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Using Remote Sensing Data to Quantify Changes in Glacial Lakes in the Chinese Himalaya

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To assess changes in glacial lakes in the Chinese Himalaya, 2 inventory phases were conducted on the basis of 278 aerial survey topography maps from the 1970s and 38 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images from the 2000s. In the past 30 years, the number of glacial lakes has decreased, from 1750 to 1680 (a decrease of 4.0%), whereas the average area of glacial lakes expanded from 166.48 to 215.28 km^2 (an increase of 29.7%). Between 3400 and 6000 m, glacial lake areas expanded at rates of 2–84% in almost all 100-m elevation bands, and the dominant expansion rates at different elevations were inversely correlated with glacier area retreating rates to some degree. Glacial lake expansion was a dominant contributor to the increase in glacial lake area, accounting for about 67% of the net changes in lake area, whereas newly formed lakes accounted for the remaining 33%.

Keywords: *Chinese Himalaya; glacial lake change; remote sensing; spatial variability.*

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Introduction

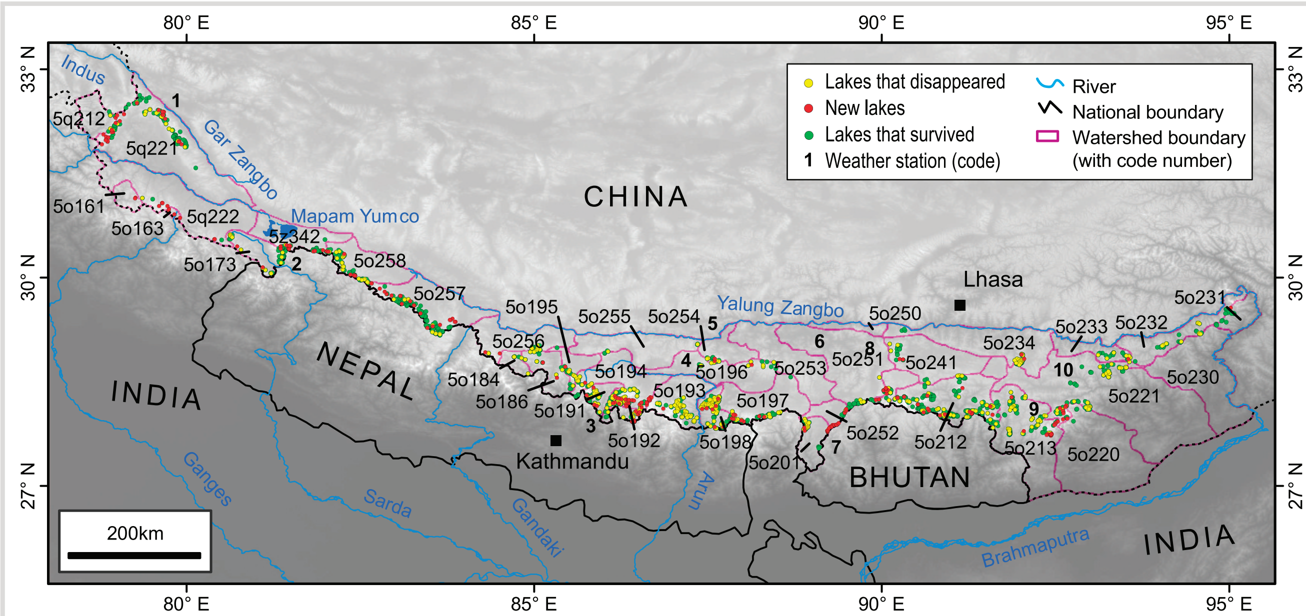
In the context of global warming, glacial lake changes are of wide concern and have become a vital parameter to identify the dangers of glacial lakes (Bajracharya et al 2007; McKillop and Clague 2007; Bolch et al 2008, 2011; Wang et al 2008; Bajracharya and Mool 2009). Currently, research on changes in glacial lakes is mainly based on remote sensing data by using methods such as combining multispectral data (Kargel et al 2005), water surface index (Huggel et al 2002), and reclassification remap tables (Wu and Zhu 2008) to analyze variations in area. Inventories and/or investigations of glacial lakes have been conducted mainly in the Hindu Kush–Himalaya region (Mool et al 2001a, 2001b; Gardelle et al 2011) and British Columbia, Canada (McKillop et al 2007) based on remote sensing data.

The region of the Chinese Himalaya, the boundary of Gar zangbu-Mapam Yumco-Yarlung Zangbu to the north and the international boundaries of China-India-Bhutan to the south, is home to thousands of present-day glacial lakes (Figure 1). As early as 1987, glacier lakes in the Pumqu and Boqu basins of Chinese Himalaya were investigated and cataloged (Liu and Sharma 1988). Chinese researchers subsequently analyzed glacial lake changes in typical regions based on Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper images acquired in the 2000s and aerial survey topographical maps constructed in the 1970s and 1980s, which indicated that changes in glacial lakes varied in different typical regions of the Chinese Himalaya (Che et al 2004, 2005; Chen et al 2007; Ye et al 2008). At present, we still lack sound knowledge about the distribution of and the changes in glacier lakes across the whole Chinese Himalaya. To address this, we present 2 phases of glacial lake inventories by using aerial survey topographical maps and ASTER images to investigate the distribution and changes in glacial lakes in the Chinese Himalaya.

Material and methods

The data used here included topographic maps, digital elevation models (DEM), and ASTER images. There were 241 topographic maps at a scale of 1:50,000, 31 at 1:100,000, and 6 at 1:25,000, which originated from aerial photos and reflected glacial lake information from the 1970s. Two topographic maps were produced in 1969, 14 maps in 1970, 83 maps in 1974, 21 maps in 1978, and 158 maps in 1980. The DEM data were digital products derived from the topographic maps. There were 38 ASTER images that covered the region of interest, and 7 Land-sat TM images were used to fill the minor gaps with ASTER images. ASTER image data were from the United States Geological Survey and acquired in the 2000s at the 1A and 1B processing levels, 3 images were captured in 2008, 9 in 2007, 10 in 2006, 10 in 2005, and 6 in 2004. Of the 1970s source data, 94% was taken in the months from October to December. Regarding the source data for the

FIGURE 1 Distribution of glacial lakes in the 2000s in the Chinese Himalaya (international borders are shown as dashed lines where disputed; weather stations are the following: 1 Gar, 2 Burang, 3 Nyalam, 4 Tingri, 5 Lhaze, 6 Xigaze, 7 Pagri, 8 Gyangze, 9 Cona, 10 Lhunze).



2000s, 82% of the ASTER images were acquired in the months from September to March. So the 2 glacial lake inventory phases largely reveal lake status in the fall and winter.

Data processing was related to digitizing of topographic maps and processing of ASTER images. Digitizing topographic maps involved manually scanning, registering, and digitizing the 278 topographic maps as well as generating DEMs from the topographic maps. The 1A and 1B levels of the ASTER images were coregistered and orthorectified by using the topographical maps and DEMs so that the effects of perspective distortion and displacement were eliminated. The accuracy of orthorectification was within one image pixel, and the root mean square error and the standard deviation of the control points were <15 m. The 4 bands in the visible and near-infrared and multiple-target instrumentation radar of ASTER images can be used to distinguish the glacial lake (Wessels et al 2002). The ratio of band 1 (0.52–0.60 μm) to band 4 (1.60–1.70 μm) of the ASTER images was calculated because this could distinguish the glacial lake and terrain-shadow from the other ground features. We categorized ground features in the band 1–band 4 ratio map into 3 types: glaciers and snow were >47, moraines (including bedrock and debris) were <17, and glacial lakes and shadows were 17–47. Because glacier lake surfaces are usually gentle, although shadows often occur on steep slopes, we differentiated glacier lakes from shadows with a slope threshold value of 5°. After the necessary manual modification, the boundaries of glacial lakes were obtained.

Errors in glacial lake extent are determined by image resolution and coregistration errors (Hall et al 2003; Paul et al 2004). The original pixel resolution of band 1 and band 4 of the ASTER images was 15 m, the registration error of the ASTER images was controlled to within 1 pixel, and lake boundaries were vectorized along pixel diagonals from raster lake maps, that is, possibly 50% of an individual pixel was included or excluded erroneously when glacial lake boundaries were vectorized. The uncertainty in a glacial lake's area due to registration and pixel resolution can be calculated by

$$u_a = \frac{\lambda^2 p}{2\sqrt{\lambda^2 + \lambda^2}} = \frac{\lambda p}{2\sqrt{2}} \qquad (1)$$

where u_a is a glacial lake's area uncertainty, λ is the original pixel resolution, and p is the perimeter of a glacial lake. Accordingly, the mean relative error of the Chinese Himalaya glacial lake area in the 2000s was ±2.4%. Glacial area uncertainties of the fourth-order watersheds are shown in Table 1. Because the original topographical map source data were aerial photos with a spatial resolution of 5 m, the errors in glacial lake area in the 1970s should be theoretically less than those in the 2000s.

Results

Distribution of glacial lakes

The distribution of Chinese Himalaya glacial lakes in the 2000s is shown in Figure 1. A total of 1680 glacial

TABLE 1 Glacial lake variation in different basins in the Chinese Himalaya. Fourth-order watersheds based on Chinese glacier inventories are listed from west (top) to east (bottom); the codes correspond to the codes featured on Figure 1. (Table continued on next page.)

Watersheds		1970s		2000s		Change (%)	
Name	Code	Num[a)]	Area (km^2)	Num[a)]	Area (km^2)	Num[a)]	Area
Sangbo River	5q212	11	0.259	15	0.655 ± 0.032	36.4	153.5
Left of Gar Zangbo	5q155	44	2.297	46	3.260 ± 0.129	4.5	41.9
Right of Langqen Zangbo	5q221	62	2.408	69	3.329 ± 0.148	11.3	38.2
Left of Langqen Zangbo	5q222	18	1.336	19	1.415 ± 0.047	5.6	5.9
Jazaganga River	5o161	–	–	2	0.090 ± 0.050	–	–
Daoli Zangbo	5o163	–	–	4	0.222 ± 0.010	–	–
Maja Zangbo	5o173	43	2.206	37	2.984 ± 0.101	−14.0	35.3
Mapam Yumco	5z342	22	3.496	35	4.683 ± 0.123	59.1	34.0
Right of Diemayangzong	5o258	51	7.692	49	10.024 ± 0.211	−3.9	30.3
Xiongqu-Ronglai Zangbo	5o257	137	18.596	143	26.006 ± 0.533	4.4	39.8
Galixiong–Wengbuqu	5o256	32	0.721	28	1.203 ± 0.058	−12.5	66.9
Dogar River	5o184	8	0.264	4	0.125 ± 0.007	−50.0	−52.6
Gyirong Zangbo	5o186	41	1.632	29	2.009 ± 0.074	−29.3	23.1
Peik Co	5o195	37	11.563	28	15.690 ± 0.180	−24.3	35.7
Pengji Zangbo	5o255	9	0.157	6	0.265 ± 0.012	−33.3	68.7
Mazhang Zangbo	5o191	76	10.373	63	14.771 ± 0.244	−17.1	42.4
Rongxar Zangbo	5o192	88	4.565	101	8.182 ± 0.269	14.8	79.2
Manqu-Requ	5o194	38	6.077	28	7.570 ± 0.121	−26.3	24.6
Ganma Zangbo	5o193	100	8.602	77	8.039 ± 0.227	−23.0	−6.5
Shakya Zangbo	5o254	11	1.861	13	2.164 ± 0.050	18.2	16.3
Banqu	5o196	17	1.437	15	1.534 ± 0.050	−11.8	6.7
Natangqu	5o198	128	10.365	114	11.968 ± 0.339	−10.9	15.5
Yairu Zangbo	5o197	51	7.949	52	10.189 ± 0.223	2.0	28.2
Hangbomaqu	5o201	29	1.655	31	2.279 ± 0.074	6.9	37.7
Saiqu	5o253	12	0.117	7	0.111 ± 0.009	−41.7	−4.6
Doqen Co	5o252	9	2.154	24	4.600 ± 0.104	166.7	113.6
Nyangqu	5o251	35	21.478	37	23.725 ± 0.210	5.7	10.5
Menqu	5o250	8	0.480	6	0.422 ± 0.017	−25.0	−12.1
Puma Yumco	5o240	16	1.900	18	2.375 ± 0.061	12.5	25.0

TABLE 1 Continued. (First part of Table 1 on previous page.)

Watersheds		1970s		2000s		Change (%)	
Name	Code	Num[a)]	Area (km^2)	Num[a)]	Area (km^2)	Num[a)]	Area
Yamzhog Yumco	5o241	37	1.215	32	1.714 ± 0.067	−13.5	41.1
Luozaxiongqu-Zhangqu	5o212	193	15.245	179	21.252 ± 0.588	−7.3	39.4
Siqunama	5o234	37	0.623	34	0.791 ± 0.050	−8.1	27.0
Nyabxangqu	5o213	123	9.142	103	10.067 ± 0.269	−16.3	10.1
Kamau River	5o220	2	0.061	8	0.552 ± 0.025	300.0	803.2
Xibaxaqu	5o221	147	4.056	152	5.481 ± 0.276	3.4	35.1
Jindongqu	5o233	30	0.299	27	0.465 ± 0.037	−10.0	55.2
Zelongnongba	5o232	31	2.743	29	3.035 ± 0.095	−6.5	10.7
Xilepaban	5o230	10	0.368	9	0.479 ± 0.016	−10.0	30.1
Yanglang Zangbo	5o231	7	1.088	7	1.574 ± 0.034	0.0	44.6
Total		1750	166.480	1680	215.279 ± 5.126	−4.0	29.7

[a)]Number of glacial lakes.

lakes with a total area of 215.28 km^2 existed at this time, surviving in 39 fourth-order watersheds based on the watershed division method for Chinese Glacier Inventories (Table 1). Because the total area and glacier-covered area differ in each watershed, the comparison of absolute lake area between watersheds is not meaningful. The lake area has been normalized with the overall glacierized area of each watershed. As shown in Figure 2, the Chinese Himalaya can be divided into 3 parts according to the magnitude of normalized lake areas. The middle part of Chinese Himalaya (from 5o251 to 5z342) shows the largest normalized lake areas (with an average value of about 0.47×10^{-2} km^2/km^2). In both the eastern (from 5o241 to 5o231) and western part (from 5q212 to 5o173) of the Chinese Himalaya, the lake areas are about 1 order of magnitude lower, with average normalized lake areas of 0.82×10^{-3} km^2/km^2 and 0.30×10^{-3} km^2/km^2, respectively.

Glacial lakes were distributed between 3400 and 6100 m, when lake elevations were organized in 100-m

FIGURE 2 Normalized glacial lake area of each fourth-order watershed; watersheds are arranged from east (right) to west (left).

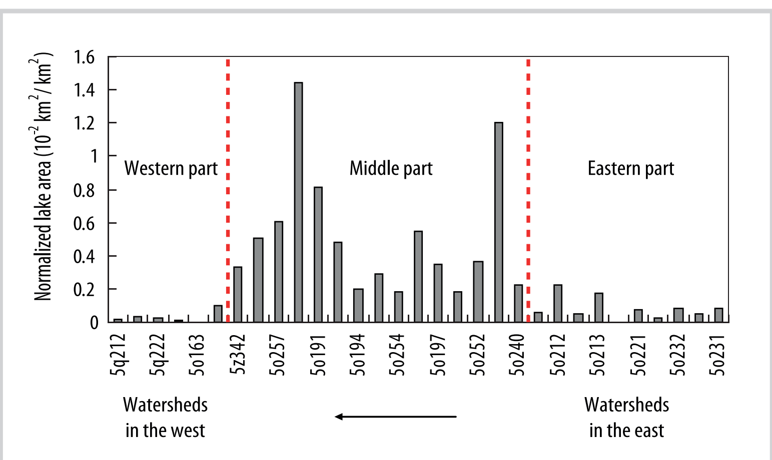
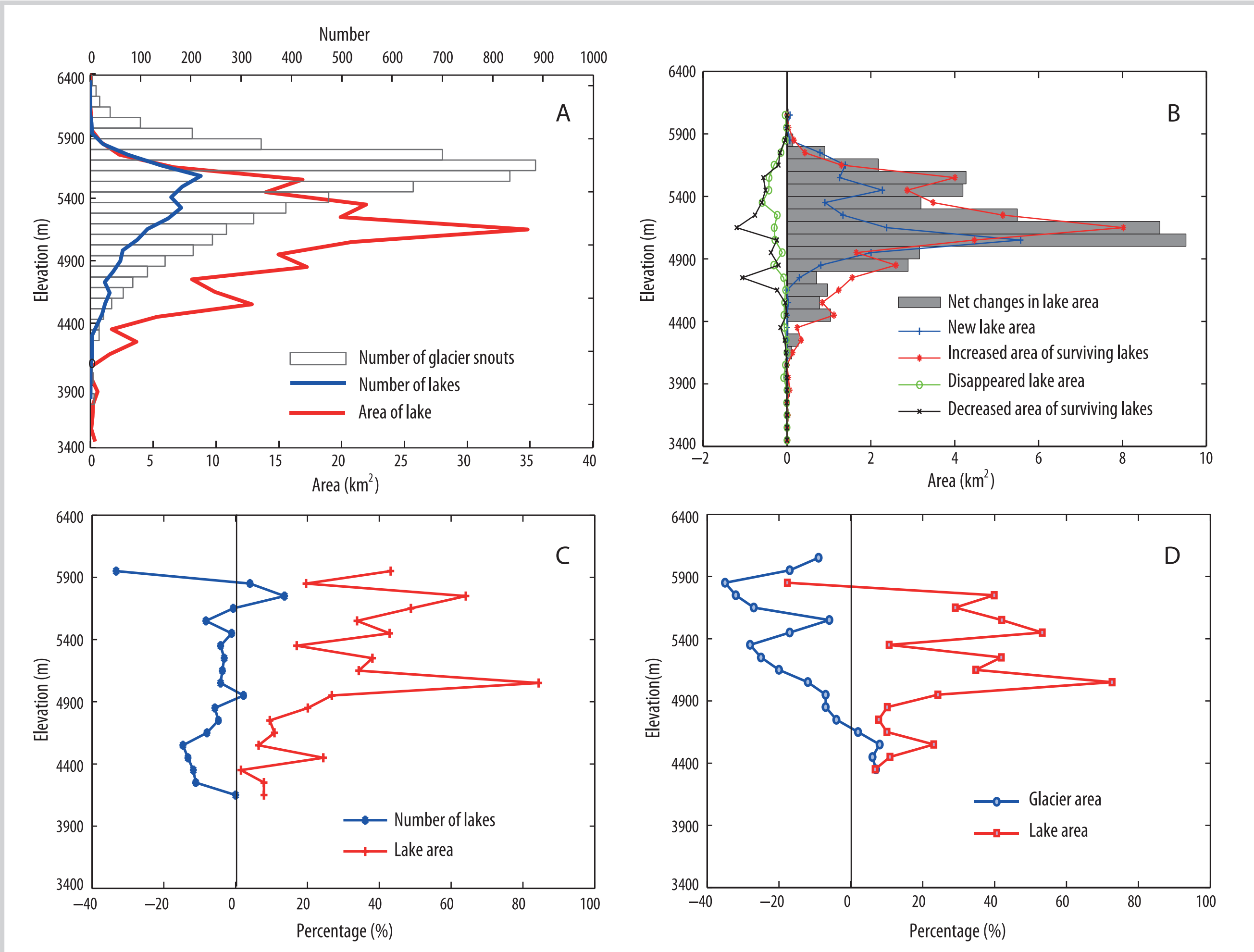


FIGURE 3 Distributions and changes of glacial lakes in the Chinese Himalaya, organized in 100-m elevation bands over the past 30 years. (A) Distributions of lake area, number, and glacier snout number; (B) area variations of surviving lake, new lake, disappeared lake area, and net changes; (C) lake changes in percentages over the past 30 years (only 100-m elevation bands with more than 10 lakes are shown); (D) contrasted area changes of glacier and lake in Mt Qomolangma National Natural Preserve Region.



elevation bands (Figure 3A). Seventy-five percent of the lake area was between 4800 and 5600 m, and 77% of the lakes were between 4900 and 5700 m. The maximum elevation range of lakes was ~5500–5600 m, and the highest elevation range of lake areas was ~5100–5200 m, that is, the elevation of the maximum number and peak area of lakes differed by ~400 m in the Chinese Himalaya.

Changes of glacial lakes

As far as the glacial lake changes are concerned during the past 30 years, the number of lakes in the Chinese Himalaya decreased by 4%, from 1750 to 1680, whereas the area of lakes increased by 29.7%, from 166.48 km^2 to 215.28 km^2. In the past 30 years, 224 lakes with a total area of 19.18 km^2 were newly formed. Of the 1456 surviving lakes, the areas of 905 (65% of the total) expanded significantly (>2% increase in lake extent). Eighty-five lakes (6% of the total) had variable changes, of ±2%, in lake extent. A total of 431 lakes (32% of the total) had areas that decreased significantly (≤2% decrease in lake extent). In the past 30 years, of the 39 fourth-order watersheds, 60% had average decreases in number, and 90% had average increases in area (Table 1).

When changes are considered in 100-m elevation bands over the past 30 years, the number of lakes decreased and area expanded. In each 100-m elevation band above 4100 m, there was an average increase in area, with a maximum increase of 84% at 5000–5100 m and a secondary peak of 64% at 5700–5800 m. However, the change in the number of lakes showed an average decrease (−1 to −17%), except for increases at 4900–5000 m (2%) and 5700–5900 m (12%) (Figure 3C). For a 100-m elevation band (i), the net changes in lake area (A_{ni}) can be expressed as

$$A_{ni} = E_i^{+} - E_i^{-} + N_i - D_i \qquad (2)$$

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FIGURE 4 Schematic diagram, showing the lake-glacier dynamic types in the Chinese Himalaya; d_{1970s} and d_{2000s} indicate the distances between the glacial lakes and their parent glaciers in the 1970s and 2000s.

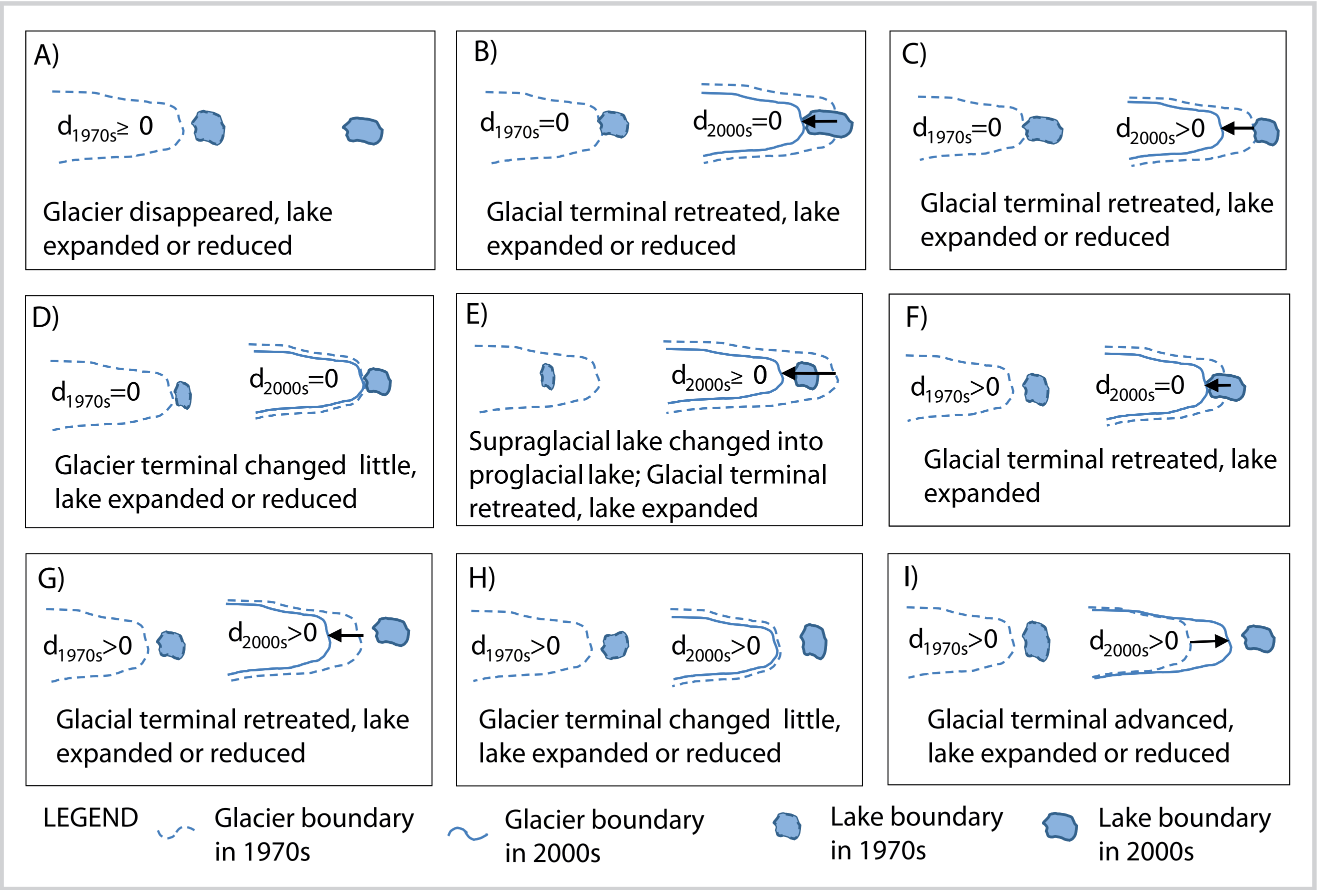

TABLE 2 Lake-glacier dynamic types and their changes in existing lakes in Chinese Himalaya; types are illustrated in Figure 4 and follow the same coding.[a)]

Type code	Number of lake	Average change of parent glacier terminal (m)	Area in 1970s (km^2)	Area in 2000s (km^2)	Rate of lake area variation (%)
A	299	/	15.88	16.37	+3
B	86	−424	35.02	50.68	+45
C	95	−498	13.16	15.79	+20
D	21	0	8.17	8.35	+2
E	18	−1467	4.63	9.15	+98
F	20	−272	1.78	4.81	+171
G	776	−268	74.05	80.09	+8
H	137	0	9.70	10.37	+7
I	4	+191	0.30	0.24	−20
Total	1456	/	162.69	195.86	+20

[a)]+, advance or expanding; −, retreating or reducing; /, null.

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TABLE 3 Variation in linear trends of mean annual temperature and precipitation from the 1960s to 2006 in the Chinese Himalaya; the weather stations are arranged from west (top) to east (bottom). The locations of weather stations are shown in Figure 1. (Table extened on next page.)

Weather station	Location			Average annual precipitation (mm)	Precipitation variation in linear trend (mm/year)	Significance
	°E	°N	m			
Gar	80.08	32.50	4279	70.7	1.4	0.72
Burang	81.25	30.28	3900	160.8	−2.7	0.02
Nyalam	85.97	28.18	3810	649.1	−0.4	0.86
Tingri	87.08	28.63	4300	280.7	1.7	0.08
Lhaze	87.60	29.08	4000	327.4	5.9	0.02
Xigaze	88.88	29.25	3836	432.5	1.0	0.46
Pagri	89.08	27.73	4302	420.6	1.5	0.04
Gyangze	89.60	28.92	4040	290.1	0.3	0.74
Cona	91.95	27.98	4280	400.5	1.9	0.11
Lhunze	92.47	28.42	3860	280.2	0.8	0.24

where E_i^+ is the increased area of survival lakes, E_i^- is the decreased area of survival lakes, N_i is the new lake area, and D_i is the disappeared lake area. As shown in Figure 3B, all the values of A_{ni} in elevation bands are positive, except in the altitude band at 3900–4100 m, and the 2 peak values of A_{ni} (18.41 km^2) occurred at 5000–5200 m, which accounted for 38% of the total net glacial lake area ($\sum A_{ni} = 48.80$ km^2). At different altitude bands, the total increased area of survival lakes ($\sum E_i^+ =$ 39.78 km^2) was about 6 times larger than the total decreased area of survival lakes ($\sum E_i^- = 6.47$ km^2). However, although the number of the newly formed lakes (224) was fewer than those that disappeared (294), the total area of the new lakes ($\sum N_i = 19.18$ km^2) was much larger than that of those that disappeared ($\sum D_i =$ 3.69 km^2), because the new lakes were larger in size (0.09 km^2) on average than those that disappeared (0.01 km^2).

Lake and glacier dynamics

To detect the hydrological connections of lake change and its parent glacier dynamics, the distances between the lake and its parent glacier were measured both in the 1970s and 2000s (labeled as d_{1970s} and d_{2000s}, respectively). When the values of d_{1970s} and d_{2000s} combined with changes of lake area and glacier snout shift were compared, 9 dynamic categories of lakes and parent glaciers were generalized, as shown in Figure 4 and Table 2. Among the 9 lake-glacier dynamic types, type "F" (lakes that expanded rapidly upstream toward the retreating parent glacier snout and ultimately contacted the parent glacier in the 2000s) had the highest rate of area growth at +171%. Type "E" (the supraglacial lakes in 1970s that evolved into proglacial lakes as the parent glacier retreated) had the second highest growth rate, at +98%, followed by type "B" (lakes that expanded along the contacted glacier terminal in a retreating direction), with a growth rate of 45%.

However, the lakes whose parent glacier terminal shifted little (types "D" and "H") presented relatively smaller growth rates, of 2 and 7%, respectively, whereas the lakes whose parent glaciers were advancing (type "I") decreased at a rate of approximately −20%. In addition, ~50% of the new lakes formed at the place that used to be covered by parent glaciers and were the direct outcomes of glacier recession.

Discussion

It is of scientific interest to understand why glacial lakes grow across most watersheds and peaks in a narrow elevation range. This calls for detailed study of the physical links between climate change, glacier response, and lake development. Analysis of daily meteorological data from 10 weather stations (Figure 1) over the past 40 years in the Chinese Himalaya shows that temperatures rose by 0.015–0.059°K/year, with statistically significant reliability levels (Table 3). From the middle to the western part of the Chinese Himalaya, relatively higher rates occurred, which ranged from 0.037 to 0.059°K/year (Nyalam is an exception, of 0.23°K/year), whereas, from the middle to the eastern part of the Chinese Himalaya, the temperature rose at 0.015–0.029°K/year. Although most of the weather stations revealed minor trends in increased precipitation, only those at Burang, Lhaze, Pagri, and Tingri showed statistically significant trends (Table 3). Thus, precipitation trends differ, and no

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TABLE 3 Extended. (First part of Table 3 on previous page.)

Average annual temperature (°C)	Temperature variation in linear trend (°C/year)	Significance
0.584	0.037	<0.001
3.448	0.042	<0.001
3.687	0.023	<0.001
2.555	0.059	<0.001
6.891	0.047	<0.001
6.508	0.015	<0.001
0.166	0.016	0.002
4.954	0.019	<0.001
−0.175	0.029	<0.001
5.329	0.024	<0.001

evident trends in variation were found over the past 40 years for the whole region. However, due to a warming climate in the study area, the glaciers have retreated overall, at a reduced rate of 1.5–9% over the past 30 decades (Ren et al 2004; Jin et al 2005; Yao et al 2007; Ye et al 2006, 2007). Field measurements also indicated that the glacier terminals were continuously retreating, with average retreat rates of ~4–10 m/year in recent decades in the Chinese Himalaya (Table 4). Thus, broadly rising air temperatures and glacier retreat are the main features of Chinese Himalayan climate change and glacial fluctuations.

The number of glacier snout distribution characteristics closely resembled the number of the distribution of lakes and peaks at 5500–5700 m, which implies that lake formation and development is correlated with the position of glacier snout, because meltwater is the main source of lake water (Figure 3A). However, more glacier snouts do not directly result in larger growth rates of lake area, because maximum lake area growth appears in the band at 5000–5100 m (Figure 3B). It was reported that the maximum rate of glacier retreat occurs at 5700–5900 m in Mt Qomolangma National Natural Preserve Region (Nie et al 2010). When the percentage changes of lakes are compared with the percentage changes of glaciers at different elevation bands in Mt Qomolangma National Natural Preserve Region, with covered glacier area of ~2710.17 km^2 and lake area of ~90.58 km^2, we found that the glacier decreased at 4700–6100 m, whereas the glacial lake increased, at 4300–5900 on the whole, and 2 reduced peak bands of glacier percentage change (5800–5900 m and 5300–5400 m) largely contrasted with 2 expansion peak bands of glacial lake percentage change (5400–5500 m, 5000–5100 m, respectively) (Figure 3D). Consequently, rates of glacial lake change at different elevations are inversely correlated with glacier area change rates to some degree and may possibly indicate differential glacier response to climate change in the Chinese Himalaya.

Glacial lake area variation is closely related to the dynamics of the parent glacier, and the expansion rate of glacial lakes shows differences between proglacial lakes in contact or not in contact with glacier ice (Gardelle et al 2011). The highest area expansion rate was detected in the lakes that contacted the retreating parent glacier, which indicates that parent glacier meltwater flowing into a lake made the dominant contribution to lake area growth in the Himalaya during the past 30 years. However, the lakes that cannot be fed by meltwater because the parent glacier disappeared during the past 30 years also expanded, although at the relatively low rate of +3% (type

TABLE 4 Observed retreat rates of glacier termini in Chinese Himalaya.

Glacier name	Location	Study period	Retreat rate (m/y)	Reference
Rongbuk Glacier	85.85°N; 28.03°E	1966–1997	8.7	Ren et al 1998
		1997–2004	9.2	Ren et al 2006
East Rongbuk Glacier	86.96°N; 28.02°E	1966–1997	5.5	Ren et al 1998
		1997–2004	8.0	Ren et al 2006
Far East Rongbuk Glacier	86.96°N; 28.02°E	1966–1997	7.4	Ren et al 1998
Dsuopu Glacier	85.77°N; 28.35°E	1968–1997	4.0	Pu et al 2004
Kangwure Glacier	85.45°N; 28.27°E	1974–2007	8.9	Ma et al 2010
5o194E10	85.77°N; 28.41°E	1997–2001	4–5	Pu et al 2004
		2005–2008	7.1	Ma et al 2010
Naimena'nyi Glacier	81.44°N; 30.27°E	1976–2006	5.0	Yao et al 2007

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"A" in Figure 4), which suggests that glacial lake variation cannot be solely accounted for by the water budget of glacier, lake, and parent glacier snout dynamics. In addition, the low surface slopes ($<2°$) and the speed of the glacier tongue (10 m/year), relatively thin debris layers that caused a reduction in the glacier surface, and an overdeepened part of the glacier bed argue favorably for lake formation and development (Reynolds 2000; Quincey et al 2007; Suzuki et al 2007; Röhl 2008; Sakai and Fujita 2010; Frey et al 2010). Thus, the coupling of glaciers and lakes in hydrology, dynamic patterns of glaciers and lakes, topography of the glacierized region, debris thickness and surface, and the speed of the glacier tongue are the keys to explain lake formation and evolution. Data for a detailed study are being produced by the ongoing compilation of the Second Glacier Inventory of China.

Conclusions

There were 1680 glacial lakes, with a total area of 215.28 km^2, in the 2000s, and the normalized glacial lake area of the middle part was 1 order of magnitude larger than those of the western and eastern parts of the Chinese Himalaya. In the past 30 years, the number of glacial lakes decreased by 4.0%, whereas the area of glacial lakes increased by 29.7%. From 3400 to 6000 m, the lake area expanded at rates of 2 to 84%, and the number of lakes decreased at the rate of -1 to -17% in almost all 100-m elevation bands. The discrepant change rates of lakes at different elevation bands may indicate differential glacier responses to climate change. Expansion of surviving glacial lakes was a dominant contributor to the increase in glacial lake area, which accounted for ~67% of the total increase in lake area, and newly formed lakes contributed to the remaining 33%. The closer the glacial lake was to its parent glacier, the more rapid was the rate of increase in the area of the glacial lakes. The greatest area expansion rate was detected in the lakes that contacted their retreating parent glaciers, which indicates that parent glacier meltwater that flowed into glacial lakes made the greatest contribution to lake area expansion in the Himalaya.

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