral Sea recovering. *Nature* http://dx.doi.org/10.1038/news070409-8 (2007).
17. Malone, E. L. *Changing Glaciers and Hydrology in Asia: Addressing Vulnerabilities to Glacier Melt Impacts*. Technical Report USAID (2010).

18. Niederer, P. *et al*. Tracing glacier wastage in the Northern Tien Shan (Kyrgyzstan/Central Asia) over the last 40 years. *Climatic Change* **86**, 227–234 (2008).
19. Kutuzov, S. & Shahgedanova, M. Glacier retreat and climatic variability in the eastern Terskey-Alatoo, inner Tien Shan between the middle of the 19th century and beginning of the 21st century. *Global Planet. Change* **69**, 59–70 (2009).
20. Kotlyakov, V. M. & Severskiy, I. V. Glaciers of Central Asia: current situation, changes and possible impact on water resources. *Assess. Snow Glacier Water Resources Asia* **8**, 160–177 (2009).
21. UNDP. *Second National Communication of the Kyrgyz Republic to the United Nations Framework Convention on Climate Change* (Bishkek, 2009).
22. Aizen, V. B., Aizen, E. M., Melack, J. M. & Dozier, J. Climatic and hydrologic changes in the Tien Shan, Central Asia. *J. Clim.* **10**, 1393–1404 (1997).
23. Dyurgerov, M. B. *et al*. Mass balance monitoring of three Tien Shan glaciers. *Data Glaciol. Stud.* **77**, 79–86 (1992) [in Russian].
24. Glazirin, G. E. *Distribution and Regime of Mountain Glaciers* (Hydrometeoizdat, 1985).
25. Bolch, T. Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data. *Global Planet Change* **56**, 1–12 (2007).
26. Mamatkanov, D. M., Bazhanova, L. V. & Romanovskij, V. V. *Water Resources of Kyrgyzstan* (National Academy of Science of the Kyrgyz Republic, Institute of Water Problems and Hydropower, 2006) [in Russian].
27. Tao, H., Gemmer, M., Bai, Y., Su, B. & Mao, W. Trends of streamflow in the Tarim River Basin during the past 50 years: Human impact or climate change? *J. Hydrol.* **400**, 1–9 (2011).
28. Kuzmichenok, V. A. *Changes in Climate Characteristics and Altitude of Firn Line in Kyrgyzstan during the Second Half of the 20th Century* (Bishkek, 2010).
29. Cruz, R. V. *et al*. in *IPCC Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L. *et al*.) 469–506 (Cambridge Univ. Press, 2007).
30. Kuzmichenok, V. Monitoring of water, snow and glacial resources of Kyrgyzstan. *Assess. Snow Glacier Water Resources Asia* **8**, 84–99 (2009).
31. Giese, E., Mossig, I., Rybski, D. & Bunde, A. Long-term analysis of air temperature trends in Central Asia. *Erdkunde* **61**, 186–202 (2007).
32. Giese, E. & Mossig, I. *Climate change in Central Asia* (Institute for Geography, Justus-Liebig University, Giessen, 2004) [in German].
33. Williams, M. W. & Konovalov, V. G. Central Asia temperature and precipitation data, 1879–

2003. (USA National Snow and Ice Data Center, 2008); http://nsidc.org/data/g02174.html

34. Böhner, J. Secular climate fluctuatians and recent climate trends in Central and High Asia [Säkuläre Klimaschwankungen und rezente Klimatrends Zentral-und Hochasiens]. *Göttinger Geogr. Abh.* **101** (1996).
35. Uppala, S. M. *et al*. The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.* **131**, 2961–3012 (2005).
36. Kalnay, E. *et al*. The NCEP/NCAR 40-year reanalysis project *Bull. Am. Meteorol. Soc.* **77**, 434–471 (1996).
37. Schneider, U., Becker, A., Meyer-Christoffer, A., Ziese, M. & Rudolf, B. *Global Precipitation Analysis Products of the GPCC* 1–13 (Global Precipitation Climatology Centre, 2011).
38. Wright, C. K., de Beurs, K. M., Akhmadieva, Z. K., Groisman, P. Y. & Henebry, G. M. Reanalysis data underestimate significant changes in growing season weather in Kazakhstan. *Environ. Res. Lett.* **4**, 045020 (2009).
39. IPCC *Special Report on Emissions Scenarios* (eds Nakicenovic, N. & Swart, R.) (Cambridge Univ. Press, 2000).
40. Qin, D., Liu, S. & Li, P. Snow cover distribution, variability, and response to climate change in Western China. *J. Clim.* **19**, 1820–1833 (2006).
41. Glazirin, G. Hydrometeorological monitoring system in Uzbekistan. *Assess. Snow Glacier Water Resources Asia* **8**, 65–83 (2009).
42. Dikikh, A. N. *Glacial Water Resources in the Issyk-Kul Region (Kyrgyzstan) and their Current and Future Situation* (Institute for Geography, Justus-Liebig Univ., Giessen, 2004) [in German].
43. Schröder, H. *et al*. *Assessment of Renewable Ground and Surface Water Resource and the Impact of Economic Activity on Runoff in the Basin of the Ili River, Republic of Kazakhstan* (Kazakh Academy of Sciences, 2002).
44. Severskiy, I. V. & Zichu, X. *Snow Cover and Avalanches in the Tien Shan Mountains* (VAC, 2000).
45. Khalsa, S. J. S. & Aizen, V. B. Variability in Central Asia seasonal snow cover during the MODIS period of record. *Geophys. Res. Abstr.* **10**, EGU2008-A-0443 (2008).
46. Aizen, V. B., Aizen, E. M. & Kuzmichenok V, A. Glaciers and hydrological changes in the Tien Shan: simulation and prediction. *Environ. Res. Lett.* **2**, 045019 (2007).
47. Kuzmichenok, V. A. Glaciers of the Tien Shan. Computerized analysis of the inventory. *Data Glaciol. Stud.* **77**, 29–40 (1993) [in Russian].
48. Hydrometeoizdat. *Glacier Inventory of the USSR 14/2: Central Asia* (Hydrometeoizdat, 1973) [in Russian].

49. Yao, T. *et al*. *Recent Glacial Retreat in the Chinese part of High Asia and its Impact on Water Resources of Northwest China* (IHP/HWRP, Almaty, 2009).
50. Savoskul, O. S. Modern and Little Ice Age glaciers in 'humid' and 'arid' areas of the Tien Shan, Central Asia: two different patterns of fluctuation. *Ann. Glaciol.* **24**, 142–147 (1997).
51. Makarevich, K. G. & Liu, C. in *Glaciers of Tien Shan* (eds Dyurgerov, M., Liu, C. & Zichu, X.) 189–213 (VINITI, 1995) [in Russian].
52. Vilesov, E. N. & Morozova, V. I. Change of current glaciation and glacier runoff in the Northern Dzungary in the second half of the 20th century. *Hydrometeorol. Ecol. [Gidrometeorologija I Ekologija]* **4**, 124–143 (2008) [in Russian].
53. Aizen, V. B., Kuzmichenok, V. A., Surazakov, A. B. & Aizen, E. M. Glacier changes in the Tien Shan as determined from topographic and remotely sensed data. *Global Planet. Change* **56**, 328–340 (2007).
54. Liu, S. *et al*. Glacier retreat as a result of climate warming and increased precipitation in the Tarim river basin, northwest China. *Ann. Glaciol.* **43**, 91–96 (2006).
55. Shangguan, D. *et al*. Glacier changes during the last forty years in the Tarim Interior River basin, northwest China. *Prog. Nat. Sci.* **19**, 727–732 (2009).
56. Cao, M. S. Detection of abrupt changes in glacier mass balance in the Tien Shan Mountains. *J. Glaciol.* **44**, 352–358 (1998).
57. WGMS *Glacier Mass Balance Bulletin (2006–2007)* (WGMS Zurich, 2009 and earlier volumes).
58. Dolgushin, L. D. & Osipova, G. B. *Glaciers* (Mysl, 1989) [in Russian].
59. Jacob, T., Wahr, J., Pfeffer, T. W. & Swenson, S. Recent contributions of glaciers and ice caps to sea level rise. *Nature* **482**, 514–518 (2012).
60. Dyurgerov, M. B. *et al*. On the cause of glacier mass balance variations in the Tian Shan mountains. *GeoJournal* **33**, 311–317 (1994).
61. Bolch, T. *et al*. The state and fate of Himalayan glaciers. *Science* **336**, 310–314 (2012).
62. Narama, C., Shimamura, Y., Nakayama, D. & Abdrakhmatov, K. Recent changes of glacier coverage in the western Terskey-Alatoo range, Kyrgyz Republic, using Corona and Landsat. *Ann. Glaciol.* **43**, 223–229 (2006).
63. Dyurgerov, M. B., Liu, C. & Zichu, X. *Glaciers of Tien Shan* (VINITI, 1995) [in Russian].
64. Hagg, W., Mayer, C., Lambrecht, A. & Helm, A. Sub-debris melt rates on southern Inylchek glacier, Central Tien Shan. *Geogr. Ann. A* **90**, 55–63 (2008).
65. Wang, L., Li, Z. & Wang, F. Spatial distribution of the debris layer on glaicers of the Tuomuer

Peak, Western Tien Shan. *J. Earth Sci.* **22**, 528–538 (2011).

66. Nuimura, T. *et al*. Temporal changes in elevation of the debris-covered ablation area of Khumbu Glacier in the Nepal Himalaya since 1978. *Arct. Antarct. Alp. Res.* **43**, 246–255 (2011).
67. Bolch, T., Pieczonka, T. & Benn, D. I. Multi-decadal mass loss of glaciers in the Everest area (Nepal, Himalaya). *The Cryosphere* **5**, 349–358 (2011).
68. Sakai, A., Takeuchi, N., Fujita, K. & Nakawo, M. Role of supraglacial ponds in the ablation process of a debris-covered glacier in the Nepal Himalayas. *Int. Assoc. Hydrol. Sci. (IAHS) Publ.* **265**, 119–130 (2000).
69. Zhang, Y., Liu, S., Ding, Y., Li, J. & Shangguan, D. Preliminary study of mass balance on the Keqicar Baxi Glacier on the south slopes of Tianshan mountains. *J. Glac. Geocry.* **28**, 477–484 (2006) [in Chinese with English abstract].
70. Vilesov, E. N. & Uvarov, V. N. *Evolution of the Recent Glaciation in the Zailyskiy Alatau in the 20th Century* (Kazakh State Univ., 2001) [in Russian].
71. Khromova, T. E., Dyurgerov, M. B. & Barry, R. G. Late-twentieth century changes in glacier extent in the Ak-shirak Range, Central Asia, determined from historical data and ASTER imagery. *Geophys. Res. Lett.* **30**, 1863 (2003).
72. Aizen, V. B., Kuzmichenok, V. A., Surazakov, A. B. & Aizen, E. M. Glacier changes in the central and northern Tien Shan during the last 140 years based on surface and remote-sensing data. *Ann. Glaciol.* **43**, 202–213 (2006).
73. Viviroli, D., Weingartner, R. & Messerli, B. Assessing the hydrological significance of the world's mountains. *Mountain Res. Dev.* **23**, 32–40 (2003).
74. Schulz, V. L. *Rivers of Central Asia* (Hydrometeoizdat, 1965) [in Russian].
75. Kemmerikh, A. O. The role of glaciers in runoff of Central Asian rivers. *Data Glaciol. Stud.* (1972) [in Russian].
76. Chen, Y., Takeuchi, K., Xu, C., Chen, Y. & Xu, Z. Regional climate change and its effects on river runoff in the Tarim Basin, China. *Hydrol Process* **20**, 2207–2216 (2006).
77. Dyurgerov, M. B., Uvarov, V. N. & Kostjashkina, T. E. Mass balance and runoff of Tuyuksu Glacier and the north slope of the Zailiyskiy Alatau range, Tien Shan. *Z. Gletscherk. Glazialgeol.* **32**, 41–54 (1996).
78. Siegfried, T. *et al*. Will climate change exacerbate or mitigate water stress in Central Asia? *Clim. Change* **112**, 881–889 (2012).
79. Bernauer, T. & Siegfried, T. Climate change and international water conflict in Central Asia. *J. Peace Res.* **49**, 227–239 (2012).

80. Dikikh, A. N. & Hagg, W. Climate driven changes of glacier runoff in the Issyk-Kul basin, Kyrgyzstan. *Z. Gletscherk. Glazialgeol.* **39**, 75–86 (2004).

81. Aizen, V. B., Aizen, E. M. & Kuzmichenok, V. A. Geo-informational simulation of possible changes in Central Asian water resources. *Global Planet. Change* **56**, 341–358 (2007).

82. Ming, J. *et al*. Black carbon (BC) in the snow of glaciers in west China and its potential effects on albedos. *Atmos. Res.* **92**, 114–123 (2009).

83. Scherler, D., Bookhagen, B. & Strecker, M. R. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geosci.* **4**, 156–159 (2011).

84. Marchenko, S. S., Gorbunov, A. P. & Romanovsky, V. E. Permafrost warming in the Tien Shan Mountains, Central Asia. *Global Planet. Change* **56**, 311–327 (2007).

85. Aizen, V., Aizen, E., Glazirin, G. & Loaiciga, H. A. Simulation of daily runoff in Central Asian alpine watersheds. *J. Hydrol.* **238**, 15–34 (2000).

86. Jansky, B., Sobr, M. & Yerokhin, S. Typology of high mountain lakes of Kyrgyzstan with regard to the risk of their rupture. *Limnol. Rev.* **6**, 135–140 (2006).

87. Bolch, T. *et al*. Identification of potentially dangerous glacial lakes in the northern Tien Shan. *Nat. Hazards* **59**, 1691–1714 (2011).

88. Narama, C., Duishonakunov, M., Kääb, A., Daiyrov, M. & Abdrakhmatov, K. The 24 July 2008 outburst flood at the western Zyndan glacier lake and recent regional changes in glacier lakes of the Teskey Ala-Too range, Tien Shan, Kyrgyzstan. *Nat. Hazards Earth Syst.* **10**, 647–659 (2010).

89. Watkins, K. *Beyond Scarcity: Power, Poverty and the Global Water Crisis* (United Nations Development Programme, 2006).

90. Kezer, K. & Matsuyama, H. Decrease of river runoff in the Lake Balkhash basin in Central Asia. *Hydrol. Process* **20**, 1407–1423 (2006).

91. Thevs, N. Water scarcity and allocation in the Tarim Basin: decision structures and adaptations on the local level. *J. Curr. Chin. Affairs* **40**, 113–137 (2011).

92. Kramer, M. *Integrative and Sustainable Water Management: Potential for Cooperation between Germany and Central Asia* (Gabler/Springer, 2010) [in German].

93. Klerx, J. & Imanackunov, B. *Lake Issyk-Kul: Its Natural Environment* (NATO Science Series, 2003).

94. Hagg, W. & Braun, L. N. in *Climate and Hydrology in Mountain Areas* (eds De Jong, C., Ranzi, R. & Collins, D.) 263–275 (Wiley, 2005).

95. Böhner, J. General climatic controls and topoclimatic variations in Central and High Asia.

Boreas **35**, 279–295 (2006).

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Competing financial interests

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