Supplementary Material

Controls on Alpine Lake Dynamics, Tien Shan Region, Central Asia

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Supplementary figures

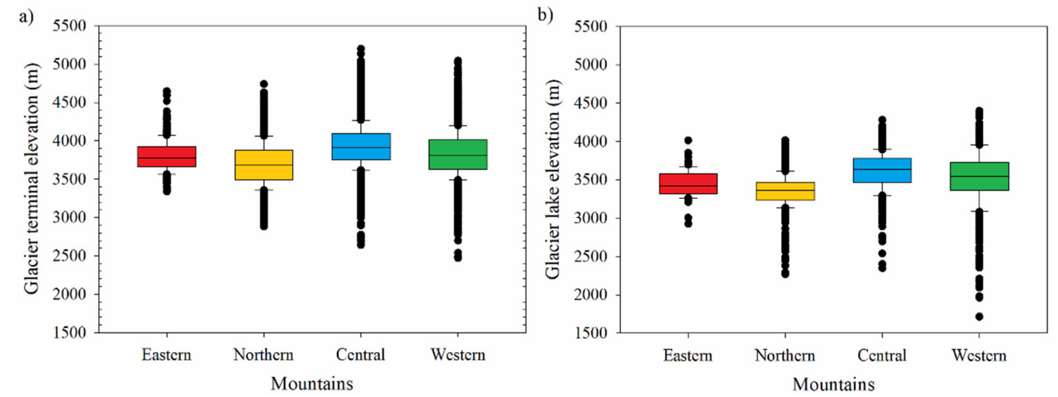

Figure S1. Distribution of glacier terminal elevation and glacier lake elevation in the Eastern, Northern, Central and Western Tien Shan. (a) Distribution of glacier terminal elevation; (b) Distribution of glacier lake elevation.

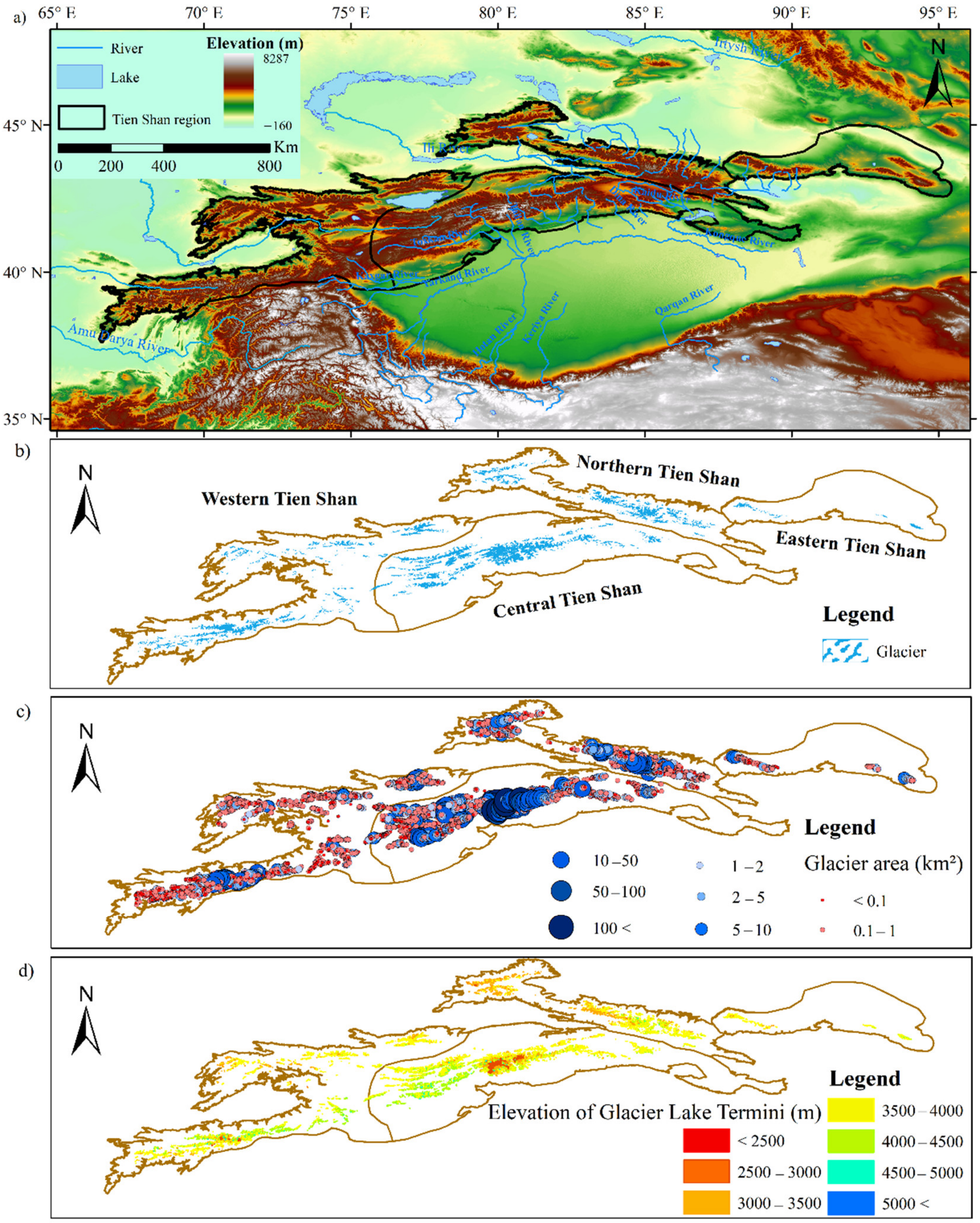

Figure S2. Characteristics of rivers, glacier area, and glacier lake termini in the Tien Shan region. (a) Spatial distribution of rivers; (b) Spatial distribution of glaciers; (c) spatial distribution of glacier areas; (d) spatial distribution of glacier termini.

Supplementary tables

Table S1. Variations in alpine lake number and area from 1990 to 2015.

Year	Eastern		Northern		Central		Western		Total	
	Number	Area	Number	Area	Number	Area	Number	Area	Number	Area
	/	km^2	/	km^2	/	km^2	/	km^2	/	km^2
1990	57	2.73	460	19.79	567	48.20	625	32.31	1709	103.03
2000	77	3.51	516	22.39	613	48.57	779	35.94	1985	110.42
2010	78	3.70	586	24.91	725	55.22	815	38.22	2204	122.05
2015	98	3.95	675	27.55	813	58.47	835	39.79	2421	129.76
1990–2015	41	1.22	215	7.76	246	10.27	210	7.48	712	26.73
1990–2015 (%/a)	2.88	1.80	1.87	1.57	1.74	0.85	1.34	0.93	1.67	1.04

Table S2. Changes in glacier number and area between 1990 and 2015.

Year	Eastern		Northern		Central		Western	
	Number	Area	Number	Area	Number	Area	Number	Area
1990–2015 (km^2)	5	−73.19	−110	−456.43	−188	−805.08	226	−374.16
1990–2015 (%/a)	0.04	−0.85	−0.10	−0.64	−0.10	−0.41	0.16	−0.46

Table S3. Summary of temperature changes in different regions documented by previous investigations.

Regions	Increasing temperature rate (°C/10a)	Sources
Tien Shan	0.30	This study
Global	0.12	IPCC. [1]
Central Asia	0.31	Deng and Chen. [2]
China	0.20	Shi et al. [3]
Eastern Xinjiang	0.27	Li et al. [4]

Table S4. Fraction of the total lake number/area to glacier number/area in 2015.

Regions	Glacier number/Lake number (%)	Glacier area/Lake area (%)
Eastern Tien Shan	18.46	1.60
Northern Tien Shan	15.77	1.24
Western Tien Shan	14.29	1.39
Central Tien Shan	10.86	0.82
Total	13.75	1.04

Supplementary methodological information

Extracting glaciers

We evaluated many different image classification methods for glacier mapping, including band ratio thresholding, supervised and unsupervised classification, the normalized difference snow index (NDSI), the decision tree classifier, and the object-oriented image interpretation [5-8]. The presence of snow, shadowing, moraines and water interfer with the process of data-gathering at glacier sites, making it difficult to ensure the accuracy of the information being extracted. There are also many limitations to automatically extracting glacier outlines. Despite our interest in using these methods, visual interpretation was finally applied using characteristics and criteria such as terminal moraines, the heads of glacier meltwater streams, glacial lakes and lateral moraines. Misclassified areas (e.g., snow patches, cast shadows and lakes) had to be corrected manually using multispectral band combinations (TM bands 3, 5 and 7; OLI bands 4, 6 and 7) on Landsat imagery taken in 1990 and 2015.

The accuracy of extracted glacier boundaries generally depends on the image-quality, resolution of the imagery, geometric-correction and manual experience. In this study, high-quality Landsat TM/ETM+/OLI scenes during the ablation period (from July to September, mainly in mid-August) with minimal cloud cover or nearly cloud-free conditions were chosen to reduce the potential uncertainty in glacier outline extraction. To fill in minor gaps caused by poor-quality images, multi-temporal images (from 1–3 years outside the aforementioned years) helped to identify the glacier margins. In total, glacier area error was estimated within 1 pixel of the glacier boundary in this paper. In order to largely reduce error by manual delineation, glaciers in the same region were extracted and checked by the same people for the different periods Finally, extracted boundaries were checked and revised several times by other people.

The error in glacier area is strongly inversely proportional to the length of the glacier outline [9], which means that the extraction of larger sized glaciers often causes larger errors in the areas of the glacier outlines. Thus, in our study, we estimated the uncertainty of these glacier areas by using the buffer method suggested by Bolch et al. [10] and Guo et al. [11]. Visual interpretation was adopted to delineate the glacier information. We found the uncertainty to be half to one pixel of the glacier margin. Therefore, the buffer size was chosen to be one pixel to estimate the glacier area error. Thus, the buffer size was 30 m for the Landsat TM/OLI imagery during the periods in 1990 and 2015. The average uncertainty of the extracted glacier area was 14% for 1990 and 4% for 2015.

Calculation of lake/glacier area change rate

The annual percentage of area change (APAC) is defined as glacier/lake area change within the period from 1990 to 2015. The annual percentage of area change rate (APACR) is regarded as a kind of common indicator to represent the variations in glacier/lake area, and can be better compared with the results of research on glacier/lake change for different periods. AAC and AACR were calculated as follows:

$$\mathrm{APAC} = \frac{\mathrm{A_e} - \mathrm{A_s}}{\mathrm{A_s}} \times 100\% \quad \text{(S1)}$$

$$\mathrm{APACR} = \frac{\mathrm{A_e} - \mathrm{A_s}}{\mathrm{A_s}\Delta\mathrm{T}} \times 100\% \quad \text{(S2)}$$

where A_e is the glacier/lake area in year e (km^2); A_s is the glacier/lake area in year s (km^2); and ΔT is the time-span from year s to year e (a).

Supplementary references

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