Glaciers and hydrological changes in the Tien Shan: simulation and prediction

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Abstract
In this study, we estimated the current glacier state and forecast the potential impact of global and regional climate change on the glaciers and glacier runoff in the Tien Shan. General (G) and detailed (D) simulations were developed based on assessment of the Tien Shan glacier recession between 1943 and 2003 using an iterative stepwise increase in the equilibrium line altitude of 20 m. The G simulation was developed for 2777 grids each of which covered over 1000 km² of glacier surface and D for the 15 953 Tien Shan glaciers. Both simulations employed glacier morphometric characteristics derived from Digital Elevation Model based on remote sensing data, high resolution maps and in situ GPS validation. Simulated changes in glacier area demonstrated that a possible increase in air temperature of 1 °C at ELA must be compensated by a 100 mm increase in precipitation at the same altitude if Tien Shan glaciers are to be maintained in their current state. An increase in mean air temperature of 4 °C and precipitation of 1.1 times the current level could increase ELA by 570 m during the 21st century. Under these conditions, the number of glaciers, glacier covered area, glacier volume, and glacier runoff are predicted to be 94%, 69%, 75%, and 75% of current values. The maximum glacier runoff may reach as much as 1.25 times current levels while the minimum will likely equal zero.

Keywords: Central Asia, Tien Shan, climate, glaciers, river runoff, modelling

1. Introduction
The water-issue problems are extremely important for arid and semi-arid regions of central Asia. With the total population over 100 million, reached at the end of the 1990s, water demand is increasing while the supply is potentially decreasing. Despite the presence of large deserts and prairies with very low precipitation and extremely dry climates, Central Asian mountains hold one of the greatest concentrations of perennial snow and ice in the mid-latitudes of the North Hemisphere, that are the vital source of water for Central Asian rivers and lakes. Within the Tien Shan mountains (figure 1), there are 15 953 glaciers with a total area of 15 416 km² and a total volume of 1048 km³ [5, 6].

Alpine glaciers are highly labile with fluctuating length, area, volume, and shape. The behavior of a glacier is determined primarily by climate-mediated glacial mass balance (the net gain or loss of snow and ice). During the last 60 years, glaciers of the Tien Shan have been reduced up to 14% [2–4], which increases the glacier melt in the heads of the river basins where large-scale glaciation is still present. In the river basins with relatively small-glacierized areas, the increase of glacier melt has led to a decline of glaciers and has thus reduced the contribution of glacier melt to river runoff. In addition, increased irrigation, and the construction of hydroelectric power plants and water storage facilities along the middle and lower reaches of the river systems have increased demand for water in the densely populated urban areas of Central Asia.

The drastic aridization in the interior of the continent due to an aggregation of global and local anthropogenic causes resulted in the environmental problems in the Aralo-Caspian and Balkhash basins. Further warming would accelerate drought and aridization. At the same time, there are plans for
further water consumption including an extension of irrigated areas along the middle and lower Central Asian rivers reaches. Only precise simulation of the changes in the natural snow/ice storage over the Tien Shan will allow predictions upon which future development options can be based. Consequently, an improved quantitative understanding of potential climate-mediated hydrological changes in Tien Shan is needed. The objective of this research is to quantify potential effects of predicted climate change [1] on the glaciers of the Tien Shan using simulation modeling.

2. Data

Information on the altitudinal distributions of glacier area \((S_i)\), amount of glaciers \((K)\), glacier length \((L)\), glacier area \((S)\), lower \((H_L)\) and upper level \((H_H)\), and long-term, mean equilibrium line altitude, \(\bar{ELA} = (\bar{H}_E)\) computed for 1960–70 was obtained from the Catalogue of Glaciers in the USSR [5] and the Glacier Inventory of China [6]. The data were collected using large-scale topographic maps, geodetic surveys, and aerial photographs.

Ice thickness \((h)\) and glacier bedrock topography data were obtained from ground penetrating radar surveys of 60 glaciers, that is about 25% of the total number of glaciers at Akshirak glacierized massifs in Central Tien Shan, 7% in the Ala-Archa River basin of northern Tien Shan, and 2% in the Urumqi River basin of eastern Tien Shan. The radio-echo sounding survey was carried out mainly on the valley, cirque–valley, and cirque glaciers with different area and exposure [7–11].

Digital Elevation Map (DEM). The Tien Shan DEM was developed using Shuttle Radar Topography Mission 2000 (SRTM) data and Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) data. The SRTM data included elevation, slope, and exposition terrain properties with an absolute vertical accuracy of 16 m (6 m after applying local GPS corrections) at a horizontal resolution of 3 arcsecond (approximately 90 m). For fusion purposes with other remotely sensed and topographic data, the SRTM data was converted from WGS-84 to Pulkovo 1942 (Russian) coordinate system by seven-parameter Helmert transformation with 2 m accuracy. The SRTM void areas on steep slopes were filled with DEM derived from ASTER stereophotogrammetry. The ASTER DEM was generated in the Leica Photogrammetry Suite (LPS) software using ASTER bands 3N and 3B and Ground Control Points (GCP) collected from the topographic maps [2, 12–15].

Remote sensing data. Landsat TM (1984–present), Enhanced Thematic Mapper (ETM+; 1999 to present), and ASTER (1999 to present) images with resolution of 15–30 m provided an efficient method of estimating current glacier distribution and were used for comparison with the topographic maps and the aerial survey data. High resolution (2.5–1.6 m) Advanced Land Observing Satellite (ALOS/PRISM; 2006 to present), Corona (1962–1982) images were used in selected benchmark glacier basins for detailed studies of their changes and validation of glacier boundaries derived from Landsat and ASTER images.

Geographic Information Systems (GIS). The Tien Shan glaciers were sub-divided into seven regions with specific climatic features described in [16] and into seven basins (figure 1).

3. Computation of the glacier area and volume

Glacier covered area (GCA). A glacierized massif in any alpine compound basin consists of a complex of glaciers occurring in different morphologies such as valley, cirques, slope, ice
An individual glacier may react to regional and global climatic changes in different ways. For example, large glaciers with areas over 3 km² may respond to climatic changes with decadal lag, while small glaciers may respond to annual climatic changes [17]. The first step in the simulation of glacier response to climate should be estimation of glacier area distribution within a compound glacierized massif (figures 3 and 4). In regions with scarce data, GCA was estimated based on information about the lower and upper altitude of the glacier boundary [5, 6] assuming that the upper glacier boundary was constant in time. For an earlier glacier state, the lower boundary of GCA has been found from topographic surveys conducted at the end of the 19th and 20th centuries [18–20] and from the Catalogue of Glaciers [5] and the Glacier Inventory [6]. To approximate the distribution of GCA by altitude in basins with glacierized areas exceeding 20 km² Ahlmann [21], Erasov [22], Glazirin [23], and Aizen [17] applied a normal function (equations (A.1) and (A.2), appendix) or a log-normal functions [13]. Mean altitude of GCA and standard deviation are the defining parameters of the normal distribution. Calibration and validation have been accomplished in the Ala Archa and Akshiyrak glacierized basins. In Ala Archa and Akshiyrak, respectively, the mean

Figure 2. Inylchek glacierized area, Central Tien Shan (ASTER, August 2003).

Figure 3. Distribution of types (a), and size of glaciers (b) in Tien Shan regions and representative basins by number of glaciers (K), glacier covered areas (S), and glacier volume (V).
altitude of GCA was determined to be 3916 m, and 4405 m and the standard deviation was determined to be 225 m, and 222 m.

The frequency distribution approximated by the normal function closely resembled the empirical histogram of GCA by altitude in a compound glacierized basin (figure 4(a)). The Pearson moment correlation coefficient between the normal and empirical frequency distribution of GCA by altitude was 0.98 for Ala Archa Basin and 0.99 for Akshiyrak glacierized massif. The calculated values of skewness and kurtosis were found to be close to zero, which validated the normal approximation of GCA in compound glacierized basins.

The simplified calculation of GCA. Approximation of the distribution of GCA by a normal function permits estimation of the mean and standard deviation for altitude of glaciation based on information about the low and upper altitude of total glacierized area in the basin. According to the central limit theorem, the mean altitude of a compound glacierized basin must tend to the mean altitude of individual glaciers in the basin. At the same time, according to Kurowski’s method [24], the long-term equilibrium line altitude ($\bar{H}_{EL}$) is determined as the mean altitude of the group of individual glaciers in the basin:

$$\bar{H}_{g} = \frac{1}{K} \sum_{j=1}^{K} (H_{lj} + H_{hj})/2$$

(1)

where $\bar{H}_{g}$ is mean altitude of GCA; $H_{lj}$ and $H_{hj}$ are the altitude of low and upper boundaries of each individual glacier in the basin; $K$ is the number of glaciers. By equation (1), ELA is 3910 m for Ala Archa Basin and 4400 m for Akshirak glacierized massif. The difference ($d_{j}$) between mean altitude ($\bar{H}_{g}$, equation (A.3) appendix) and the half-sum of the lower and upper glacier altitudes for each glacier (equation (2)) is close to zero.

$$d_{j} = (H_{lj} + H_{hj})/2 - \bar{H}_{g}.$$  

(2)

Root mean square error ($se_{d_{j}}$) of $d_{j}$ coincides with root mean square error ($se_{\bar{H}_{g}}$) of $\bar{H}_{g}$ determined by equation (1) and checked by equation (A.3) (appendix). For Ala Archa and Akshirak, respectively, these values were found to be 7.70 and 3.83 m and standard deviation of $d_{j}$ ($\sigma_{d_{j}}$) was found to be 50.5 and 51.0 m.

Assuming that errors are normally distributed, then the accuracy of $d_{j}$ is $se_{d_{j}} = \sigma_{d_{j}}/\sqrt{(K-1)}$. To estimate $\bar{H}_{g}$ with an accuracy of 20 m, the number of glaciers comprising glacier massif should be not less than 27, i.e., $\sigma_{d_{j}} = 51$ m and $20 \leq 2|se_{d_{j}}| = 2|\sigma_{d_{j}}/\sqrt{(K-1)}| \Rightarrow K \geq [(2|\sigma_{d_{j}}|)^2/20] + 1$.

The standard deviation also can be determined by nomogramm based on the GCA and the difference between the lower and upper altitude of GCA [23]. The correlation coefficient between $\sigma$ calculated by nomogramm and by equation (A.3), appendix is 0.97 based on data from 200 independent measurements. For instance, for Ala Archa the
standard deviation was 260 m, when calculated by [23], and 225 m, when calculated by equation (A.3) (appendix). For the Akshirak, the calculated values of the standard deviation were 255 and 222 m, respectively.

Glacier ice volume \( V \): Glacier ice volume \( V \) was estimated using data from radio-echo sounding surveys and sub-glacial topography by ordinary least squares methods:

\[
V = (0.033 S^{1.08} e^{0.121 L}) / (E_{0.088 46})
\]

\( 0.1 < S < 25 \text{ km}^2 \) \hspace{1cm} (3)

\[
V = 0.018 48 S + 0.021 875 S^{1.3521} \quad S > 25 \text{ km}^2 \hspace{1cm} (4)
\]

\[
V = 0.037 82 S^{1.21} \quad S < 0.1 \text{ km}^2, \hspace{1cm} (5)
\]

where \( S \) is the individual area of a glacier; \( L \) is the length of the glacier.

4. Simulation of glacier changes

**ELA simulation:** Glaciers exist while ELA is below the upper boundary of GCA in the basin. Glaciers are advancing if ELA falls and are retreating if ELA increases. The causal chain can be diagrammed as follows: climate \( \rightarrow \) ELA \( \rightarrow \) glacier dimensions/configuration, and, ultimately, glacier ice volume. The annual ELA \( (\bar{H}_{E}, \text{km}) \) was simulated using the mean summer air temperatures \( (T_{E_{\text{ELA}}, \text{C}}) \) and annual precipitation at \( \bar{L} \) \( (P_{E_{\text{ELA}}, m}) \), equation (6), measured at the Tien Shan glacier monitoring stations (table 1). These glaciers were selected at the time of IGY (international geophysical year) as most representative of the glacier basins and have long-term glacio-climatic records. The standard error for the \( \bar{H}_{E} \) simulation is 0.024 km. Furthermore, there is a strong relationship between summer air temperatures and annual precipitation at the ELA (figure 5; equation 7).

\[
\bar{H}_{E} = 1.175 + 0.161 \cdot T_{E_{\text{ELA}}} - 1.586 P_{E_{\text{ELA}}}
\]

\[
\Rightarrow \text{if } \Delta \bar{H}_{E} = 0 \quad \text{then } \Delta P_{E_{\text{ELA}}} = 0.101 \Delta T_{E_{\text{ELA}}} \hspace{1cm} (6)
\]

\[
P_{E_{\text{ELA}}} = 0.0995 T_{E_{\text{ELA}}} + 0.744 \quad r = 0.99. \hspace{1cm} (7)
\]

Thus, to maintain Tien Shan glaciers at the current state, the increasing summer air temperature at the ELA must be offset by a corresponding increase in annual precipitation (equations (6) and (7)). For example, the glaciers of Tien Shan will not retreat if an increase in mean summer air temperature of 1.0°C at ELA coincides with an increase of annual precipitation of 100 mm at ELA.

**General (G) and detailed (D) simulations of changes in GCA, glacier numbers and glacier volume** were developed based on an assessment of the glacier recession that occurred in the Tien Shan from 1940 to 2003 using the least squares method. Each simulation was based on stepwise iteration with a consequent increase of ELA of 0.20 m.

**G simulation/iteration** was based on 2777 grids, each with area of 1000 km\(^2\) (see equations (A.4)–(A.7), appendix). D simulation/iteration was computed for each of the 15 953 glaciers. To estimate changes in GCA and changes in mean altitude of each glacier, differential equations were developed considering length and average width of each glacier (see equations (A.8)–(A.12), appendix).

**Spatial and temporal dynamics of GCA:** To analyze the relationship between spatial distribution of glaciers and compound glacier basin topography, the index of glacier intensity \( (K) \) [16] was calculated for 21 Ala Archa glacier sub-basins (figure 6) based on data for periods of 2003, 1961 and 1949 (table 2).

\[
R = \sum S_{g} / D, \hspace{1cm} (8)
\]

where \( \sum S_{g} \), is glacier area in a sub-basin; \( D \) is the compound length of the main water divide in the basin and its branches in sub-basins (figure 6).

Analysis of the relationship between the indices of glacier intensity \( (R) \) and spatial characteristics of glacier distribution was implemented for three periods (table 2) based on the average area of a glacier \( (S_{g}) \); figure 7(a)) and on the number of glaciers in a sub-basin per km of the range length \( (\sum K / D) \), figure 7(b)).

Growth/shrinkage/decay of GCA may occur by increasing/decreasing each individual glacier area or by increasing/decreasing the number of glaciers in each sub-basin. Analysis of GCA dynamics in a compound glacier basin revealed that at the beginning of GCA degradation, when \( R \geq 0.5 \),
Figure 6. Spatial distribution of glaciers in a compound Ala Archa glacierized basin, northern Tien Shan.

the number of glaciers in sub-basins ($\sum K/D$) did not change (figure 7(b)) because shrinkage of GCA occurred only by a reduction in the size of large-valley glaciers (figure 7(a)). Subsequently, when $0.12 \leq R \leq 0.5$, the large-valley glaciers started to disintegrate increasing the number of glaciers by forming many small glaciers with average area of 0.1–2.0 km². Among them, the large glaciers continued to decay while small glaciers disappeared. This resulted in decreasing the number of glaciers per length of water divide when $R < 0.12$. After 2000, the index of glacier intensity in each glacier sub-basin in Ala Archa reached the boundary condition of $R \leq 0.5$ (table 2) when small glaciers were decayed and split while the area of large glaciers continued to decrease.

Glacier decay occurred when average glacier width ($W$) exceeded $25^3$ and glacier intensity was less than 0.5. The area of larger glaciers ($S_{(L)}$) that appeared among two recently decayed glaciers was computed from (9)

$$S_{(L)} = S(0.5 + 0.2154S)/(1 + 0.2154S).$$ (9)

Threshold conditions: if $S_{i+1} < 0.015$ km² and $H_{(L)} > H_{(ij)} + D^{(ex)}$, then degradation of GCA is accelerating and glaciers will disappear. $D^{(ex)}$ is the permissible over-elevation for glaciers slopes with different expositions:

$$D^{(ex)} \in [0.86^{(N)}, 0.55^{(NE)}, 0.37^{(E)}, 0.49^{(SE)}, 0.59^{(S)}, 0.68^{(SW)}, 0.63^{(W)}, 0.77^{(NW)}],$$ (10)

where N, NE, E, SE, S, SW, W, NW are northern northeastern, eastern, southeastern, southern, southwestern, western, northwestern expositions. The precision of results of D and G simulations are shown in figure 8. D simulation has results that are more realistic because this simulation is based on detailed data of the glaciers and their spatial variability considering the glaciers decay and their threshold conditions.
Table 2. Dynamics of glaciers characteristics in the Ala Archa sub-basins. (Note: \(N\) is number of a sub-basin (see figure 6); \(\sum K\) is number of glaciers in a sub-basin; \(R\) is index of glacier intensity; \(\sum S_g\) is glacier area in a sub-basin; \(\overline{S}_g\) is average area of a glacier in the sub-basin; \(D\) is compound length of the main water divide and branch ranges in a sub-basin.)

| \(N\) | 2003 | 1961 | 1949 | \(\sum K\) (km\(^2\)) | \(\sum S_g\) (km\(^2\)) | \(R\) (km) | \(\sum K/D\) (km\(^{-1}\)) | \(\overline{S}_g\) (km\(^2\)) | \(D\) (km) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 2 | 0.15 | 0.19 | 0.48 | 0.02 | 0.03 | 0.07 | 0.14 | 0.14 | 0.29 | 0.15 | 0.19 | 0.24 | 7 |
| 2 | 5 | 5 | 2 | 0.66 | 0.7 | 2.21 | 0.13 | 0.14 | 0.44 | 1.0 | 1.0 | 0.4 | 0.13 | 0.16 | 1.1 | 5 |
| 3 | 2 | 2 | 1 | 0.56 | 0.57 | 6.64 | 0.11 | 0.11 | 0.47 | 0.4 | 0.4 | 0.07 | 0.28 | 0.29 | 6.64 | 5 |
| 4 | 5 | 6 | | 3.85 | 3.9 | | 0.43 | 0.43 | | 0.56 | 0.67 | 0.77 | 0.65 | 9 |
| 5 | 1 | 3 | | 0.04 | 0.17 | | 0.01 | 0.02 | | 0.14 | 0.43 | | 0.05 | 0.06 | 7 |
| 6 | 3 | 4 | | 0.4 | 0.44 | | 0.03 | 0.11 | | 0.75 | 1.0 | | 0.05 | 0.11 | 4 |
| 7 | 3 | 3 | 2 | 0.53 | 0.53 | 0.89 | 0.09 | 0.09 | 0.15 | 0.5 | 0.5 | 0.33 | 0.18 | 0.18 | 0.45 | 6 |
| 8 | 1 | 2 | 2 | 0.92 | 1.2 | 1.78 | 0.31 | 0.4 | 0.59 | 0.33 | 0.67 | 0.67 | 0.92 | 0.61 | 0.89 | 3 |
| 9 | 5 | 5 | 1 | 7.26 | 7.38 | 9.87 | 0.48 | 0.49 | 0.66 | 0.33 | 0.33 | 0.07 | 1.45 | 1.48 | 9.87 | 15 |
| 10 | 1 | 2 | 2 | 0.1 | 0.13 | 0.36 | 0.05 | 0.07 | 0.18 | 0.5 | 1.0 | 0.1 | 0.07 | 0.18 | 2 |
| 11 | 4 | 4 | 2 | 0.74 | 0.67 | 1.6 | 0.19 | 0.17 | 0.4 | 1.0 | 1.0 | 0.5 | 0.19 | 0.18 | 0.8 | 4 |
| 12 | 3 | 3 | 1 | 5.54 | 5.54 | 6.27 | 0.55 | 0.55 | 0.63 | 0.3 | 0.3 | 0.1 | 1.85 | 1.85 | 6.27 | 10 |
| 13 | 3 | 4 | 1 | 4.59 | 4.62 | 5.77 | 0.46 | 0.46 | 0.58 | 0.3 | 0.4 | 0.1 | 1.53 | 1.16 | 5.77 | 10 |
| 14 | 1 | 1 | 2 | 3.07 | 2.94 | 4.55 | 0.38 | 0.37 | 0.38 | 0.26 | 0.13 | 0.15 | 3.07 | 1.47 | 2.28 | 8 |
| 15 | 4 | | | 0.1 | | | 0.03 | | 1.0 | | | 0.04 | | | 4 |
| 16 | 2 | 2 | | 0.32 | 0.3 | 0.11 | 0.09 | | 0.67 | 0.67 | | 0.16 | 0.16 | | 3 |
| 17 | 1 | 1 | 1 | 0.34 | 0.3 | 0.68 | 0.06 | 0.06 | 0.14 | 0.2 | 0.2 | 0.2 | 0.34 | 0.32 | 0.78 | 5 |
| 18 | 3 | 3 | 2 | 6.77 | 6.81 | 8.85 | 0.45 | 0.45 | 0.59 | 0.2 | 0.2 | 0.13 | 2.26 | 2.27 | 4.43 | 15 |
| 19 | 1 | 2 | 3 | 0.03 | 0.04 | 0.15 | 0.01 | 0.02 | 0.04 | 0.25 | 0.5 | 0.75 | 0.03 | 0.03 | 0.05 | 4 |
| 20 | 1 | 2 | 3 | 0.12 | 0.18 | 0.35 | 0.02 | 0.03 | 0.06 | 0.17 | 0.35 | 0.5 | 0.12 | 0.1 | 0.12 | 6 |
| 21 | 2 | 1 | 1 | 0.3 | 0.26 | 1.84 | 0.08 | 0.07 | 0.50 | 0.5 | 0.25 | 0.25 | 0.1 | 0.26 | 0.84 | 4 |

Figure 7. Relation between the indices of glacier intensity (\(R\)) and average area of a glacier (\(\overline{S}_g\)) (a), and number of glaciers per km of the range length (\(\sum K/D\)) (b) in the Ala Archa basin.

5. Forecast: changes in number of glaciers, GCA, glacier volume, and glacier river runoff

Variation of ELA with varying air temperature and precipitation was evaluated by equation (6), which allowed simulation of changes in mean altitude of each glacier (\(\overline{H}_g\), equation (A.10), appendix), area (\(dS\)) (equations (A.8) and (A.9), appendix), number of glaciers (equation (A.6), appendix), and glacier volume (equations (3)–(5)).

Estimation of changes in glacier runoff was based on the following assumptions: (1) accumulation is equal to ablation at ELA, (2) accumulation at the ELA is closed to annual precipitation over GCA, (3) evaporation losses are compensated by condensation gains over the Tien Shan glaciers [17, 25–27, 31]. Changes were estimated as the product of predicted changes in annual precipitation and changes in predicted GCA.

Both models forecast that significant glacier degradation begins when ELA is increased by 600 m (figure 8). The Tien Shan GCA may shrink to about half of the current state if ELA increases another 1000 m. The number of glaciers could decrease by 40% and glacier volume may decrease by 60%.

The simulation of effects of climate change are based on hypothetical scenarios in the Tien Shan between the end of the 20th (1961–90) and 21st (2070–99) centuries suggested by four global climate models reviewed by IPCC (2001) as a stepwise progression [1]. These scenarios predict, on average, an increase in summer air temperature of 2°C to 8°C (about 4°C) and an increase in precipitation of 0.84–1.24 (about 1.1) in magnitude of precipitation. Consequently, the ELA may increase 570 m. The number of glaciers, glacier covered areas, glacier volume and glacier runoff are predicted to be 94%, 69%, 75% and 75% of the current state (figure 9).

If air temperature increases to the greatest predicted value, i.e. by 8°C, and precipitation also increases to its maximum predicted value, then the model predicts a 970 m increase in ELA. The number of glaciers, GCA, glacier volume and glacier runoff are predicted to be 40%, 47%, 57% and 59% of the current state (figure 8). If air temperature increases by the
minimum predicted value, i.e. by 2°C, and if precipitation increases to 1.24 times the current value, then the simulation model predicts almost no changes in the number of glaciers, GCA, and glacier volume, while glacier runoff will increase by 1.25 times the current value. However, under the opposite predicted threshold conditions, if air temperature increases by 8°C and precipitation decreases to the minimum predicted value, i.e. by 0.84 times the current rate, then current glaciation probably will disappear.

6. Conclusion

In Tien Shan, the distribution of GCA versus altitude approximates a normal distribution with an accuracy of 20 m if at least 27 glaciers occur in a compound glacier basin or glacierized massif. The GCA distribution by altitude also can be calculated by a simplified method based on data on the total area of glaciers, lower and upper glacier elevations.

In Tien Shan, the large-valley glaciers are the major component of the GCA. The number of glaciers in each compound basin is inversely proportional to their size. That is, as the size of glaciers decreases they begin to degrade and split, and the number of glaciers increases relative to threshold conditions.

There is a statistically significant relationship between mean summer air temperature and annual precipitation at the ELA. Increase of mean summer air temperature by 1°C should correspond to a 100 mm increase in annual precipitation to maintain ELA at the same altitude. Increase in air temperature
in the Tien Shan during the last 60–40 years has not been compensated by an increase in precipitation [28–30]. During this time the Tien Shan lost 14–12% of GCA [2–4].

Two simulation models of changes in GCA, glacier numbers, glacier volume and glacier runoff were developed based on a stepwise, iterative process with a consequent increase in ELA of 20 m. Both models predicted significant glacier degradation if ELA increases by 600 m from current elevation.

Simulation of effects of climate change, showed that the increase in summer air temperature and precipitation that is predicted for the 21st century [1], will increase ELA by 570 m. The number of glaciers, glacier covered areas, glacier volume, and glacier runoff are predicted to be 94%, 69%, 75%, and 75% of current values. Predicted glacier runoff may increase by 1.25 times current values (maximum scenario) or disappear (minimum scenario).

The developed simulation adequately estimates the effects of predicted climate change on the Tien Shan glaciers. Obviously, the validity of forecast estimations decreases with elimination from the initial/current state. Validation of the developed simulation through independent data revealed that its reliability significantly decreases when ELA rises more than 600–700 m.

The presented simulation of predicting the Tien Shan glacier and river runoff changes could be applied to develop integral and effective mitigation approaches, both the direct and root causes of climate and water resources changes in Central Asian countries.

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Appendix

Glacier covered area (GCA). Mean altitude of GCA ($\bar{H}_g$) and standard deviation ($\sigma$) are the defining parameters of the normal distribution (equation (A.3)).

\[ p_i = \frac{[\Delta i / (\sigma \sqrt{2\pi})]}{\int_{H_{lo}}^{H_{hi}} \exp\left[-(H_i - \bar{H}_g)^2/(2\sigma^2)\right]} \]  
\[ S_i = p_i S_g = [S_g \Delta i / (\sigma \sqrt{2\pi})] \times \int_{H_{lo}}^{H_{hi}} \exp\left[-(H_i - \bar{H}_g)^2/(2\sigma^2)\right] dH \]  
\[ \bar{H}_g = \frac{1}{\sum S_i} \sum_{i=1}^{n} H_i S_i; \]  
\[ \sigma = \left(\frac{1}{\sum S_i} \sum_{i=1}^{n} (H_i - \bar{H}_g)^2 S_i \right)^{1/2}, \]  
\[ Y_{t+1} = Y_t + V^{(t)}_{t+1} - V^{(t)}_t \]
\[ Y_h = f_h(X) \]
\[ Y \in [S, K, V] \text{ and } X \in [(H_{lo} - H_{hi}); \lambda'; \psi; S] \]
where $H_{lo}$ is the altitude of the upper glacier boundary; $H_{hi}$ is the weighted, area-averaged ELA; $\lambda'$ is longitude reduced to a base meridian; $\lambda'$ and $\psi$ are related to the centers of each grid.

\[ S^{(t)} = a_0 + a_1(H_{hi} - H_{hi}^{(t)}) + a_2H_{hi} + a_3\lambda' + a_4\psi \]  
\[ K^{(t)} = b_1S + b_2S^2 \]
\[ V^{(t)} = c_1S + c_2S^2. \]

Coefficients in equations (A.5)–(A.7) were computed using the least square method.

D simulation/iteration

\[ dS = -3.456693 S d(H_{hi}) \quad S < 2.4 \text{ km}^2 \]
\[ dS = (19.9105/S - 16.592) d(H_{hi}) \quad S > 2.4 \text{ km}^2 \]
\[ d(H_{hi}) = \beta d(H_{hi}) \quad \beta = 1/4 \]
\[ L^{(t)} = 1.6724S^{0.561}; \quad W^{(t)} = 0.6182S^{0.4467} \]
\[ S_{t+1} = S_t + \Delta S_t; \quad L_{t+1} = L_t + L^{(t)} - L^{(t)}; \]
\[ W_{t+1} = W_{t} + W^{(t)} - W^{(t)}; \quad V_{t+1} = f(S_{t+1}; L_{t+1}) \]
where $dS$ is changes in GCA; $d(H_{hi})$ is changes in mean altitude of each glacier; $L$ is length of each glacier; $W$ is average width of each glacier.

G simulation/iteration: A new state of glaciers was calculated as:

\[ Y_{t+1} = Y_t + V^{(t)}_{t+1} - V^{(t)}_t \]
\[ Y_h = f_h(X) \]

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