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

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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

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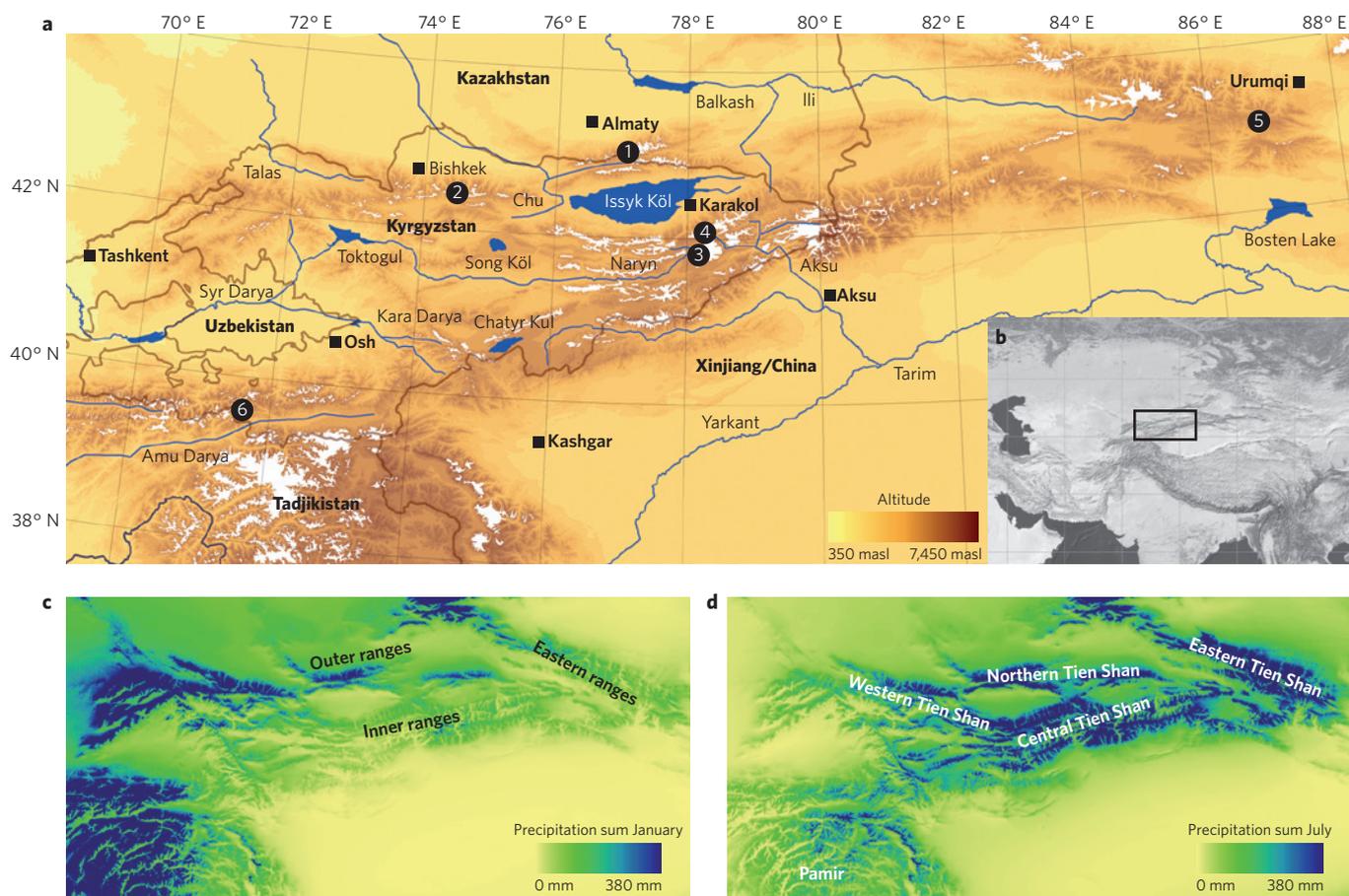**Figure 1 | Location map of the Tien Shan mountains and seasonal distribution of precipitation in Central Asia. a**, Hydrological network in Central Asia, including glaciers, main lakes, reservoirs and rivers. Glaciers with mass balance measurements are indicated with numbers corresponding to Fig. 2. 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].
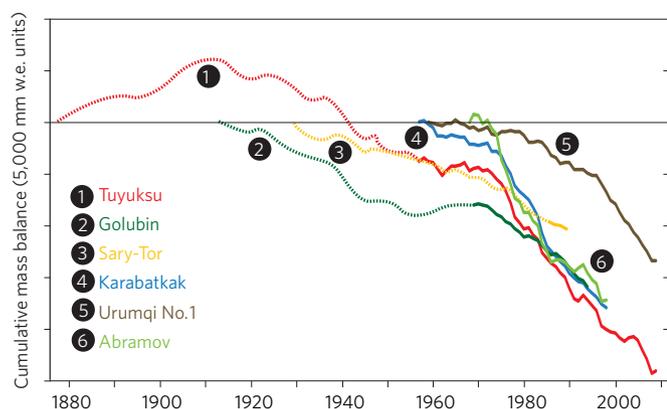
Figure 2 | Net mass balances for selected glaciers in Central Asia.
Long-term cumulative mass balances (solid lines) and reconstructions
(dashed lines) of Central Asian glaciers. The horizontal black line indicates
the level at first measurement. Sources: see Supplementary Table S3.

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 km² (refs 46,47) to 16,427 km² (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 km²) 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 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
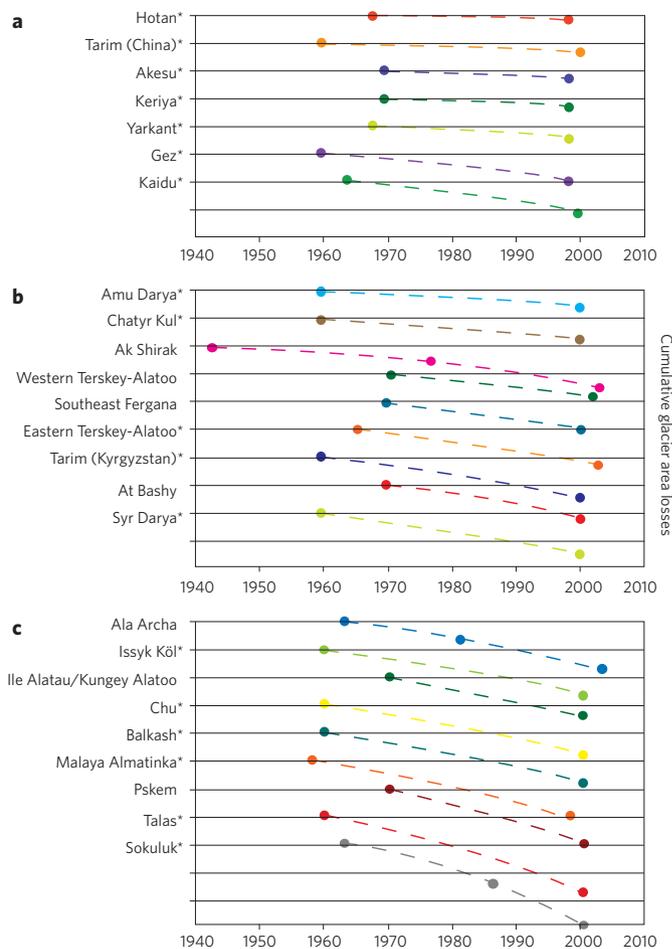area shrinkage rates since the middle of the twentieth century were

**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
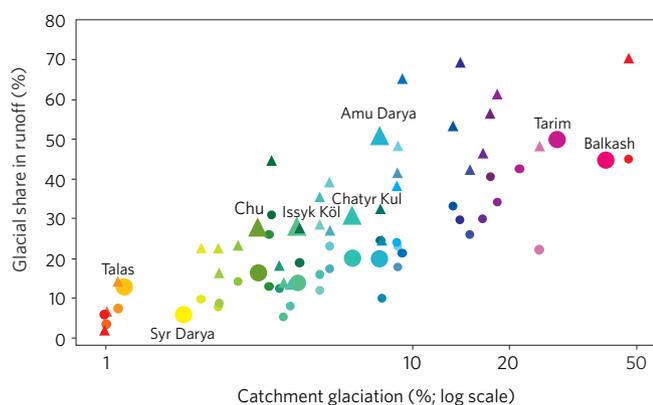reported for the largest glaciers of the inner ranges such as Inylchek

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 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.

Long-term average annual runoff in Kyrgyzstan has increased from 47.1 km³ (~1947–1972) to 50 km³ (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 km²) 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 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.