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

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Abstract

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. With an annual area loss of 0.36 to 0.76%, glaciers are retreating particularly fast in the northern Tien Shan, 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, which we then force with downscaled data from phase five of the Climate Model Intercomparison Project CMIP5. 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* being reached 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 is projected to 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 in the densely populated forelands of the Tien Shan.

 Online supplementary data available from stacks.iop.org/ERL/9/104018/mmedia

Keywords: climate change, glacier retreat, hydrology, water resources, Tien Shan

(Some figures may appear in colour only in the online journal)

1. Introduction

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 hydropower potential (Barnett *et al* 2005). 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 and area. A crossing of this tipping point (*peak water*) is expected to occur earlier in northern Tien Shan (Vilesov and Uvarov 2001, Kotlyakov and Severskiy 2009) than in the higher inner and eastern Tien Shan ranges (Hagg *et al* 2013b, Ye *et al* 2005), but studies using sophisticated distributed glacio-hydrological models and state-of-the-art climate projections are still rare (Lutz *et al* 2013, Zhang *et al* 2007, Hagg *et al* 2013a).

In this study, we assess past and future glacier- and runoff changes with the distributed Glacier Evolution Runoff



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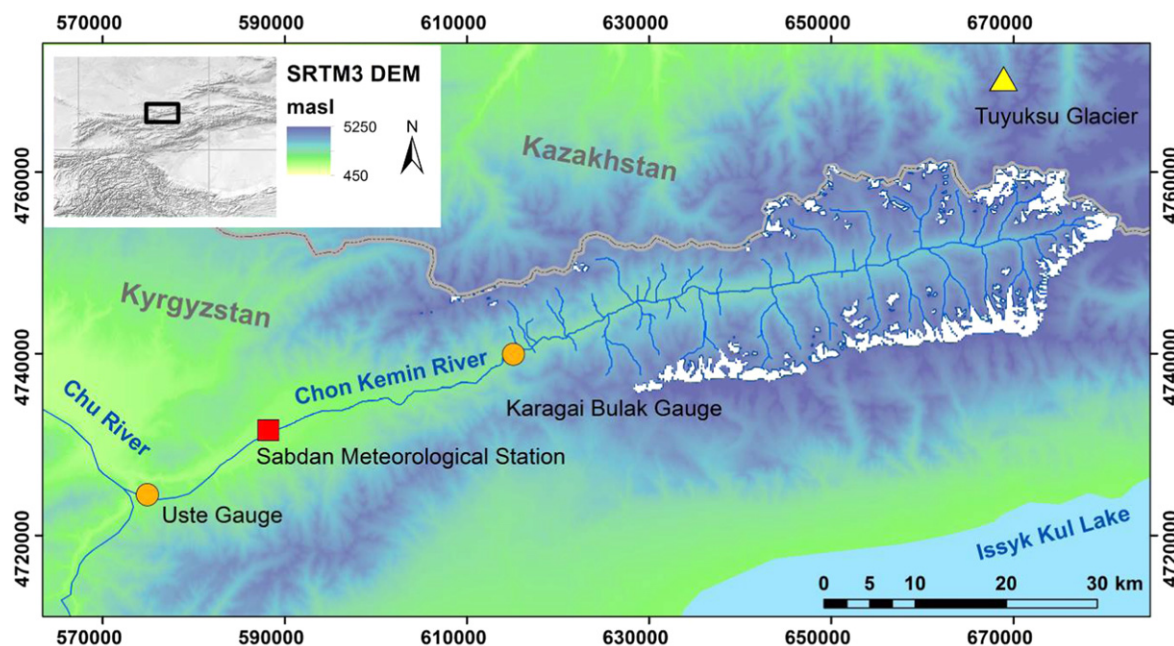


Figure 1. Overview of the glacierized Chon Kemin catchment in the Kyrgyz-Kazakh border region.

Model GERM (Huss *et al* 2008). In a novel approach, we combine several observational time series covering large parts of the 20th century with satellite-derived snow cover data to calibrate and validate all relevant processes in the glacio-hydrological model. Although the Tien Shan mountains are generally referred to as a data-sparse region (Lutz *et al* 2013, Unger-Shayesteh *et al* 2013), we rely here on exceptionally long data series of temperature and precipitation (1937–90), discharge (1951–98) 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 1985–89) and daily snow coverage from Landsat scenes (1977/1979) as well as information on high-altitude precipitation and basin evaporation (Aizen *et al* 2007) to calibrate all relevant parameters and processes.

Unprecedented for Central Asia, we then force the model with downscaled data from phase five of the Climate Model Intercomparison Project CMIP5 (Taylor *et al* 2012) to close the meteorological data gap of the past 20 years since the collapse of the Soviet Union and to make scenario-based glacier and runoff projections in the unregulated Chon Kemin catchment up to the end of the 21st century.

2. Study area

The deeply incised Chon Kemin valley (figure 1) 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 km from west to east, the valley stretches from 1500 m above sea level to Chok Tal peak at 4760 m asl, with an average elevation of 3170 m asl. The headwater catchment above Karagai Bulak gauge (42.8°

N, 76.41°E) covers an area of 1037 km², of which around 11% (112 km²) have been covered by 217 glaciers in 1999 (Bolch 2007). Eastern and Western Aksu are the largest glaciers in the valley, covering 6.65 and 5.52 km², respectively.

The Chon Kemin river is the most important tributary (40% of total runoff) to the Chu river (Katchaganov 2011), providing Kyrgyzstan's capital Bishkek with fresh water before running further northwest to the Kazakh steppe. During summer, the Chon Kemin river is fed mostly by 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 (Aizen *et al* 1997, Bolch 2007). 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 (Katchaganov 2011). 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 1937–98). 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 (Böhner 1996).

3. Data, models and methods

3.1. Glacio-hydrological model

For this study, we use the fully distributed, deterministic, conceptual glacio-hydrological Glacier Evolution Runoff Model (GERM) (Huss *et al* 2008). The model calculates all components of the surface water balance with a focus on accumulation and melt processes on glaciers, and 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 (Huss *et al* 2008). 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 (Huss and Farinotti 2012). Transient changes in 3D glacier surface geometry and ice volume are assessed with the empirical, mass conserving Δh -parameterization (Huss *et al* 2010). 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.

We use a simplified energy-balance approach (Oerlemans 2001), which outperforms temperature-index-methods for long modeling periods and in continental climates as it is less sensitive to temperature changes (Oerlemans 2001, Pellicciotti *et al* 2005). This renders the simplified energy balance approach particularly adequate for modeling in arid regions like Central Asia and over multi-decadal time periods with significant trends in air temperature. The energy available for melt is calculated as

$$\psi = \{a(1 - \alpha)Q_E\} + \{c_0 + c_1T\}, \quad (1)$$

where a is the atmospheric transmission to solar irradiance (reduced incoming shortwave radiation due to cloudiness or haze), α the surface albedo for snow, ice or firn, and Q_E the clear-sky shortwave radiation (mean daily potential global radiation calculated from slope, aspect and topographic shading) representing the short-wave radiation balance. The sum of the long-wave radiation balance and turbulent heat exchanges is parameterized using the parameters c_0 , c_1 (set to $10 \text{ W m}^{-2}\text{K}^{-1}$, according to Oerlemans (2001)), and air temperature T .

An empirical evaporation model is implemented in GERM, which calculates daily potential evaporation based on air temperature and the saturation vapor pressure (Huss *et al* 2008, Hamon 1961). 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 that includes a function accounting for the decrease of soil moisture.

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 (Huss *et al* 2008). The runoff routing model is based on the concept of linear storage, with an interception-, slow- and fast reservoir (Farinotti *et al* 2012, Huss *et al* 2008).

3.2. Multi-variable calibration and validation

We developed a new multi-variable calibration and validation approach combining several observational time series that cover large parts of the 20th century with satellite-derived

snow cover data to calibrate all relevant processes in the glacio-hydrological model. It has been shown that parameters of glacier melt models can be subject to long-term variations (Huss *et al* 2009). To obtain a robust parameter set for application over the next century, we used the longest possible period for parameter determination and therefore did not split the datasets, which would be important if only one variable (e.g. discharge) were used to constrain model parameters. Here, we rely on a suite of different observational variables and can thus use some datasets for calibration (i.e. glacier mass balance, snow cover evolution, equilibrium line altitudes) and others for independent validation (i.e. discharge, glacier area change). This approach allows a realistic reproduction of all runoff components, which reduces the problem of equifinality ('right answers for wrong reasons'; (Hagg *et al* 2013a).

The model has been manually calibrated and validated to determine the key model parameters. In a first step, parameters describing the spatial distribution of meteorological variables were constrained based on values from a previous study (Aizen *et al* 2007) to reach a realistic level of mean annual runoff. Then, the melt parameters were calibrated to accomplish a reasonable agreement with observed accumulation and ablation processes of snow and ice. Last, the runoff routing parameters were tuned to optimize the seasonally realistic distribution of runoff as indicated by the field data series.

3.3. Input and calibration data

We rely here on exceptionally long data series of temperature and precipitation (1937–90), discharge (1951–98) and annual glacier mass balance and ELA (1957–today) for forcing and calibrating the model. We also included annual snow cover duration from the Advanced Very High Resolution Radiometer (AVHRR 1985–89) and daily snow coverage from Landsat scenes (1977/1979) as well as information on high-altitude precipitation and basin evaporation (Aizen *et al* 2007) to calibrate all relevant parameters and processes (supplementary figures S1, S4–S7 and supplementary tables S1–S3 available at stacks.iop.org/ERL/9/104018/mmedia).

Temperature and precipitation time series from Sabdan meteorological station (1524 m asl) were available in daily resolution for the time period 1937–90 from the Royal Netherlands Meteorological Institute. The precipitation data series contained gaps, which we filled with daily data from the National Climatic Data Center (NOAA). Discharge data from Karagai Bulak gauge (2078 m asl) were available in daily resolution for the time period 1951–96 (Kirgizgidromet 1936–2002). Mass balance and ELA have been assessed since 1957 at Tuyuksu glacier, which makes them the longest series in Central Asia (WGMS 2009). Glacier outlines are from Bolch (2007), who mapped the glacier coverage in the Chon Kemin and surrounding valleys using a snow-free Landsat ETM+ scene from 08/08/1999. We have also digitized glacier outlines reflecting the situation in the 1950s based on topographic maps at the scale of 1:100 000 (Soviet Topographic Map 1988) to calibrate the

model. Land use classification has been derived from a supervised classification of the same Landsat ETM+ scene as used for the glacier outlines (08/08/1999). 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). Annual snow cover duration has been assessed from the Advanced Very High Resolution Radiometer (AVHRR) at a resolution of 1 km starting in 1986 (Dietz *et al* 2013). The digital elevation model (DEM) and catchment area delineation are based on data from the Shuttle Radar Topography Mission SRTM3 (Jarvis *et al* 2008).

3.4. Downscaling of future climate data

The calibrated model was then forced with daily time series of future temperature and precipitation. To cover the whole range of possible 21st century climatic changes in the glacio-hydrological modeling (Vuuren *et al* 2011), we evaluated all available Global Circulation Model (GCM) runs for the two most extreme Representative Concentration Pathways scenarios (Meinshausen *et al* 2011), RCPs 2.6 and 8.5, which have been generated under the CMIP5 (Taylor *et al* 2012). Similar to previous studies (Lutz *et al* 2013, Immerzeel *et al* 2013), we selected the four GCM runs spanning the 10th and 90th percentiles of changes in summer temperature and in total precipitation and downscaled these four scenarios with the delta-change approach (Prudhomme *et al* 2002) to obtain transient daily time series of temperature and precipitation until 2099 with the same resolution, characteristics and variance as the station data. This procedure intentionally suppresses some of the year-to-year variability observed in the past in order to reveal interpretable long-term trends in the output variables. All modeling results span the range of the four possible future scenarios (dry-cold, dry-warm, wet-cold and wet-warm future climates) and are compiled for the past (1955–99), the present and near future (2000–49) and the far future (2050–99).

3.5. Statistical trend analysis of past temperature, precipitation and runoff

Trends in measured temperature, precipitation, mass balance and runoff were analyzed with the 2-sided non-parametric Mann-Kendall test at the 80, 90 and 95% significance levels (Kendall 1975, Helsel and Hirsch 1992). Serial correlation was removed using Sen's slope method (Sen 1968) and a pre-whitening approach (Zhang *et al* 2000). 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 1937–90 period. Two matrices were compiled for each parameter: trends are indicated with the standardized test statistics τ , trend significance is indicated by the 2-sided p -value.

4. Results

4.1. Observed changes in climate and runoff

Like in other parts of Central Asia, mean annual air temperature (MAAT 1937–98: 4.9 °C) and mean annual precipitation (MAP 1937–98: 445 mm) have increased in the Chon Kemin valley over recent decades (Sabdan meteorological station, 1524 m asl; supplementary figure S2), probably as a result of the weakening of the Siberian anticyclone (Giese *et al* 2007). 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 (Kriegel *et al* 2013, Bolch 2007).

4.2. Projected changes in climate, glaciers and runoff

MAAT and MAP are likely to increase further by +1.6 to +7.8 °C and –2 to +20%, respectively, according to the four GCM runs spanning the range of dry-cold, dry-warm, wet-cold and wet-warm future CMIP5 climates (2081–99 versus 1961–90; supplementary figure S3).

These changes in climate are projected to result in negative glacier mass balances and to cause a rise in ELA from 3922 (average 1955–99) to 3976–4031 (2000–49) and 3991–4409 (2050–99) m asl, depending on the scenario, and thus cause significant losses in glacier area and volume. In the more 'glacier-friendly', dry-cold and wet-cold scenarios, glaciers are projected to cover 38 and 53 km² 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 around 2080 (figures 2(a), (b), table 1). These distinct differences between the cold and warm scenarios confirm that enhanced glacier shrinkage is strongly correlated with increasing air temperatures in the Tien Shan (Lutz *et al* 2013, Ye *et al* 2005, Kriegel *et al* 2013).

The projected depletion of glacial reserves translates into three different response types of glacial- and total runoff (figure 2(c), 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 in glacial and total runoff. The dry-cold scenario leads 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 (Mamatkanov *et al* 2006), whereas results from the cold scenarios correspond more with comparable studies for higher altitude catchments in Central Asia (Hagg *et al* 2013a) and the Himalayas (Immerzeel *et al* 2013, Lutz *et al* 2014).

These fundamental changes in the headwater catchment will ultimately influence seasonal runoff in the Chon Kemin

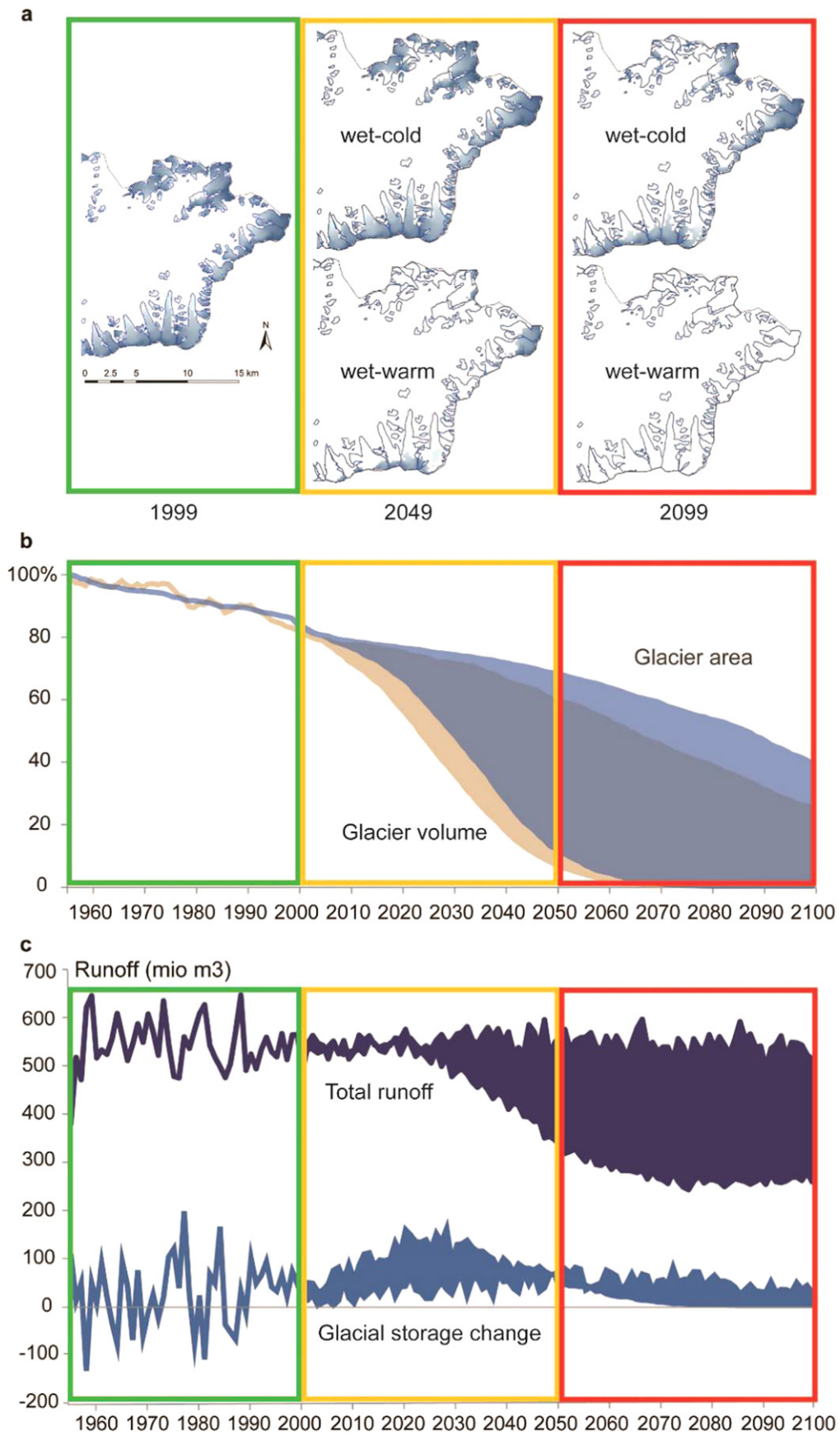


Figure 2. Glacier and runoff evolution in the Chon Kemin catchment in the past (1955–99; green), the present and near future (2000–49; orange) and the far future (2050–99; red): (a) Changes in glacier extent at the end of each period (outlines are from 1955). (b) Glacier area and ice volume evolution 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).

Table 1. Percentual changes in glacio-hydrological key parameters for all scenarios (dry-warm, wet-cold, wet-warm, dry-cold) relative to the past (1955–99).

All numbers are in percent		Present and near future (2000–49)				Far future (2050–99)			
Scenario		Dw	Wc	Ww	Dc	Dw	Wc	Ww	Dc
Glacier area		–40	–19	–43	–19	–97	–41	–98	–48
Glacier volume		–49	–23	–52	–24	–98	–56	–99	–64
Glacier storage change		+275	+17	+288	+36	–54	+62	–67	+93
Precipitation		0	+5	+7	+1	–1	+15	+17	–1
Evaporation		+15	+8	+22	+4	+25	+21	+46	+9
Total runoff		–19	–1	–6	–4	–49	0	–37	–13
Total summer runoff		–15	–4	–13	–9	–66	–9	–61	–22
Snow cover duration		–2	+5	–5	+5	–21	–1	–29	–2

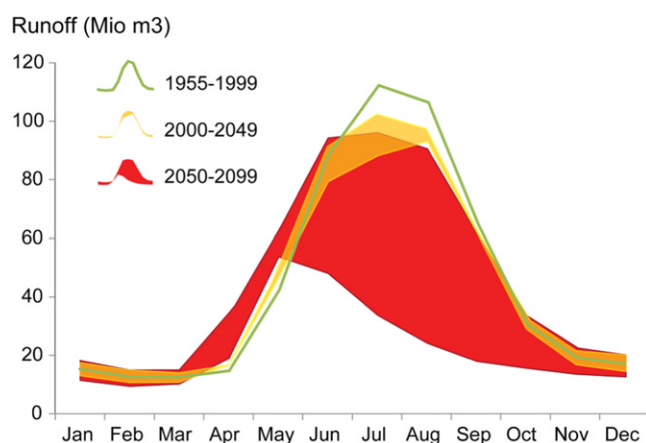


Figure 3. Averaged monthly runoff distribution of the Chon Kemin River in the past (1955–99), the present/near future (2000–49) and the far future (2050–99) including all simulated scenarios.

river (figure 3)—as in other catchments in the same region (Hagg *et al* 2007)—with potentially immense repercussions on agriculture and fresh water supply in the Bishkek area. Summer runoff (JJA) in the Chon Kemin River is projected to decrease by –4 to –15% (2000–49), before reaching a total reduction of –9 to –66% (2050–99) as compared to the past (1955–99). Winter runoff is likely to decrease for the warm scenarios and to increase for the cold scenarios. Although all scenarios predict increasing winter precipitation, air temperatures are still cool enough so that most winter precipitation is snow at high elevation. The slight decrease in winter runoff for the warm scenarios is attributed to the stronger depletion of the groundwater storage during the much drier previous summer season. 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 reflective of more winter precipitation and enhanced snowmelt in spring. Hence, average annual snow cover duration is projected to decrease from

153 d (1955–99) to 108–151 d (2050–99), after having fluctuated between 145–161 d (2000–49).

As a result of higher air temperatures, mean annual actual evaporation is projected to increase from 384 (past) to 405–96 and further up to 433–622 mm a^{–1} (averages 2000–49 and 2050–99, respectively), which is comparable to other studies carried out in the region (Vilesov and Uvarov 2001, Aizen *et al* 2007). The losses due to evaporation are thus becoming more important and will exacerbate the situation of reduced melt water availability.

5. Discussion

Uncertainties occur at all stages of glacier and runoff modeling, and may stem from various sources (Huss *et al* 2014). We discuss here the influence of measured input and calibration data, the parameterization of the glacio-hydrological model, climate models and the downscaling procedure, as well as feedback mechanisms.

The errors in measured data are likely to be rather small, as all data series were systematically checked for inhomogeneities. Moreover, the multi-variable calibration implemented in GERM keeps the impact of single data sets limited. Whereas the current glacier extent has been assessed with high precision, past glacier extent used for the initialization of the model calibration might possibly be slightly overestimated due to misinterpreted snow cover on some aerial photographs used for the 1950s topographic maps (Sorg *et al* 2012). 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 (Gafurov *et al* 2012).

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 computation time. Also, the simulation of surface elevation changes for short-term advance phases is expected to be

uncertain, but this drawback has a minor influence on the results of this study as few years with glacier mass gain were observed. 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 meteorological patterns. 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 could only cover short periods. As an alternative, simulated glacier volume change could be constrained with regional volume changes from 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 (Hawkins and Sutton 2009). In the past, uncertainty contribution from climate models has shown to outweigh the uncertainty stemming from glacier models (Gosling *et al* 2011) or to be comparable (Lutz *et al* 2013). 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 (Barnett *et al* 2005). Our projected changes in evaporation are in line with another study for this region (Aizen *et al* 2007), but it would certainly be most helpful to have more informed data on future evaporation in Central Asia.

6. 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. Glaciers in the Chon Kemin valley—and in many comparable catchments in Northern Tien Shan—may disappear completely by the end of the 21st century in a worst-case-scenario. 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* being reached 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 is projected to decrease, independent of scenario uncertainty. 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 (Sorg *et al* 2014). 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.

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