Projections for headwater catchments of the Tarim River reveal glacier retreat and decreasing surface water availability but uncertainties are large

To cite this article: Doris Duethmann et al 2016 Environ. Res. Lett. 11 054024

View the article online for updates and enhancements.

Related content
- The days of plenty might soon be over in glacierized Central Asian catchments. Annina Sorg, Matthias Huss, Mario Rohrer et al.
- From dwindling ice to headwater lakes: could dams replace glaciers in the European Alps? Daniel Farinotti, Alberto Pistocchi and Matthias Huss
- Sources of uncertainty in hydrological climate impact assessment: a cross-scale study. F F Hattermann, T Vetter, L Breuer et al.

Recent citations
- Model based decision support system for land use changes and socio-economic assessments. Yang Yu et al.
- Adaptation strategies of agriculture and water management to climate change in the Upper Tarim River basin, NW China. Shaochun Huang et al.
- Global-scale hydrological response to future glacier mass loss. Matthias Huss and Regine Hock
Projections for headwater catchments of the Tarim River reveal glacier retreat and decreasing surface water availability but uncertainties are large

Doris Duethmann, Christoph Menz, Tong Jiang and Sergiy Vorogushyn

1 GFZ German Research Centre for Geosciences, Section Hydrology, Telegrafenberg, D–14473 Potsdam, Germany
2 Potsdam Institute for Climate Impact Research, Telegrafenberg, D–14473 Potsdam, Germany
3 National Climate Centre, China Meteorological Administration, Qi Xiang Ke Ji Da Lou 827, 46, Zhongguancun Nandajie, Haidian, Beijing 100 081, People’s Republic of China
4 Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing, People’s Republic of China

E-mail: doris.duethmann@gfz-potsdam.de

Keywords: climate change, hydrological modelling, glacier, Tien Shan

Abstract

In the Tarim River Basin, water resources from the mountain areas play a key role due to the extremely arid climate of the lowlands. This study presents an analysis of future climate change impacts on glaciers and surface water availability for headwater catchments of the Aksu River, the most important tributary to the Tarim River. We applied a glacio-hydrological model that underwent a comprehensive multivariable and multiobjective model calibration and evaluation, based on daily and interannual discharge variations and glacier mass changes. Transient glacier geometry changes are simulated using the \( \Delta h \)-approach. For the ensemble-based projections, we considered three different emission scenarios, nine global climate models (GCMs) and two regional climate models, and different hydrological model parameters derived from the multiobjective calibration. The results show a decline in glacier area of \(-90%\) to \(-32%\) until 2099 (reference \(\sim 2008\)) (based on the 5–95 percentile range of the ensemble). Glacier melt is anticipated to further increase or stay at a high level during the first decades of the 21st century, but then declines because of decreased glacier extents. Overall discharge in the Aksu headwaters is expected to be increased in the period 2010–2039 (reference 1971–2000), but decreased in 2070–2099. Seasonally, projections show an increase in discharge in spring and early summer throughout the 21st century. Discharge changes in mid to late summer are more variable, with increases or decreases depending on the considered period and GCM. Uncertainties are largely caused by differences between the different GCMs, with further important contributions from different emission scenarios in the second half of the 21st century. Contributions from the hydrological model parameters to the ensemble uncertainty were generally found to be small.

1. Introduction

Mountain areas influenced by snow and glacier melt play a key role in regional water supply (Viviroli et al 2007), yet these regions are particularly sensitive to temperature changes (Barnett et al 2005). Due to its semi-arid to arid lowlands, Central Asia is a prominent example for a region that strongly relies on mountain water resources (Viviroli et al 2007). Irrigation agriculture and hydropower generation are of significant economic importance. The overuse of water resources has become a severe problem since the 1960s, with the consequences of widespread desertification, the Aral Sea shrinkage (Micklin 2007), and drying-out of parts of the lower Tarim River and its previous terminal lakes (Hao et al 2009).

Observations over the last 50 years show significant temperature increase and glacier shrinkage...
Based on three emission scenarios, nine global climate and glacier mass balances. The climate projections are most important tributary of the Tarim River Basin. On glaciers and water availability for the Aksu, the uncertainties of climate impact studies is of high importance. Models scenarios, and the hydrological model parameters. The climate change impact on glaciers and water availability for the Aksu, Hotan, and Yarkand. The Aksu River is the most important tributary with a discharge contribution of 80%, (e.g., Duethmann et al 2015). As the downstream part of the Aksu is strongly influenced by water management and river discharge does not further increase (Huang et al 2015), we focused on the two mountainous headwater catchments, the Sari-Djaz (or Kumari) River and the Kakshaal (or Toshkan) River with the gauges Shaliguilanke and Xiehela, respectively (figure 1). The catchment areas are 12 950 km² for the Sari-Djaz, and 18 410 km² for the Kakshaal Basin, of which 20% and 4% are glacialized, respectively (reference year ~2008). The average annual discharge volume of the two catchments sums up to 7.6 km³ a⁻¹, equivalent to 240 mm a⁻¹ (average over 1957–2004) (Wang 2006).

Here, we analyse impacts of future climate change on glaciers and water availability for the Aksu, the most important tributary of the Tarim River Basin. The applied glacio-hydrological model includes transient glacier geometry changes, and it was calibrated thoroughly using multiple criteria based on discharge and glacier mass balances. The climate projections are based on three emission scenarios, nine global climate models (GCMs), and additionally two regional climate models (RCMs). The objectives of this study are (1) to investigate the impacts of future climate change on glacier and hydrologic variables, as well as the change mechanisms, and (2) to analyse uncertainties from three sources: the climate projections, the emission scenarios, and the hydrological model parameters.

2. Study area
The Tarim River forms at the confluence of the rivers Aksu, Hotan, and Yarkand. The Aksu River is the most important tributary with a discharge contribution of ~80%, (e.g., Duethmann et al 2015). As the downstream part of the Aksu is strongly influenced by water management and river discharge does not further increase (Huang et al 2015), we focused on the two mountainous headwater catchments, the Sari-Djaz (or Kumari) River and the Kakshaal (or Toshkan) River with the gauges Shaliguilanke and Xiehela, respectively (figure 1). The catchment areas are 12 950 km² for the Sari-Djaz, and 18 410 km² for the Kakshaal Basin, of which 20% and 4% are glacialized, respectively (reference year ~2008). The average annual discharge volume of the two catchments sums up to 7.6 km³ a⁻¹, equivalent to 240 mm a⁻¹ (average over 1957–2004) (Wang 2006).

Observed climate change signals over the recent decades include temperature increases and changes in precipitation (Xu et al 2010, Zhang et al 2010, Fan et al 2011, Tao et al 2011, Krysanova et al 2014), reductions in glacier area (Osmonov et al 2013, Pieczonka and Bolch 2015), dominantly negative glacier mass balances reported both for geodetic estimates (Surazakov and Aizen 2006, Pieczonka et al 2015, Pieczonka and Bolch 2015) as well as for glaciological measurements (Dyurgerov and Meier 2005, WGMS 2012). Runoff has increased by about 30% over the period 1957–2004 (Xu et al 2010, Kundzewicz et al 2015), which has been attributed primarily to increases in temperature (and thus glacier melt) in the Sari-Djaz catchment, and to precipitation and temperature increases in the Kakshaal catchment (Duethmann et al 2015).

3. Data and methods
3.1. Climate data and bias correction
For model calibration and evaluation over 1957–2004, precipitation and temperature were interpolated from observed station measurements. Radiation and humidity data were retrieved from the Watch Forcing Data, based on ERA-40 and ERA-Interim (Uppala et al 2005, Dee et al 2011, Weedon et al 2011, 2014). The methods used to interpolate the meteorological data are reported by Duethmann et al (2015). The climate data are reported by Duethmann et al (2015).

For the scenario analyses, we used daily climate projections from nine CMIP5 GCMs forced by three emission scenarios (RCP2.6, RCP4.5, and RCP8.5). The GCMs were selected to represent the range of changes projected by the CMIP5 ensemble in the study area (supplementary figure S1). With a spatial resolution of about 1.5°–3°, the GCMs cannot capture the small-scale topographic features. A better spatial resolution can be achieved through downscaling by RCMs. Data were available from two RCMs: the RCM REMO
forced by the CMIP3 GCM ECHAM5 under the A1B emission scenario with a resolution of 0.166° (Mannig et al. 2013), and the RCM CCLM forced by the CMIP5 GCM MPI-ESM-LR under the emission scenarios RCP2.6, RCP4.5, and RCP8.5 with a resolution of 0.44° (Wang et al. 2013). The RCM based scenarios were used for impact assessment but to keep a consistent ensemble they were not included for uncertainty evaluation.

All climate model data were summarised to subcatchments and bias corrected using an empirical quantile mapping approach (Gudmundsson et al. 2012), which allowed us to also consider changes in the variability. The bias correction was applied separately for each month.

3.2. Hydrological modelling

Discharge and glacier geometry changes were simulated with the hydrological model WASA (Güntner and Bronstert 2004), which has also previously been applied in Central Asia (Duethmann et al. 2013, 2014, 2015). The implementation, calibration, and evaluation of the WASA model to the Aksu headwater catchments is presented in detail in Duethmann et al. (2015) and summarised in the following.

The model is applied at a daily time step, and the spatial discretization is based on hydrologic response units (HRUs) defined by subcatchments and elevation zones. Each HRU is characterised by its dominant land cover (based on MODIS land cover MOD12Q1 collection 5.1; Friedl et al. 2002), and soil (Harmonized World Soils Database; FAO/IIASA/ISRIC/ISS-CAS/JRC 2012), its average elevation (derived from the SRTM DEM; Jarvis et al. 2008), and its glacier fraction (based on the glacier inventory for ~1975 (~2008) for the calibration/control (future) simulations; Osmo-nov et al. 2013, Pieczonka and Bolch 2015). The initial glacier ice thickness distribution of each glacier was based on estimates by a spatially distributed ice-thickness model (GlabTop2) (Linsbauer et al. 2012, Frey et al. 2014), with the SRTM DEM and the 1970s glacier inventory as inputs.

A comprehensive multi-variable approach was used for model calibration and evaluation. Daily discharge variations were calibrated using an average of the Nash–Sutcliffe efficiency of linear and logarithmic

![Figure 1. Headwater catchments of the Aksu Basin and their location within the Tarim River Basin.](image-url)
discharge values to achieve a balanced evaluation of high and low discharges (equation (1))

\[
\begin{align*}
\bar{Q}_t &= 0.5 \left( \frac{1}{T} \sum_{t=1}^{T} (Q_{\text{obs}}(t) - Q_{\text{sim}}(t))^2 \right) + \left( \frac{1}{T} \sum_{t=1}^{T} \left( \log(Q_{\text{obs}}(t)) - \log(Q_{\text{sim}}(t)) \right)^2 \right) \right) \\
\end{align*}
\]

(1)

\(Q_{\text{obs}}(t)\) and \(Q_{\text{sim}}(t)\) are the observed and simulated daily discharge at time \(t\), and \(T\) is the number of time steps. As high values of \(\bar{Q}_t\) may be achieved despite low performance with respect to interannual discharge variations, we also evaluated interannual variations of seasonal flow using the same criterion but applied to annual series of seasonal (DJF, MAM, JJA, SON) flow (\(\bar{Q}_t\)).

For the glacier mass balance, the following criteria were applied. The cumulative glacier mass change over the period 1976–1999 was constrained to 
\(-0.52 \pm 0.33\) m w.e. a\(^{-1}\) based on two geodetic mass balance estimates (Surazakov and Aizen 2006, Pieczonka et al. 2013) (figure 1). The criterion was represented by a function that reaches an optimal value of one for the average mass balance estimate, a value of zero outside the uncertainty range, and linearly increasing/decreasing values in between. The temporal variation of the simulated glacier mass balances was calibrated by maximising the correlation to an \textit{in situ} glacier mass balance series of Karabatkak Glacier (Dyurgerov and Meier 2005, WGMS 2012), located close to the study area (figure 1).

The model was automatically calibrated to the two discharge and the two glacier mass balance criteria with a multiobjective calibration algorithm (F−NSGAII; Kollat and Reed 2006), using 24 years (1976–1999) for model calibration, and 24 years (1957–1975 and 2000–2004) for model validation. From the results of the multiobjective optimisation, solutions were selected if they showed a good performance for daily and interannual streamflow variations (\(\bar{Q}_t > 0.75\), and \(\bar{Q}_t > -2\)), were inside the uncertainty range of the geodetic glacier mass balance estimate, and represented observed discharge trends in the past. Since the calibration period was regarded as too short for the calculation of trends, we calculated trends in seasonal discharge time series over the entire historical period 1957–2004. Trend evaluation was constricted to trend direction and trend significance. As a result, 6 and 28 parameter sets were selected for the Sari-Djaz and Kakshaal catchment, respectively.

Nash-Sutcliffe efficiencies for daily (monthly) discharge are within 0.77–0.87 (0.81–0.94) in the calibration and 0.67–0.84 (0.80–0.92) in the validation period (ranges over both catchments and the selected parameter sets). The model shows an acceptable performance with respect to the interannual variations of seasonal discharge and represents the observed discharge trends. Trends over 1957–2004 are 19–21 mm decade\(^{-1}\) (simulated) and 21 mm decade\(^{-1}\) (observed) for the Sari-Djaz catchment (mean annual runoff 382 mm a\(^{-1}\)), and 10–11 mm decade\(^{-1}\) (simulated) and 10 mm decade\(^{-1}\) (observed) for the Kakshaal catchment (mean annual runoff 151 mm a\(^{-1}\)) (trends evaluated with Sen’s slope estimator Sen 1968).

In agreement with the observed geodetic glacier mass balance estimates, the simulated glacier mass balance estimates over 1976–1999 are in a range of \(-0.83\) to 
\(-0.51\) m w.e. a\(^{-1}\) (\(-0.85\) to 
\(-0.25\) m w.e. a\(^{-1}\)) for the Sari-Djaz (Kakshaal) catchment. 3.3. Uncertainty estimation
In this study, we analysed uncertainties from three sources, including three emission scenarios, nine GCMs, and six (28) parameter sets of the hydrological model for the Sari-Djaz (Kakshaal) catchment. This led to 162 ensemble members for the Sari-Djaz catchment and 756 for the Kakshaal catchment. Uncertainties are characterised by the 5–95 percentile range of the ensemble. For consistency, only GCM-based simulations were included in the ensemble. Contributions of individual uncertainty sources were analysed by their contribution to the total variance (see supplement).

4. Results
4.1. Projected changes in climate variables
The analysis of changes in climate and glacio-hydrologic response was carried out by comparing the near future 2010–2039 (‘2020s’), mid future 2040–2069 (‘2050s’), and far future period 2070–2099 (‘2080s’) to the control period 1971–2000. Increased air temperatures are projected by all climate models under all emission scenarios (figure 2). Differences in the projected temperature increase between the different RCPs are negligible for the ‘2020s’ but substantial for the ‘2080s’. Temperature increases at a similar rate over the whole 21st century under RCP8.5, while for RCP4.5, the rate of temperature increase is projected to slow down toward the end of the 21st century, and in RCP2.6, temperature is projected to stabilise or decrease about the end of the century. The resulting temperature increase in the ‘2080s’ compared to 1971–2000 is 3.2 °C–7.2 °C for RCP8.5, 1.6 °C–4.5 °C for RCP4.5 and 0.7 °C–2.8 °C for RCP2.6. Seasonally, the strongest temperature increases are expected for winter (supplementary figure S2).

Precipitation is projected to be about 10% higher for the ‘2020s’ as compared to 1971–2000 for all RCPs, but the variability between GCMs is high. Over the 21st century, most GCMs project further small increases in precipitation. In contrast to temperature, differences between the RCPs remain small.
Compared to the median of the GCMs, the two RCMs show a tendency toward lower precipitation and temperature increases, but are mostly within the interquartile range of the GCMs. From the ensemble, we depicted three GCMs representing warm-wet (MIROC-ESM), warm-dry (IPSL-CM5A-LR), and cold (GFDL-ESM2M) conditions to better comprehend the change mechanisms of the glacier and hydrological variables described in the next sections.

Changes in humidity and radiation are mostly small and within ±5%. Larger decreases in humidity are linked to the warm-dry climate projections (supplementary figure S4).

4.2. Changes in glacier extent
The projected changes in temperature and precipitation are simulated to cause predominantly negative mass balances and significant losses in glacier extent (figure 3) and volume (supplementary figure S5). By the end of the century, projections suggest a reduction in glacier area by −66 (−89 to −28)% for the Sari-Djaz and −78 (−94 to −47)% for the Kakshaal catchment (uncertainties refer to the 5–95 percentile range). The variability of the GCM ensemble contributes most to the overall uncertainty (figure 4). As expected, the strongest glacier area reduction is projected for the warm-dry GCM (figure 3). The influence of the emission scenario increases from the 2050s, and uncertainties from the GCMs and emission scenarios are similar by the end of the century. The pattern at the beginning of the scenario period in figure 4 relates to very small total uncertainties (figure 3) and is therefore not analysed.

The glacier area reduction by the CCLM simulations is slightly lower than the ensemble median, in accordance with the lower than average temperature increase (figure 3). The REMO simulations suggest a strong glacier reduction from the 2050s onwards, which is in line with the continuous temperature increase under the A1B scenario.

4.3. Changes in the runoff regime
In the ‘2020s’, discharge is generally projected to be higher than during 1971–2000 in all seasons (figure 5). In both catchments and over the whole 21st century, discharge in spring and early summer (April–June) is higher than during the control period for nearly all ensemble members. The largest changes in relative

Figure 2. Temperature (a, b) and precipitation (c, d) changes as compared to the control period 1971–2000 for three different periods (‘2020s’, ‘2050s’, and ‘2080s’) and three different RCPs, in the Sari-Djaz (a, c) and Kakshaal (b, d) catchment. Boxes show the interquartile range, lines the median, crosses the mean value, and whiskers extend to the minimum/maximum value within 1.5 interquartile ranges of the lower/upper quartile. Coloured circles depict three selected GCMs representing cold (light blue), warm-wet (yellow), and warm-dry (red) projections. Changes of the two RCMs are shown in dark blue (CCLM) and green (REMO) circles.
terms are observed during spring, where discharge during the reference period is low (supplementary figure S6). Discharge changes in late summer are more heterogeneous. In the Sari-Djaz catchment, August discharge is increased in the ‘2020s’ but decreased in the ‘2080s’. For the Kakshaal catchment, both increases and decreases are observed during all scenario periods, and the direction of change strongly depends on the choice of GCM, which contributes most to overall uncertainties (figure 6). By the end of the century, emission scenarios are an important uncertainty source during spring and early summer, while the contribution of the hydrological model parameters generally remains small.

4.4. Mechanism of changes in the runoff regime
Snowmelt is shifted toward earlier in the season leading to higher snowmelt in spring and lower snowmelt in summer as shown for the ‘2080s’ (figure 7). Increase in spring rainfall further contributes to higher discharge during spring. During the ‘2080s’, lower summer discharge is caused by the shift in snowmelt, decreases in ice melt, and increases in actual evapotranspiration (AET). Summer rainfall shows a large variability in the GCM projections. A decrease in summer rainfall as in the warm-dry GCM may further exacerbate the discharge decreases, while rainfall increases as projected under the warm-wet GCM partly compensate the changes in snowmelt, ice melt, and AET.

4.5. Peak glacier melt and evolution of annual runoff
Glacier melt (defined as ice melt from glaciers) is simulated to change substantially over the 21st century in the Sari-Djaz catchment (figure 8(a)). After increases at the beginning of the 21st century, glacier melt drastically decreases during 2040–2060. Peak glacier melt is projected to occur roughly around 2030 (figure 8(a)). In the Kakshaal catchment, glacier melt is generally much lower and peak melt is passed earlier (figure 8(b)).
The changes in glacier melt have a significant impact on the evolution of total annual runoff of the Sari-Djaz River, resulting in the reduction of discharge by $-22\%$ in the ’2080s’ compared to the control period (figure 9(a), table 1, supplementary figure S7). In contrast, the impact of changes in glacier melt is smaller for the Kakshaal River due to its lower glacier melt contribution to discharge (figure 9(b), table 1, supplementary figure S8).

The projected evolution of glacier melt for the RCM-based simulations is similar to those of the GCM-based simulations, while the projected discharge toward the end of the century is slightly lower than the median of the GCM-based
simulations. This is in line with a lower precipitation increase than projected by the median of the GCMs.

4.6. Changes in the interannual variability of discharge

Changes in the interannual variability of discharge were evaluated using the coefficient of variation (CV). The CV was calculated after applying a 20 year moving average filter to exclude influences of systematic discharge changes. In both catchments, a tendency toward increased interannual variability of discharge can be seen; however, considering the large variability for different ensemble members, the changes are only small (figures 10(a) and (d)). A moderate glacier cover of a catchment is linked with low interannual discharge variability; in years with low precipitation, glacier melt begins earlier and can therefore (partly) compensate lower snowmelt (Jansson et al 2003, Hock et al 2005). The increase of interannual variability may therefore be caused by decreasing glacier area and glacier melt. In addition, changes in the interannual variability of climate variables might also play a role; there is a slight increase in the interannual variability of temperature (figures 10(c) and (f)), but changes in interannual variability of precipitation are small (figures 10(b) and (e)).
5. Discussion

5.1. Projected changes in glaciers and discharge
Our results for glacier area reduction of $-36$ (−69 to $-12\%$) by 2050 and $-69$ (−90 to $-32\%$) by 2099 compare well with other studies for Central Asia (supplementary table S1). The projected percentage glacier area loss is larger in the Kakshaal than in the Sari-Djaz catchment, where glaciers are generally larger and have a higher thickness.

Changes in the runoff regime with lower runoff in August and higher runoff in May/June are typical for mountain catchments influenced by snow and glacier melt and have been projected for many regions including other catchments in Central Asia (Hagg et al. 2007, Sorg et al. 2014, Gan et al. 2015, Ma et al. 2015).

While this study projects decreases in summer discharge in the '2080s' (figure 5), an earlier study for headwater catchments of the Aksu, Hotan, and Yarkand projected only little changes (±5\%) for summer discharge in the period 2081–2100 compared to 1981–2000 (Liu et al. 2013). These differences are likely due to the static (and thus overestimated) glacier areas in the model of Liu et al. (2013), which lead to an overestimation of glacier melt.

Estimates of the timing of peak melt vary by catchment and climate projection. Averaged over entire Central Asia, Bliss et al. (2014) found a steady decline in glacier runoff over the 21st century, indicating that many glaciers have already passed peak melt. For the Chon-Kemin catchment in the northern Tien Shan, peak melt is projected to occur in the 2020s under warm climate scenarios but glacier runoff may also remain constant until 2100 under cooler climate scenarios (Sorg et al. 2014). Only small decreases in glacier runoff until 2050 were projected for the Tanimas Basin in the Pamir (Hagg et al. 2013).

For estimating water availability in the mainstream of the Tarim River, one needs to consider changes in land and water management as well as

Table 1. Simulated annual rain, snowmelt, ice melt, AET, and discharge during the control period, and changes during the '2020s', '2050s', and '2080s' as compared to the control period for the Sari-Djaz and Kakshaal catchment and both Aksu headwater catchments together. Shown are the median values over all ensemble members and in parentheses the 5 and 95 percentiles.

<table>
<thead>
<tr>
<th></th>
<th>Rain</th>
<th>Snowmelt</th>
<th>Ice melt</th>
<th>AET</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sari-Djaz</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (mm)</td>
<td>207 (192/225)</td>
<td>224 (201/264)</td>
<td>179 (148/192)</td>
<td>215 (208/227)</td>
<td>395 (371/434)</td>
</tr>
<tr>
<td>Δ 2020s (%)</td>
<td>18 (3/40)</td>
<td>7 (−5/17)</td>
<td>39 (−7/87)</td>
<td>10 (5/14)</td>
<td>29 (7/44)</td>
</tr>
<tr>
<td>Δ 2050s (%)</td>
<td>26 (−6/60)</td>
<td>6 (−11/21)</td>
<td>−23 (−63/14)</td>
<td>13 (4/22)</td>
<td>4 (−39/26)</td>
</tr>
<tr>
<td>Δ 2080s (%)</td>
<td>33 (−7/87)</td>
<td>5 (−11/22)</td>
<td>−81 (−93/−65)</td>
<td>16 (5/36)</td>
<td>−22 (−51/3)</td>
</tr>
<tr>
<td><strong>Kakshaal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (mm)</td>
<td>202 (187/229)</td>
<td>178 (158/225)</td>
<td>26 (15/29)</td>
<td>271 (253/295)</td>
<td>147 (134/175)</td>
</tr>
<tr>
<td>Δ 2020s (%)</td>
<td>21 (−5/57)</td>
<td>1 (−18/12)</td>
<td>53 (19/99)</td>
<td>7 (−4/20)</td>
<td>24 (−5/57)</td>
</tr>
<tr>
<td>Δ 2050s (%)</td>
<td>28 (−6/72)</td>
<td>−8 (−20/13)</td>
<td>−40 (−68/38)</td>
<td>10 (−6/29)</td>
<td>16 (−35/34)</td>
</tr>
<tr>
<td>Δ 2080s (%)</td>
<td>30 (−4/91)</td>
<td>−6 (−27/12)</td>
<td>−72 (−87/−29)</td>
<td>13 (−5/37)</td>
<td>11 (−34/38)</td>
</tr>
<tr>
<td><strong>Aksu headwater</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (mm)</td>
<td>206 (200/209)</td>
<td>203 (190/208)</td>
<td>87 (87/91)</td>
<td>249 (245/251)</td>
<td>251 (242/256)</td>
</tr>
<tr>
<td>Δ 2020s (%)</td>
<td>20 (12/28)</td>
<td>3 (1/7)</td>
<td>43 (31/49)</td>
<td>9 (5/12)</td>
<td>26 (22/30)</td>
</tr>
<tr>
<td>Δ 2050s (%)</td>
<td>29 (16/39)</td>
<td>−1 (−6/3)</td>
<td>−28 (−41/−17)</td>
<td>12 (6/16)</td>
<td>2 (−0/13)</td>
</tr>
<tr>
<td>Δ 2080s (%)</td>
<td>38 (20/52)</td>
<td>−1 (−8/3)</td>
<td>−78 (−86/−72)</td>
<td>15 (8/21)</td>
<td>−13 (−22/−1)</td>
</tr>
</tbody>
</table>
changes in other tributaries, which provide only a small contribution to the Tarim today but possibly a higher contribution in the future. Due to lacking meteorological and glacier mass balance data in the Hotan and Yarkand Basins, glacio-hydrologic simulations and climate change impact analyses in these basins are, however, highly uncertain.

5.2. Uncertainties

In agreement with many other impact studies, our evaluation of uncertainties showed that the largest uncertainties stem from the climate models, while emission scenarios become a further important uncertainty source toward the end of the 21st century (Wilby and Harris 2006, Kay et al 2009, Prudhomme and Davies 2009, Ott et al 2013, Addor et al 2014). However, in data scarce mountain regions, uncertainties of hydrological models are large, and parameter uncertainties of hydrological models can become the largest source of uncertainties (Finger et al 2012, Ragettli et al 2013). The availability of glacier mass balance data in our study likely contributed to relatively small uncertainties from the hydrological parameters. In our case, parameter uncertainties were derived from different solutions of the multiobjective calibration. One would expect more diverse parameter sets if they had been derived by independent optimisation runs or Monte Carlo simulations and further parameter sets with a lower model performance would have been accepted. However, the simulated glacier mass changes (−0.83 to −0.51 m w.e. a⁻¹ and −0.85 to −0.25 m w.e. a⁻¹) cover large parts of the range given by the estimate from the observations (−0.85 to −0.19 m w.e. a⁻¹) and thus indicate that the parameterizations cover a good range of uncertainties. It is to note that uncertainties of the hydrological model are larger than the analysed parameter uncertainties due to uncertainties in model input and structure, as discussed below.

Further uncertainties in the climate change signal result from the coarse resolution of the climate models, which only partly resolve the complex topography of this region, and from the assumption of the stability of the bias correction under a changed climate. With respect to the glacio-hydrological modelling, further uncertainties stem from uncertainties in the calibration and input data, as well as the model structure. For example, while for the Sari-Djaz Basin, the glacier mass balance estimate used for model calibration largely overlaps with a more recent geodetic estimate derived specifically for this catchment (Pieczonka and Bolch 2015), an estimate specifically for the Kakshaal catchment is still missing. The applied ice-thickness estimates were based on a distributed ice-thickness model. While this type of thickness estimation method is seen as more reliable than approaches based on volume-area scaling, which tend to overestimate ice volume for large and steep glaciers (Frey et al 2014), uncertainties are still estimated to be in the range of 30% and contribute to uncertainties in the glacier and runoff evolution (Gabbi et al 2012, Huss et al 2014). Uncertainties in the model structure result from simplifications of the described processes and the assumption of stable model parameters under a changed climate. For example, the application of a temperature-index approach implicates that influences on the energy balance by changes in radiation or the wind field cannot be considered. However, comprehensive model testing showed that the model represents observed discharge trends and glacier mass loss in the region.
past, which increases our confidence in the model. While the average influence of debris cover on glacier melt is implicitly taken into account, influences on glacier retreat by possible changes of the debris-cover extent cannot be considered by the current model. Our simulations did also not consider feedback effects of the vegetation, such as changes in the length of the growing period, the vegetation types and the water use efficiency. These aspects should be addressed by future research.

6. Conclusions

In this study, we analysed climate change impacts on water resources for the most important headwater catchments of the Tarim River. The results revealed a strong decline of the glacier area over the next decades. However, uncertainty ranges are large. Glacier melt is projected to be high in the beginning of the 21st century and to decrease rapidly during 2040–2060. As a result of reduced glacier melt and increased AET, which are projected to be only partly compensated by precipitation increases, overall runoff in the ‘2080s’ is simulated to be lower than in the control period. Seasonally, runoff during spring and early summer is anticipated to be higher throughout the whole 21st century, while summer runoff is projected to be at a high level during the ‘2020s’ but expected to decline afterwards.

In summary, it can be expected that the currently increasing discharge trends are likely not sustained in the long term, which needs to be accounted for by land use planning and water resources management. Increases in irrigated area and water use as observed in the recent decades (Zhang et al. 2012, Feike et al. 2015) already impair ecological conditions and livelihoods today, despite currently increasing water availability in the headwaters. The region will face enormous challenges if the water availability from the Aksu headwaters declines.

Acknowledgments

This work is part of the SuMaRiO (Sustainable Management of River Oases along the Tarim River; http://sumario.de/) project, funded by the German Federal Ministry of Education and Research (BMBF grant 01LL0918A). We thank the climate modelling groups involved in CMIP5 for providing climate scenario data from global climate models, B Mannig for providing climate scenario data from REMO, and T Bolch for providing glacier outlines. Furthermore, we thank the two anonymous referees for their comments on our manuscript.

References

FAO/IIASA/ISRIC/ISS-CAS/JRC 2012 Harmonized World Soil Database (version 1.2) (Rome, Italy, Lasenburg, Austria: FAO, IIASA)
Farinotti D, Longuevergne L, Moholdt G, Duethmann D, Molg T, Bolch T, Vorogushyn S and Günther A 2015 Substantial glacier mass loss in the Tien Shan over the past 50 years Nat. Geosci. 8 716–22
Feike T, Mamintim Y, Li L and Doluschitz R 2015 Development of agricultural land and water use and its driving forces along the Aksu and Tarim River, P.R. China Environ. Earth Sci. 73 517–31
Finger D, Heinrich G, Gobiet A and Bauder A 2012 Projections of future water resources and their uncertainty in a glacierized catchment in the Swiss Alps and the subsequent effects on hydropower production during the 21st century Water Resour. Res. 48 W03521
Gabbi J, Farinotti D, Bauder A and Maurer H 2012 Ice volume distribution and implications on runoff projections in a glacierized catchment Hydrol. Earth Syst. Sci. 16 4543–56
Gudmundsson L, Brennes J B, Haugen J E and Engen-Skaugen T 2012 Technical note:downscaling RCM precipitation to the
station scale using statistical transformations—a comparison of methods Hydrol. Earth Syst. Sci. 16 3383–90

Günter A and Brunsbrown A 2004 Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas J. Hydrol. 297 136–61

Hagg W, Braun L N, Kuhn M and Nesgaard T 2007 Modelling of hydrological response to climate change in glaciated Central Asian catchments J. Hydrol. 332 40–53


Micklin P 2007 The Aral Sea disaster Annu. Rev. Earth Planet. Sci. 35 47–72


Justesen C and Davies H 2009 Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK: I. Baseline climate Clim. Change 93 177–95

Bagetti S, Pellicciotti F, Bordoy R and Immerzeel W W 2013 Sources of uncertainty in modeling the glaciohydrological response of a Karakoram watershed to climate change Water Resour. Res. 49 0048–59


Sorg A, Huss M, Rohrer M and Stoffel M 2014 The days of plenty might soon be over in glacierized Central Asian catchments Environ. Res. Lett. 9 104018


Wang Y (ed) 2006 Local Records of the Akesu River basin (Beijing: Fangzi Publisher) p 719
Xu H, Zhou B and Song Y 2010 Impacts of climate change on headstream runoff in the Tarim River Basin Hydrol. Res. 42 20–9
Zhang X, Yang D, Xiang X and Huang X 2012 Impact of agricultural development on variation in surface runoff in arid regions: a case of the Aksu River Basin J. Arid Land 4 399–410