AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE
10.1002/2013WR014724

Key Points:

- Accelerated increases in the lake area and water level on the TP in the 2000s
- The accelerated lake growth is close related to increasing precipitation
- The glacier meltwater supply augments the growth rates of the glacier-fed lakes

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Citation:
Song, C., B. Huang, K. Richards, L. Ke, and V.H. Phan (2014), Accelerated lake expansion on the Tibetan Plateau in the 2000s: Induced by glacial melting or other processes?, *Water Resour. Res.*, *50*, doi:10.1002/2013WR014724.

Received 10 SEP 2013
Accepted 19 MAR 2014
Accepted article online 25 MAR 2014

Accelerated lake expansion on the Tibetan Plateau in the 2000s: Induced by glacial melting or other processes?

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Abstract Alpine lakes on the Tibetan Plateau are minimally disturbed by human activities and are sensitive indicators of climate variability. Accelerated lake expansion in the 2000s has been confirmed by both dramatic lake-area increases (for 312 lakes larger than 10 km^2) derived from optical images, and rapid water-level rises (for 117 lakes with water-level data) measured by satellite altimetry. However, the underlying climate causes remain unclear. This paper analyzes the relationship between the water-level changes of lakes on the plateau and the potential driving factors, such as the glacier meltwater supply and a dependency on precipitation and runoff over the whole plateau and in each zone. The results show that the rates of change of non-glacier-fed lakes in the 2000s were as high as those of glacier-fed lakes across the whole plateau and the lake-level changes were closely associated with the lake supply coefficients (the basin/lake area ratio). The lake variations agreed well with the spatial pattern of precipitation changes. However, in different zones, especially at around 33°N north of the plateau, glacier-fed lakes did exhibit faster lake level increases than no-glacier-fed lakes, indicating that the presence of a glacier meltwater supply augmented the precipitation-driven lake expansions in these areas. Despite the absence of quantitative modeling due to limited data availability, this study provides qualitative support that the lake expansions on the Tibetan Plateau in the 2000s have been driven primarily by changes in precipitation and evapotranspiration and not solely by the effect of glacier wastage.

1. Introduction

The Tibetan Plateau (TP) is also known as the earth's "third pole" and as the Asian Water Tower [*Yanai et al.*, 1992]. It has many lakes that play an important role in maintaining the water balance of several large Asian river basins and are sensitive indicators of climate variability [*Yao et al.*, 2007; *Zhang et al.*, 2013]. In recent decades, with rising temperatures and changing precipitation and evaporation patterns across the TP, these alpine lakes showed strong spatiotemporal variability. For example, many large lakes (NamCo and SilingCo) in the central TP have been shown with medium-high resolution satellite imagery to have expanded since the 1970s [*Bian et al.*, 2010; *Huang et al.*, 2011; *Liao et al.*, 2012; *Zhu et al.*, 2010]. Although Lake Qinghai in the northeastern TP showed serious shrinkage in the 1980s and 1990s, it began to expand in the 2000s [*Li et al.*, 2012; *Liu and Liu*, 2008; *Shao et al.*, 2008]. In contrast, some lakes in southern Tibet, such as YamzhogYumco and PaikuCo, had significant decreases in their lake extents and water levels in the 2000s [*Chu et al.*, 2012; *Ye et al.*, 2007]. Based on satellite radar and laser altimetry (collected from the Environmental Satellite and the Ice, Cloud, and Land Elevation Satellite (ICESat)), *Kropáček et al.* [2012], *Phan et al.* [2012a, 2012b], *Song et al.* [2013b], *Wang et al.* [2013], and *Zhang et al.* [2011a, 2011b] measured lake water level changes across the TP and found that most of the lakes experienced rapid rises during 2003–2009. *Lei et al.* [2013], *Song et al.* [2013a], and *Zhang et al.* [2013] estimated the water mass budgets of Tibetan lakes. Their results showed that the water mass gains in the 2000s contributed over 70% of the total lake growth since the 1970s.

As most Tibetan lakes are minimally disturbed by human activities, lake variations are closely associated with climate change. Earlier work has focused on some typical glacier-fed lakes and has inferred that the observed lake expansions were caused by global warming, based on strong covariations with glacier shrinkage within the neighboring lake basins [*Bian et al.*, 2010; *Huang et al.*, 2011; *Liao et al.*, 2012; *Yao et al.*, 2007;

Ye et al., 2007]. Some studies have suggested that lake expansion may also be related to increased precipitation and reduced evaporation in central Tibet, in addition to the primary factor of the glacial meltwater supply [*Bian et al*., 2010; *Zhu et al*., 2010]. *Zhu et al*. [2010] provided one of the first detailed analyses by quantifying the proportions of the different effects contributing to the expansion of Lake NamCo. Although precipitation (including both direct on-lake precipitation and precipitation runoff from the lake basin) accounted for ~60% of the total supply and glacier melting contributed only ~10%, the results suggested that the increment of glacial meltwater addressed ~50.6% of the change in the lake water storage. However, *Lei et al*. [2013] recently indicated that precipitation, runoff, and evaporation were the main factors causing rapid growth in five lakes in the central TP, accounting for ~70% of the total lake increment, whereas the glacial meltwater supply accounted for total lake level rises of ~11.7% in Lake SilingCo, ~28.7% in Lake NamCo, and ~17.4% in Lake PungCo, which are all glacial-fed lakes.

The main driving forces behind lake-level changes on the TP are therefore still under debate, especially the roles of changing precipitation and evaporation patterns and glacier meltwater supplies associated with temperature in the accelerating lake expansions in the 2000s. The best method to address this issue is quantitative modeling of the lake water balances. At present, however, applying this method to the whole TP is hampered by difficulties in collecting or deriving sufficient reliable glacier mass balances estimates and by spatially insufficient meteorological or hydrological observations of the lake basins of the TP. For instance, the in situ mass balances of several measured glaciers on the TP between 2006 and 2010 reported by *Yao et al*. [2012] are not consistent with the estimates reported by *Gardner et al*. [2013] using the ICESat/GLAS altimetry data, which sample more glaciers. Although reanalysis and merged gridded precipitation products can depict the spatial pattern and temporal trends of precipitation variability, they cannot accurately estimate the amount of precipitation on the TP [*Ma et al*., 2009; *Tong et al*., 2013; *You et al*., 2012].

We therefore synthesized multiple available remote-sensing data sets to fully examine the spatial and temporal patterns of lake changes on the TP in relation to the local climate variations, focusing on the 2000s. Our main objective was to assess whether increased glacial meltwater is the primary reason for lake expansion across the TP in the past decade and, if not, what other factors are responsible. We analyzed the relationships between the water-level changes of 105 closed lakes and the potential driving factors, such as the presence or absence of a glacier meltwater supply, a dependency on the magnitude of glacier meltwater in glacier-fed lakes and a dependency on precipitation and runoff across the whole TP and in each climate zone. The ratio of the glacier area to the lake area, or glacier-lake (G-L) ratio, and the ratio of the lake basin area to the lake area, or supply coefficient, were used as relative measures for the two dependencies studied. We also examined the trends in the changes in the precipitation and potential evaporation on the TP and their relationship with the rate of lake growth.

2. Study Area and Materials

2.1. The Tibetan Lakes and Climate

The TP is located in central Asia (25°59′N–104°29′N, 73°27′E–104°30′E). It is the highest and most extensive plateau on Earth, with an average elevation exceeding 4000 m (Figure 1). It is surrounded by many large mountain ranges, such as the Himalayas, the Hengduan Mountains, and the Qilian Mountains. There are more than 1500 lakes on the TP. Three hundred and twelve lakes cover surface areas larger than 10 km^2, 104 lakes cover surface areas larger than 100 km^2, seven lakes cover surface areas larger than 500 km^2, and three lakes cover surface areas larger than 1000 km^2. The combined lake area of the TP accounts for about 49% of China's total lake area [*Ma et al*., 2010]. The TP's climate is characterized by strong seasonality. The majority of the precipitation, more than 60–90% of the annual total, falls between June and September and less than 10% falls between November and February [*Xu et al*., 2008]. In summer, several regional or large-scale atmospheric circulations, such as the Indian summer monsoon and the East Asian summer monsoon, bring most of the TP's precipitation. In winter, the climate is dominated by cold and dry westerlies [*Yao et al*., 2012]. Most of the alpine lakes thus expand in summer and autumn with supplements from the rainfall runoff and glacial meltwater. They freeze in winter until April or May of the following year when thawing starts. Due to its broad spatial cover and the strong topographic effect, the TP's climate features significant spatial and temporal variability, resulting in different lake variations in different regions. Lakes on the TP can be grouped into seven zones, shown in Figure 1, by their dominant climatic influences [*Yao et al*., 2012],

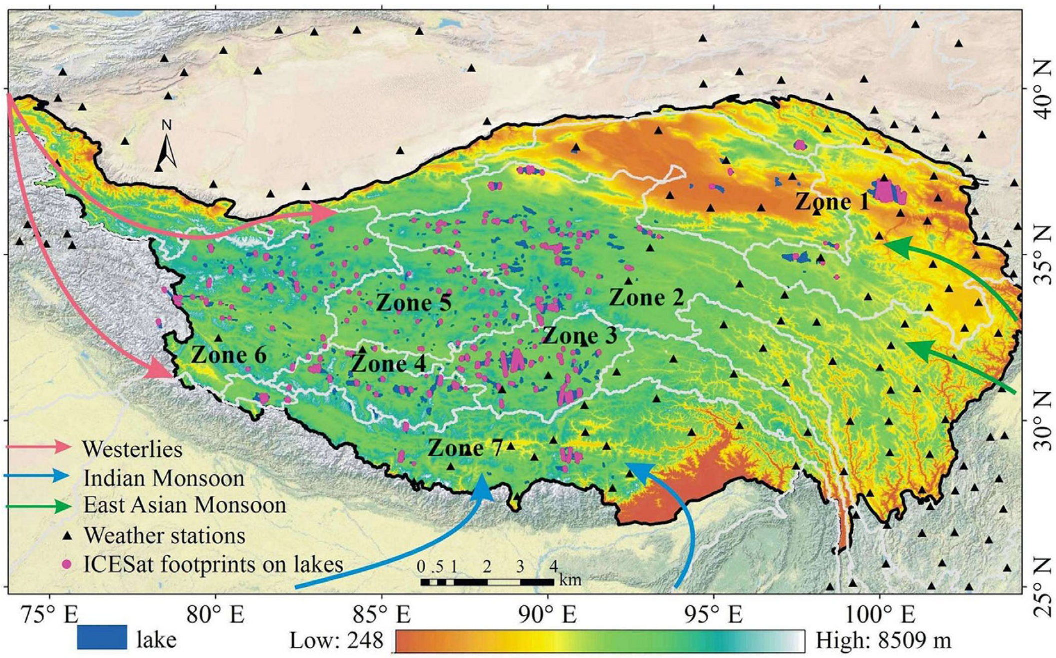

Figure 1. The geographic distribution of the lakes and the influence of large-scale atmospheric circulation on the TP.

the characteristics of their geographic regions, and the nature of the water supply to the lakes [*Wang et al*., 1998]. Zone 1 is in the eastern TP and includes the Qaidam Basin and Yellow River source. Zone 2 covers the Hoh Xil region and the Yangtze River. Zone 3 covers central Tibet. Zone 4 is the steep basins along the Gangdise Mountains. Zone 5 covers the small lake basins in the hinterland of the Changtang Plateau. Zone 6 covers the western TP and the Karakorum Mountains. Zone 7 covers southern Tibet.

2.2. Optical Images for Measuring Lake Area Variations

Landsat multispectral scanner/thematic mapper/enhanced thematic mapper (ETM) images covering the study area were used to retrieve the surface extents of 312 lakes in the early 1970, 1990, 2000, and 2011. To reduce the influence of seasonal variations when comparing interannual changes in the lake extent, all of the images used were acquired between August and October. As the number of Landsat images from the 1970s and 1980s suitable for mapping Tibetan lakes is very limited, additional images acquired in 1976 and 1992 were used to supplement the images representing the early 1970s and 1990s, respectively. All of the images used were cloud-free or showed less than 5% cloud-cover over the lake areas. Gaps in the Landsat ETM+ scan line corrector-off images were removed using the neighborhood similar pixel interpolator algorithm developed by *Chen et al*. [2011]. The images were first processed with standard procedures, including geo-referencing and radiometric correction. Each scene was geo-referenced using at least 15 ground control points, which were selected from 1:100,000 topographic maps and the Google Earth software. The corrected images were then used as the reference for the image-to-image registration of the other bands. The root mean squared errors of the rectifications for these images were lower than 0.6 pixels. The other image details were as described by *Song et al*. [2013a].

2.3. Satellite Altimetry Data for Measuring Lake Water-Level Variations

Altimetry data from NASA's ICESat were used to extract time series of water level variations in the alpine lakes on the TP between 2003 and 2009. Many previous studies have proved that this data set is useful for land surface measurement applications, atmosphere and cloud height, vegetation canopy height, and inland lake and river water levels [*Schutz et al*., 2005; *Urban et al*., 2008; *Zwally et al*., 2002]. The absolute accuracy of ICESat has been reported to 10–15 cm under normal conditions [*Zwally et al*., 2008, 2002]. The reliability of using the ICESat altimetric data for lakes on the TP to study water-level changes has been confirmed with comparisons to hydrological station data, radar altimetry, and lake area data derived from optical images [*Phan et al*., 2012a; *Song et al*., 2013a; *Wang et al*., 2013; *Zhang et al*., 2011a].

We used the ICESat's L2 Global Land Surface Altimetry Data (GLA14), provided by NASA's National Snow and Ice Data Center. The GLA14 data set contains corrected surface elevations based on one of the two implemented retracking approaches, called "alternative parameterization," which is tuned to capture the last reflection of the signal. All of the ICESat/GLA14 Release-33 data covering the TP between 2003 and 2009 were downloaded and processed. A linear regression was used to estimate the annual rates of change of the lake levels between 2003 and 2009 based on all of the available altimetric observations for each lake. To ensure reliable estimates of the trend in lake-level changes, lakes were only selected if the water level was sampled in at least five campaigns (five observation dates), if the observation period was longer than 5 years, and if the lake area was greater than 10 km^2. Altimetric data for 117 alpine lakes were analyzed.

2.4. Other Materials and Processing

The distribution and magnitudes of the glaciers on the TP were derived from the Glacier Inventory of China to examine whether each lake was supplied by glacial meltwater [*Shi*, 2005; *Wang and Liu*, 2001]. Although this inventory has been found to be incorrect (e.g., slight displacements for some glaciers) in a few parts of the study area [*Arendt et al*., 2012], it is the only publicly available glacier inventory covering the whole TP. The outlines in this inventory are also included in other widely used global glacier inventories, such as the Global Ice Measurements from the Space database and the Randolph Glacier Inventory. We compared the three inventories and found that they have approximately the same information for the TP in China, except that the Randolph Glacier Inventory had updated a few small glaciers in the southeastern TP.

The glacier area within each watershed was calculated following *Phan et al*. [2013]. Watersheds and stream networks were obtained from the HydroSHEDS data set from the U.S. Geological Survey website. Each subbasin was checked with the help of Google Earth Geomorphology and a few incorrect basin boundaries were modified by manual delineation based on the Shuttle Radar Topography Mission's digital elevation model data. For example, the mixed YamzhogYumco and PumaYumco basins were divided and the underestimated Bangongco basin extent was corrected. All of the glaciers that drain into a lake within the lake subbasin boundary were extracted for all 117 lakes with ICESat water level measurements on the TP. The lake basin area, glacier area within each basin, supply coefficient (using the average of the lake areas in 2000 and 2011), and G-L ratio for each lake is listed in Appendix . The lakes' supply sources generally matched the results of the field investigations conducted by China's scientific expedition group to the TP in the 1970–1990s [*Wang et al*., 1998]. The computed supply coefficients were in good agreement with those of dozens of lakes provided by field investigations [*Wang et al*., 1998].

We obtained yearly and monthly meteorological data of the TP and its surroundings from 1996 to 2010 from 158 stations from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). We obtained the air temperature, maximum and minimum temperature, precipitation, number of rainfall days, sunshine duration, wind velocity, and other climate variables. As the pan evaporation data cannot be acquired directly, we used the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith model [*Allen et al*., 1998; *Monteith*, 1965] to estimate the monthly and annual potential evapotranspiration. The Penman-Monteith model is considered to be one of the most favorable evaporation estimation methods for lakes [*Rosenberry et al*., 2007]. The value of the reference evapotranspiration calculated with the mean monthly weather data was very similar to the average of the daily evapotranspiration calculated with the daily average weather data for that month [*Allen et al*., 1998]. The detailed calculation procedure is shown in Appendix B. Due to the uneven, sparse distribution of the stations over the TP, gridded precipitation was also collected from the Global Precipitation Climatology Project (http://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html) (GPCP) and compared with gauge-based data.

3. Results and Analysis

3.1. Comparing the Characteristics of the Lake Variations in the 2000s and the 1970–2000

Figure 2 shows the lake area variations for the seven zones in Figure 1 from the early 1970–2011. It is clear that the lake area of different zones have different temporal variation patterns. In the northeastern TP (zone 1), the total lake area steadily decreased from the 1970s to the early 2000s (a total decrease of 417 km^2,

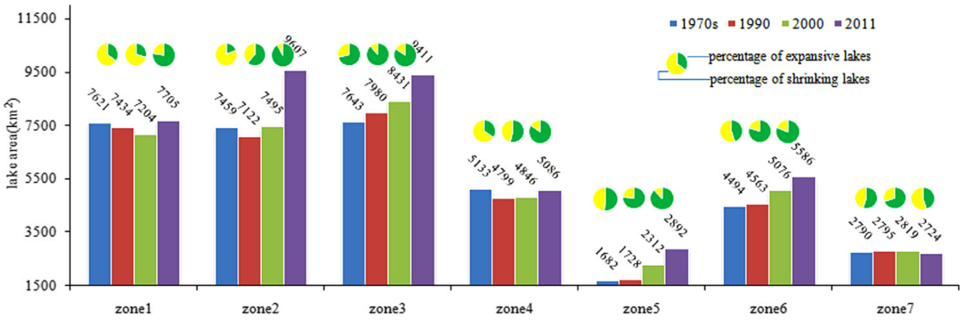

Figure 2. Changes in the lake area and the proportion of expanding and shrinking lakes from the 1970 to 2011 for the seven zones shown in Figure 1. The lake areas in km^2 are given above each column.

5.5% of the area in the 1970s). The trend is particularly clear in several of the large lakes, such as Lake Qinghai and the two sister lakes, Lake Zhaling and Lake Eling, at the source of the Yellow River. It has been reported that serious water loss poses a significant threat to the ecological environment in these lake basins [*Cui and Graf*, 2009] and that this situation may be associated with strong evaporation and decreased precipitation [*Liu and Liu*, 2008; *Zhang et al.*, 2011b]. However, in the 2000s, this tendency in zone 1 reversed with a considerable increase of 501 km^2 (6.6%) of the total lake area.

Most of the lakes in zone 2 (the HolXil region and the Yangtze River source region) began to expand in the 1990s, after shrinking from the 1970 to 1990. In the 2000s, the lakes in this region showed a dramatic enlargement and the surface area increased by 28.8% from the area in the 1970s. The total lake area in zone 3 (central Tibet, including Lakes SilingCo, NamCo, and ZigeTangCo) have rapidly and steadily increased over the last four decades, with the largest increment in the 2000s. The magnitude of the lake area variation in zone 4 (along the Gangdise Mountains) was relatively small, but the total lake area still showed a slight increase in the 2000s, after remaining almost stable in the 1990s and noticeably reducing between the 1970 and 1990. Steep lake shores lead to a less evident change in the surface extent, which may account for the relatively small variation in the area in zone 4 [*Wan et al.*, 2010]. In zone 5 (the central Changtang Plateau) and zone 6 (western TP), the lakes showed small area variations between the 1970 and 1990, but experienced rapid growth in the 1990s and 2000s. In zone 5, the lake area increased by 37.5% in the 1990s and 71.9% in the 2000s, compared to the area in 1970s. The lake area in zone 7 (southern Tibet) showed less variation than in the other zones in the past four decades and showed a slight shrinkage in the total lake area in the 2000s, not the general lake expansion tendency shown in the other zones. Most of the lakes expanded significantly in the 2000s, except for the lakes in zone 7. The number of expanding and shrinking lakes in each zone during the three periods 1970–1990, 1990–2000, and 2000–2011 suggest that more lakes across the TP shifted from shrinking or stable states to expansion or accelerated expansion in the 2000s.

The expansion of Tibetan lakes in the 2000s is also revealed in the ICESat altimetric measurements, which show that most of the lakes experienced a sharp rise in water level between 2003 and 2009 (Figure 3). Of the 117 lakes examined, 21 lakes (18.0%) had water levels that rose at a rate of over 0.4 m/yr, 61 lakes (52.1%) rose at a rate of over 0.2 m/yr, and only 17 lakes (14.5%) had a declining water level. The lakes with a declining water level are located in southern Tibet and the SilingCo basin (several of the lakes drain into SilingCo). The mean rate of change (average cumulative lake water volume relative to the total lake area) in the water level of all of the analyzed lakes was 0.23 m/yr. These results agree well with the results of *Phan et al.* [2012a], who examined 154 lakes and found a mean rate of change of 0.20 m/yr, *Zhang et al.* [2013], who examined 152 lakes and found a mean rate of change of 0.21 m/yr, and *Zhang et al.* [2011a], who examined 62 lakes and found a mean increase of 0.26 m/yr. The small differences may be caused by the different numbers of lakes and the noise removal and filtering methods used. For example, *Phan et al.* [2012a] used the 250 m moderate resolution imaging spectroradiometer (MODIS) water mask product to extract on-lake altimetry footprints, whereas *Zhang et al.* [2011a] used a 500 m MODIS snow cover product. The water levels of the lakes in zones 2, 3, and 5 showed a comparatively more significant upward tendency in the 2000s.

The accelerated water-level rise in the 2000s has been widely supported by previous studies that focused on specific lakes and used observations such as gauge data, topographic maps, and GPS measurements.

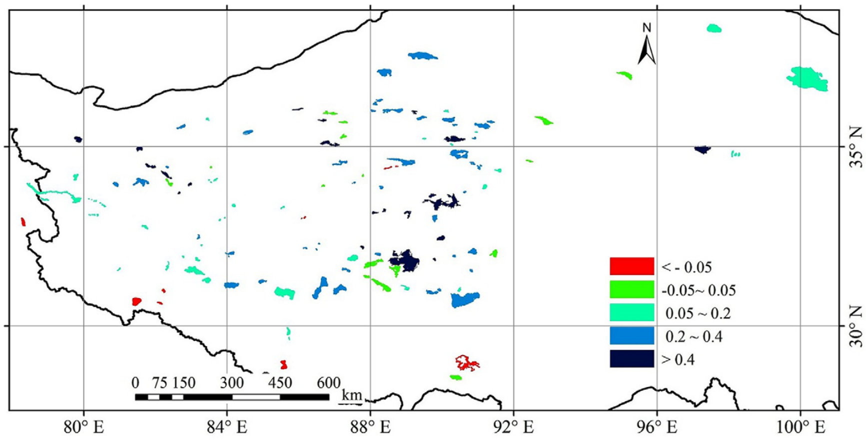

Figure 3. The rate of change in the water level of 117 Tibetan lakes from 2003 to 2009.

These kinds of data only exist for a few Tibetan lakes. According to the hydrological station records provided by the Bureau of Hydrology and Water Resources of Qinghai Province [*Zhang et al*., 2011b], the water level of Lake Qinghai experienced a steady decrease from 3196.95 m in 1959 to 3193.20 m in 2004, but increased to 3194.09 m by 2009. *Meng et al*. [2012] derived lake water level variations from topographic maps and GPS measurements and found that the water level of SilingCo increased by 8.2 m between 2003 and 2009, compared to a rise of 4.3 m between 1976 and 2000. Water level elevation data reconstructed from the lake shorelines at different dates also revealed that LingoCo in the inner plateau rose by 1.5 m (0.08 m/yr) between 1974 and 1992, by 3.0 m (0.43 m/yr) between 1992 and 1999, and by 6.70 m (0.69 m/yr) between 1999 and 2010 [*Lei et al*., 2012].

The water volume variations of 312 lakes across the TP were also computed using the empirical model proposed by *Song et al*. [2013a]. This model estimates the lake water storage changes by establishing statistical models between the lake area (obtained from optical images) and water-level time series (derived from satellite altimetry) and defining similarity measurement criteria for the lakes. The total water storage variations of all of the examined lakes were 4.3 Gt from the early 1970 to 2000 and 88.1 Gt from 2000 to 2011, using 1.0×10^3 kg/m^3 as the density of water. The empirical estimates of the annual rate of lake mass change between 2003 and 2009 [*Song et al*., 2013a; *Zhang et al*., 2013] partly account for the positive mass change rate observed from the Gravity Recovery and Climate Experiment satellite gravimetry [*Jacob et al*., 2012]. All of this evidence consistently suggests that rapid water-level rises occurred in the 2000s for most of the TP lakes.

3.2. Analysis of the Relationship Between Lake Changes and the Glacier Meltwater Supply and Lake Supply Coefficient at the Plateau Scale

The debate on the role of glacial meltwater in the lake water balance can be largely attributed to the difficulty in deriving reliable quantitative estimates of the glacier mass budget in the mountainous areas of the TP. Many studies have shown using field observations that glacier mass loss on the TP accelerated during the past decades [*Kang et al*., 2009; *Pu et al*., 2008; *Yang et al*., 2013, 2008; *Yao et al*., 2010, 2012]. However, it is still difficult to estimate the total glacier mass balance in this region based on the limited number of field measurements, which are biased toward the low-lying ablation area of small, accessible glaciers. Quantitative glacier mass balances and the spatial heterogeneity over TP is still unclear [*Gardner et al*., 2013; *Kääb et al*., 2012].

We qualitatively analyzed whether the presence of glacier meltwater at lakes is a significant factor leading to different rates of water-level rise of those lakes. We used the G-L ratio to infer the magnitude of the effect of glacier meltwater on the lake water balance. Figure 3 and Appendix A show the locations, rates of water level increase, and other information for the 117 examined Tibetan lakes with ICESat measurements. The lakes can be broadly classified as glacier-fed closed lakes, non-glacier-fed closed lakes and unclosed lakes. As shown in Figure 4a, the rate of change of the non-glacier-fed lakes' water level was not statistically

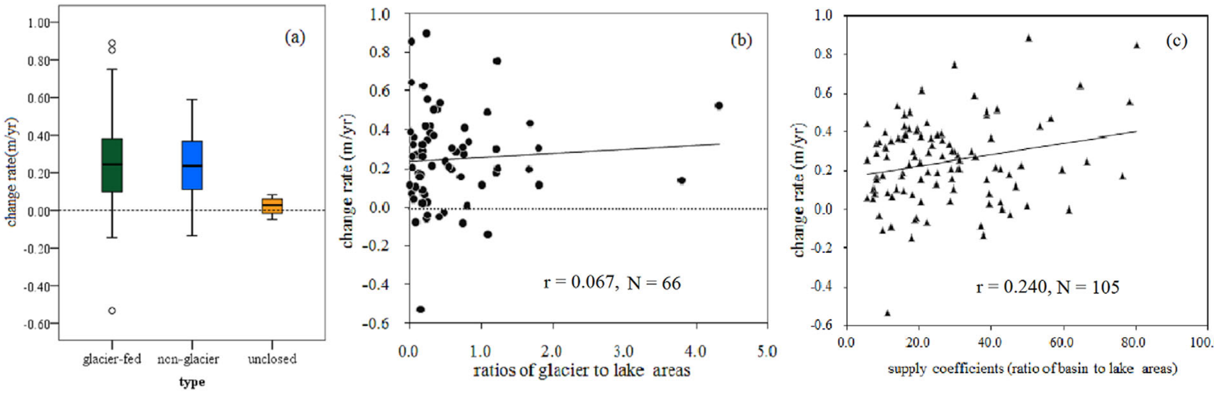

Figure 4. A comparison of the rate of water-level changes of different types of lakes across the TP. (a) The average rate of change of the glacier-fed lakes (66 closed lakes), the nonglacier lakes (39 closed lakes), and the unclosed lakes (12); (b) the relationship between the rate of lake-level change and the glacier areas within the lake basins of the 66 glacier-fed lakes; and (c) the relationship between the rate of lake-level change and the supply coefficients of 105 closed lakes, measured with ICESat altimetric data.

significantly different from that of the glacier-fed lakes. The average rate of change of the non-glacier-fed lakes was 0.23 m/yr, which was similar to the average rate of change of 0.25 m/yr for the glacier-fed lakes. Glacier meltwater is therefore probably not the dominant factor leading to the general growth tendency of most Tibetan lakes in the 2000s, as the non-glacier-fed lakes also had a comparably marked rise in their water levels. The maximum rising rates (the 75–100th percentile range) of the glacier-fed lakes was noticeably higher than those of the nonglacier lakes, which implies that a few glacier-fed lakes experienced faster water-level increases in the 2000s. As the 12 unclosed lakes can adjust their water storage seasonally by discharging to lakes or rivers downstream, their water levels showed little interannual change.

We further examined the contribution of glacial meltwater to the water-level increase of glacier-fed lakes by analyzing the relationship between the change rate of the water level and the G-L ratio of the lakes, as illustrated in Figure 4b. There was no linear correlation between the two. In contrast, the stronger relationships between rising rates of lake level and supply coefficients were observed among the examined closed lakes (105 lakes) (shown in Figure 4c). The positive correlation of water-level rising rates with supply coefficients was also reported for lakes in the Pamir and Tienshan Mts, and northern TP [*Li et al*., 2011]. It suggests that the precipitation runoff within basins had remarkable effects on the lake dynamics on the TP. One typical example is the contrast between two large lakes SilingCo (with a G-L ratio of ~1.3) and NamCo (with a G-L ratio of ~1.0) in central Tibet: SilingCo experienced a markedly faster water-level rise (0.625 m/yr) than NamCo (0.210 m/yr), although the two lakes have a similar glacial meltwater supply, according to the field glacier mass balance measurements [*Gardner et al*., 2013; *Lei et al*., 2013; *Yao et al*., 2012]. The much larger supply coefficient of SilingCo (20.74) may partly account for the more rapid grow rates than NamCo (5.36).

The weak relationship between change rates of lake level with G-L ratios, as shown in Figure 4b, may be associated with the spatial heterogeneity in glacier mass balances or dominant climate forces on lake dynamics. Note that the glacier-fed lakes are not evenly distributed over the plateau (Figure 3 and Table 1). For these reasons, the impacts of glacier meltwater on lake expansions cannot be simply denied. It is therefore necessary to examine the role of glacier meltwater supply at the scale of subzones, which is stated in section 3.3.

Table 1. Comparison of Average Rates of Change in Water Levels and Supply Coefficients for Glacier-Fed (G) and Nonglacier-Fed (N) Lakes in Different Zones

Zone	Zones 1–7		Zones 2, 3, 5, 6		Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6		Zone 7	
G	N	G	N	G	N	G	N	G	N	G	N	G	N	G	N	G	N	
Lake number	66	39	48	38	2	1	22	12	4	11	10	0	5	8	17	7	6	0
Change rate (m/yr)	0.246	0.232	0.301	0.236	0.14	0.1	0.273	0.196	0.355	0.336	0.21	/	0.358	0.215	0.309	0.17	−0.102	/
Supply coefficient	25.63	29.19	27.69	29.76	7.53	7.59	25.25	29.68	38.61	24.03	24.43	/	32.62	41.11	26.84	25.93	17.17	/

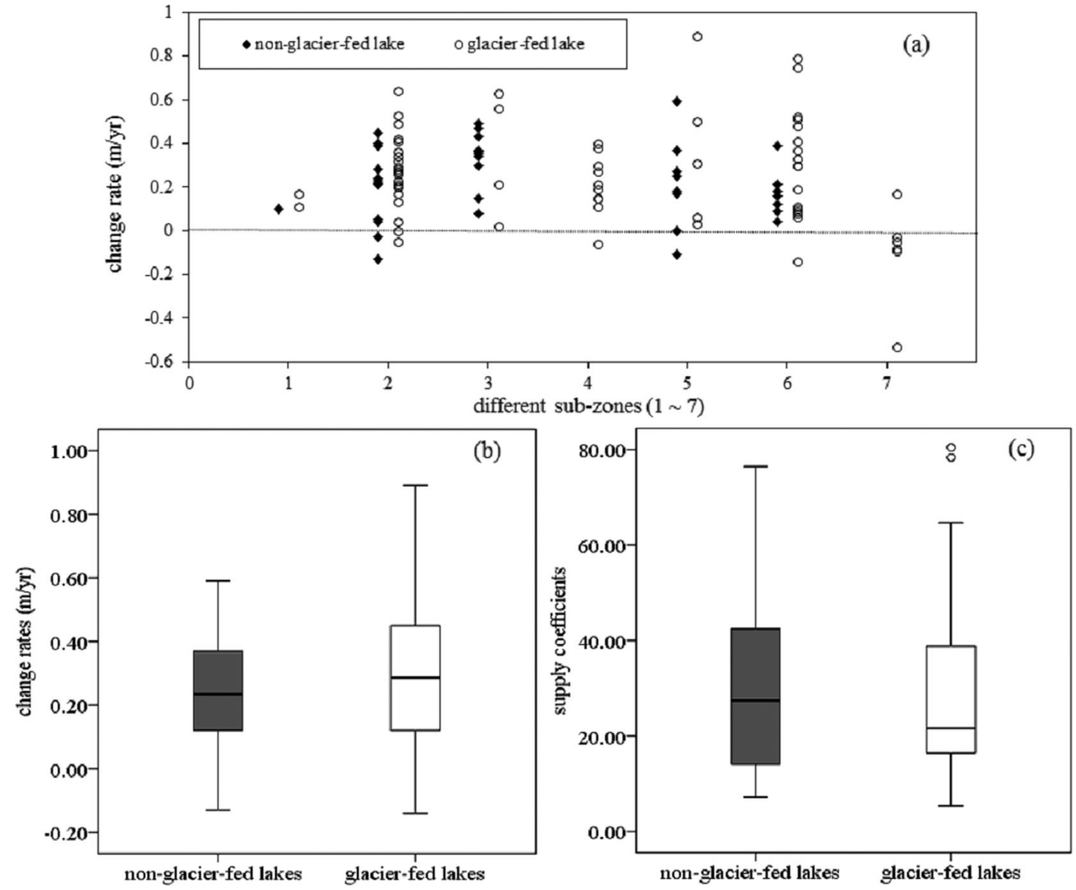

Figure 5. A comparison of the rate of water-level changes of the 105 closed lakes, divided into zones. (a) The rate of change of glacier-fed lakes and non-glacier-fed lakes in zones 1–7; (b) the rate of change of glacier-fed lakes and non-glacier-fed lakes in zones 2, 3, 5, and 6; and (c) the supply coefficients between non-glacier-fed and glacier-fed lakes in zones 2, 3, 5, and 6.

3.3. Analysis of the Interzone Difference in the Relationship Between Lake Changes and the Glacier Wastage and Supply Coefficient

The rates of lake-level changes for glacier-fed lakes and non-glacier-fed lakes in each zone are illustrated in Figure 5a. A summary of the statistics in Figure 5 is listed in Table 1. Note that zones 4 and 7 only contain glacier-fed lakes and zone 1 only includes four lake records. The widespread expansion of non-glacier-fed lakes in each zone and the contrast in the rates of change between zone 7 and the other zones confirms that the lake expansion in the TP in the 2000s was not solely the effect of glacier wastage. However, the significance of the glacier meltwater supply differs across the zones. Zones 2, 3, 5, and 6 contain sufficient glacier-fed and non-glacier-fed lakes for a comparison. Figure 5a and Table 1 show that the mean rates of change of the glacier-fed lakes were all noticeably higher than those of the glacier-fed lakes in these zones, except for zone 3, in which both types of lakes had comparably rapid rising rates. The average rates of change of the two types of lakes are shown in Figure 5b, excluding the records in zones 1, 4, and 7. The results reveal a noticeably faster rise in glacier-fed lakes (0.30 ± 0.22 m/yr) than in non-glacier-fed lakes (0.24 ± 0.17 m/yr), despite the smaller supply coefficients in the glacier-fed lakes (Figure 5c). Nevertheless, the difference between the mean rates of change for the two groups was not statistically significant, as the standard deviation of the rates of change were relatively large in the two groups and in each zone (Table 1), indicating a considerable variation in the rates of change within each group and each zone (2, 3, 5, and 6).

We statistically evaluated the contribution of glacier wastage, the supply coefficient, and the zone division to the variation in the rates of change of lake levels on the TP. We used two linear fitting models of the rate of change (dependent variable) with predicted variables, such as the supply coefficient, the absence or presence of a glacier meltwater supply, and the zone code. See Appendix C for the resulting model.

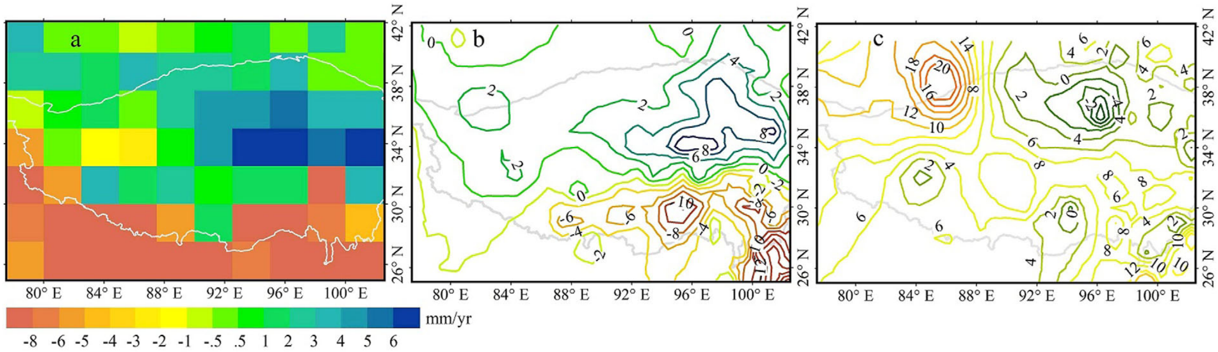

Figure 6. Maps of the changing trends in (a) precipitation calculated by GPCP; (b) gauge-based precipitation; and (c) potential evaporation from 1996 to 2010 across the TP.

The first model did not consider the zone division and fitted a multiple linear relationship between the rate of change and two predictors, the supply coefficient and the absence or presence of a glacier meltwater supply (binary variable, "1" is a glacier-fed lake and "0" is a non-glacier-fed lake). The results of this model showed that the supply coefficient was marginally significant at the 90% confidence level, whereas the absence or presence of a glacier meltwater supply was not significant ($p > 0.1$).

The second model fitted a linear model between the rate of change and three predictors, including the zone code (categorical variable with four possibilities, 2, 3, 5 and 6). This model showed that the supply coefficient was significant at the 90% confidence level, whereas the absence or presence of the glacier meltwater supply was significant at the 95% confidence level. The rate of change for zone 3 was also significantly higher than for zone 2 at the 95% confidence level. The linear regression models support the hypothesis that the supply coefficients are consistently important factors influencing the rate of water-level changes of closed lakes in the 2000s across the whole TP, whereas in the TP zones, especially at around 33°N north of the TP (zones 2, 5, and 6), the presence of a glacier meltwater supply generally encourages faster increases of the lake level.

3.4. The Relationship Between Lake Changes and the Precipitation and Evapotranspiration Variability

Glacial meltwater only supplies a fraction of lakes, whereas precipitation and evaporation are important factors that control the water budget of nearly all lakes. The statistical analysis discussed above revealed a significant correlation between the supply coefficients (which are associated with the contribution from precipitation) with the rates of lake-level change on the TP and in each subclimate zone. To confirm whether changes in the precipitation and evaporation on the TP are closely associated with the lake changes, as shown by the statistics, we analyzed the spatial pattern of the interannual changes in the total annual precipitation and the potential evaporation between 1996 and 2010 on the TP.

Figures 6a and 6b show the annual precipitation trends on the TP from 1996 to 2000, based on GPCP data and meteorological station records, respectively. The two maps show a generally similar spatial pattern in the precipitation tendency across the TP. The total annual precipitation significantly increased by 1–8 mm/yr in the northeastern and central TP, with the wetting center around Tuotuohe in the central TP. There is a strong signal suggesting a precipitation decrease in the southeastern periphery of TP, including the Hengduan Mountains, West Nyainqêntanglha Mountains, and Himalayas. Gauge-based precipitation data over a longer time scale has confirmed the wetter tendency in the central and northeastern TP and the drier tendency on the periphery of the TP [*Xu et al.*, 2008; *Yang et al.*, 2011; *You et al.*, 2012].

As shown in Figure 6c, the potential evaporation tended to increase in most of the TP regions between 1996 and 2010, most significantly in the northern TP and the Tarim Basin, whereas it weakly decreased in the Qaidam Basin and surroundings over the same time. The potential evaporation in the inner plateau increased by 2–8 mm/yr during the study period. Previous studies have reported different trends in the potential evaporation [*Yin et al.*, 2010; *Zhang et al.*, 2009] because they focused on evaporation variation from the 1970s to the early 2000s. The trend in the change in the potential evapotranspiration reversed in the 2000s, possibly due to the recovery of wind speed and solar [*Lin et al*., 2013]. Rapid warming over the TP in recent decades may be an important reason for the enhanced land evaporation.

The increase in potential evaporation implies that lake evaporation and evaporation in the lake basin was enhanced, causing a negative effect on the lake water budget. This effect may offset the increased precipitation for some lakes and add to the variation in the rates of change of the lakes' water levels. The trade-off between an increase in precipitation and an increase in evaporation during the study period resulted in an increase in runoff in the central TP, as suggested by both station observations [*Liu et al*., 2009] and modeled results [*Yang et al*., 2011]. Nevertheless, the spatial pattern of precipitation changes agreed well with the general pattern of the rate of change of lakes. For example, the fastest increase in a lake level in zone 3 in the central TP occurred at the center of a large wetting trend, and the decrease in the lake levels in zone 7 was consistent with the drying trend in the southern TP, as shown in Figures 2 and 3, Table 1, and Figure 6.

We analyzed the relationship between the water-level change of closed lakes in the wet seasons (from March/April to October/November) and the precipitation, as measured from GPCP data, between 2003 and 2009. Lakes with more than two seasons of missing water level data were excluded from the analysis. The correlation coefficients for 58% of the lakes were higher than 0.4 (data not shown). Over 50% of the large lakes with an area greater than 100 km^2 had correlation coefficients higher than 0.6, especially the large lakes in central Tibet and the Hoh Xil region. This result suggests that the water balance of these large lakes tended to be highly correlated with the interannual precipitation variability during the study period.

3.5. Contrasting Typical Lake Cases

One of the simple ways to evaluate the contribution of glacier wastage and supply coefficients (which express the contribution from precipitation) to lake expansion is to compare the rates of change of glacier-fed and non-glacier-fed lakes in adjacent areas with similar supply coefficients. These comparable pairs are rare. Contrasting the changes of the few adjacent lakes does reflect the balanced effect between large supply coefficients and the presence of glacier meltwater supply on determining the rates at which the lakes increase.

Figure 7 displays six groups of paired lakes that are spatially close to each other, of which one has a glacier meltwater supply (glacier-fed) and the other does not (non-glacier-fed). The six groups of lakes are in different climatic zones and the glacier-fed lakes are supplied by different mountain glaciers. For each pair of lakes, the climatic conditions (precipitation and evaporation) were assumed to be similar as they are spatially close. Figure 7a shows that the water level of the glacier-fed NamCo experienced a slower increase (0.21 m/yr) than that of the non-glacier-fed RingcoKongma (0.37 m/yr), largely due to a much smaller supply coefficient (5.36) than that of RingcoKongma (14.05). Similarly, the comparisons in Figure 7c (in the eastern Gangdise Mountains), Figure 7d (in the southeastern Karakorum Mountains), and Figure 7f (in the Hol Xil region) all show that the lakes without a glacial meltwater supply rose more rapidly than the glacier-fed lakes, often due to larger lake watershed areas (large supply coefficients). This result implies that in these regions, a sufficiently large supply coefficient rather than meltwater from a glacier are superior for rapid lake expansion. However, this does not mean that meltwater from glaciers does not contribute to lake growth. Lakes supplied by many glaciers within their catchments may be more affected by increasing glacial meltwater than by precipitation. For example, in Figures 7b and 7e, although the glacier-fed lakes had smaller supply coefficients than the nearby non-glacier-fed lakes, they showed a faster increase in their water levels. This may be largely due to a substantial meltwater supply from the nearby glaciers, as these lakes had large G-L ratios.

4. Discussion

As noted in the analysis, the lake changes discussed here, the area, water level and volume changes, and the precipitation and evaporation change patterns, have been widely confirmed in previous studies. In the absence of reliable mass balance measurements, we found a broad consistency between lake changes and precipitation changes across the TP and found that precipitation-driven changes are augmented in glacier-fed lakes in the northern TP zones. However, there are uncertainties with this analysis due to data limitations. It has been reported that the Glacier Inventory of China is incorrect (e.g., slight displacements of some glaciers) in a few parts of the area [*Arendt et al*., 2012], leading to inaccurate estimates of G-L ratios.

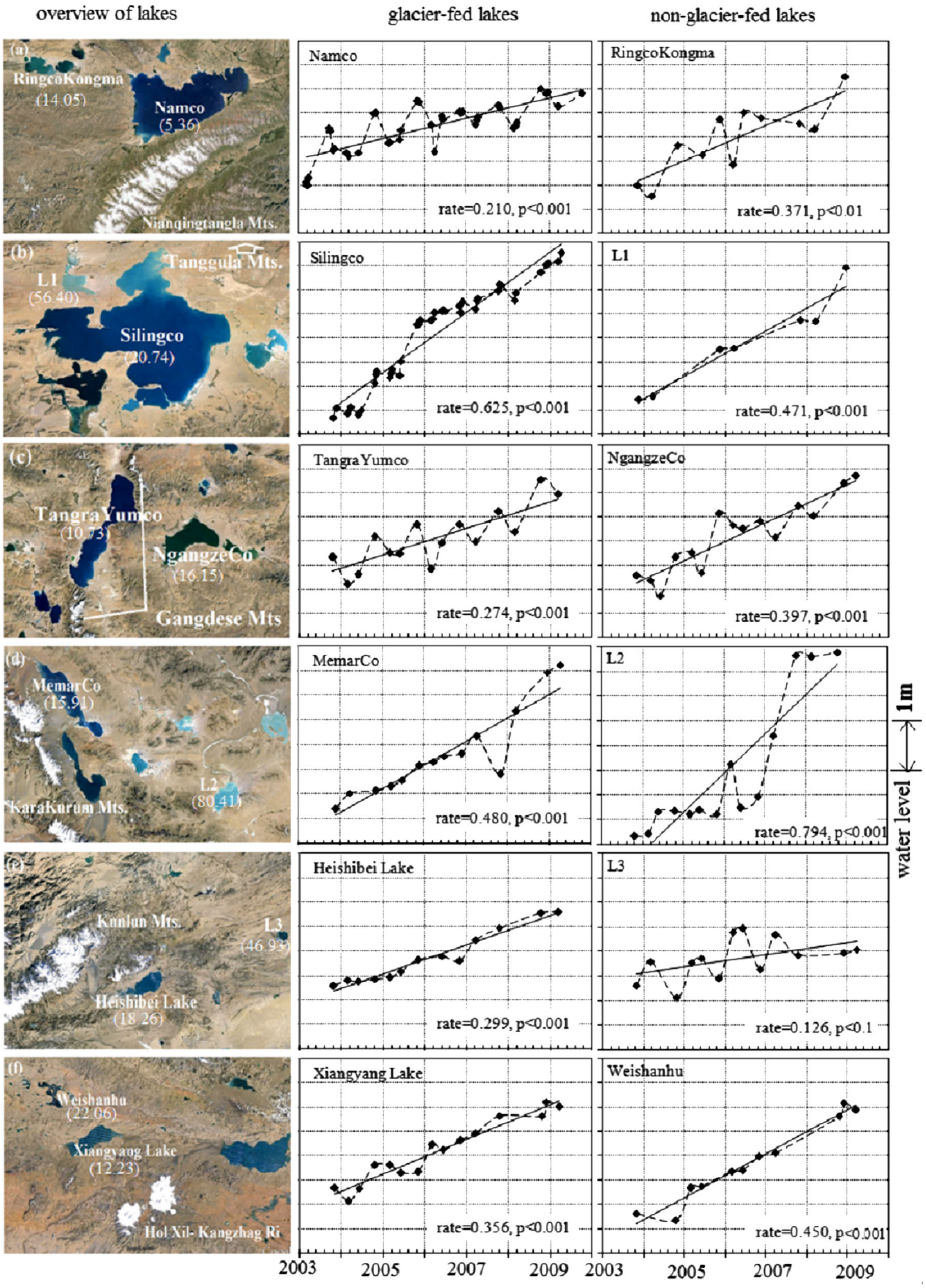

Figure 7. A comparison of the changes in six pairs of adjacent lakes (rate: m/yr) with and without a glacial meltwater supply in (a) zone 3, (b) zone 3, (c) zone 4, (d) zone 6, (e) zone 6, and (f) zone 2. The numbers below the lake names refer to their supply coefficients.

The use of the binary glacier present/absent variable in the linear model provided a better fit than using the G-L ratio (as shown in Figure 4b), which may reflect the uncertainties in the glacier area data or differences in the glaciers' mass balance conditions. These uncertainties may cause a bias in the evaluation of the effect of glacier meltwater on the expansion of specific lakes. The limited number of observations (at most six years, 2003–2009) and the coarse spatial resolution ($2.5^\circ \times 2.5^\circ$) of the GPCP data may also lead to uncertainties in the estimates of the correlation coefficients between the water-level changes and precipitation.

The water-level changes for most Tibetan lakes show a close association with the precipitation change. However, the spatially variable climatic change patterns, including precipitation, evaporation, and temperature changes on the TP, and the different mass balances of the different glaciers will result in different contribution weights from precipitation and the meltwater supply toward the water budgets of specific lakes. As revealed by the large variability in the rates of change within the zones, the heterogeneous response of the lakes may also be related to other factors, such as the characteristics of the lake bathymetry, the land surface conditions of the lake basin, and the groundwater discharges, which we cannot assess individually because this information is not available. These factors or other unclear causes may explain the rates of change of the water level in some lakes. Future studies should use comprehensive, multiple site, consecutive observations of typical lake basins integrated into numerical models to reveal the specific reasons for the varied response of individual lakes to climate change.

5. Summary

Observations from long-term Landsat imagery and ICESat altimetry data from 2003 to 2009 show that most inland lakes over the TP were shrinking or stable before 2000, then expanded or rapidly expanded in the 2000s. The water level data of 117 lakes derived from ICESat altimetry show that most lakes experienced a markedly rapid increase in their water level ($>$0.1 m/yr for 81 lakes) from 2003 to 2009. The changes in these lakes have been documented in previous studies using different kinds of observations. However, the driving force behind these changes, especially the fast expansion of the lakes in the 2000s, has remained unclear.

An analysis of the rates of change of the water level of 105 closed lakes shows that the rates of change of non-glacier-fed lakes were as high as those of glacier-fed lakes across the TP. The rates of change of lake levels are closely associated with the lakes' supply coefficients, but not with the G-L ratio. The spatial pattern of lake variations in the 2000s agrees well with the spatial pattern of long-term precipitation changes. However, in different zones, especially at around 33°N north of the TP (zones 2, 5, and 6), the glacier-fed lakes did exhibit noticeably faster increases in their levels than the non-glacier-fed lakes. The presence of a glacier meltwater supply augmented the precipitation-driven lake expansions in these areas. Local comparisons of the rates of water-level change in six pairs of adjacent lakes, one with and one without a glacier supply, showed the balanced effect between large supply coefficients and the presence of a glacier meltwater supply on the rate at which a lake increases. In conclusion, the lake expansions across the TP in the 2000s were driven primarily by changes in precipitation and evapotranspiration and were not solely the effect of glacier wastage.

The heterogeneous response of the lakes to TP climate change may be partly attributed to the spatially variable climatic change patterns across the TP and the different mass balances of the different glaciers. The variability of the rate of change of the examined lakes may also be related to other factors, such as the characteristics of the lake bathymetry, the land surface conditions of the lake basin, and the groundwater discharges. Our results suggest caution when considering the overall climate change patterns of a local area to determine the driving forces behind the water mass budgets of specific lakes in recent decades. Quantitative modeling of the water balances of lakes, including the contributions from precipitation, evaporation, and the meltwater supply from glaciers, would best explain the causes of lake changes. However, it is difficult to model at the plateau scale, partly due to a lack of reliable estimates of glacier mass balances across the TP and limitations in the quality and spatial and temporal coverage of the available observations of lake and climate changes. In the future, enriched observations, including those from higher-density meteorological stations and remotely sensed satellites, together with advanced data assimilation and modeling techniques are expected to quantitatively clarify the climate-driven mechanism of alpine lake changes over the TP.

Appendix A : Data for 117 Lakes Across the TP[a,b]

[a] The lake type is coded "1" for a closed lake and "0" for an unclosed lake.

[b] The six pairs of lakes with or without a glacial meltwater supply are italicized.

Table A1.

Lake	Lon. (°)	Lat. (°)	Lake Area (km^2)	Change Rate (m/yr)	Lake Basin Area (km^2)	Glacier Area in Basin (km^2)	Lake Basin/Lake	Glacier/Lake	Lake Type
Zone 1									
Lake Qinghai	100.19	36.89	4307.89	0.11	30473.00	38.84	7.07	0.01	1
Har Lake	97.59	38.29	606.88	0.17	4846.20	100.08	7.99	0.16	1
Gyaring Lake	97.27	34.93	557.09	0.29		0.00		0.00	0
Xingxinghai	98.18	34.80	83.23	0.10	631.90	0.00	7.59	0.00	1
Zone 2									
Aqikekule Lake	88.41	37.08	430.23	0.28	13186.10	280.24	30.65	0.65	1
Ayakeku Lake	89.44	37.53	791.02	0.21	24310.60	432.97	30.73	0.55	1
Dogai Coring	88.96	34.58	447.99	0.23	7611.30	224.72	16.99	0.50	1
KuSai Lake	92.87	35.72	304.09	−0.05	5855.70	74.79	19.26	0.25	1
HolXil Lake	91.14	35.59	323.64	0.29	2637.50	60.72	8.15	0.19	1
MC&DC	90.07	33.43	979.75	0.53	13524.00	422.91	13.80	0.43	1
UlanUla Lake	90.48	34.80	575.74	0.32	6024.10	34.55	10.46	0.06	1
XijinUlan Lake	90.34	35.21	390.67	0.42	6685.90	87.26	17.11	0.22	1
Dabuxun Lake	91.36	35.70	63.99	0.40	670.60	0.00	10.48	0.00	1
	92.45	34.60	22.10	0.04	448.50	1.45	20.30	0.07	1
	91.59	34.34	68.16	0.06		0.00		0.00	0
	91.20	33.89	46.34	0.20	1035.74	56.98	22.35	1.23	1
	90.96	35.41	10.68	0.06		0.00		0.00	0
	90.91	35.24	22.67	0.22	932.73	0.00	41.14	0.00	1
	90.36	35.61	26.58	0.28	701.30	0.00	26.38	0.00	1
LexieWudan Lake	90.19	35.75	249.10	0.34	2031.20	61.42	8.15	0.25	1
Kushuihuan	90.12	35.99	35.18	0.17	342.10	42.54	9.73	1.21	1
	90.27	35.07	17.43	0.05	125.60	0.00	7.21	0.00	1
	90.86	34.55	29.25	0.24	585.90	0.00	20.03	0.00	1
	91.04	34.43	42.07	0.23	2031.00	0.00	48.28	0.00	1
	89.72	33.64	79.45	0.41	1537.80	23.18	19.36	0.29	1
YaggainCo	89.80	33.01	129.04	0.21	3729.20	0.00	28.90	0.00	1
Xiangyang Lake	*89.42*	*35.80*	*103.26*	*0.36*	*1263.00*	*37.85*	*12.23*	*0.35*	*1*
Weishanhu	*89.23*	*35.96*	*36.19*	*0.45*	*798.30*	*0.00*	*22.06*	*0.00*	*1*
Yuye Lake	88.78	36.01	116.14	0.27	2184.40	12.90	18.81	0.11	1
	88.47	36.01	54.68	0.39	1436.70	0.00	26.27	0.00	1
Xianhe Lake	88.08	36.00	29.91	0.20	1783.70	1.44	59.64	0.05	1
Yinbo Lake	88.20	36.25	83.06	0.26	2583.70	3.88	31.11	0.05	1
	89.51	35.23	13.63	0.13	337.32	51.32	24.76	3.77	1
	88.56	34.42	33.83	−0.13	1276.40	0.00	37.74	0.00	1
Deyuhu	87.26	35.69	54.39	−0.03	2455.10	0.00	45.14	0.00	1
Zhenquancuo	86.89	35.93	92.67	0.00	3975.30	74.98	42.90	0.81	1
YurbaCo	86.69	35.74	59.39	0.49	2304.10	64.43	38.80	1.08	1
	87.25	35.29	78.33	0.04	3326.70	0.00	42.47	0.00	1
	85.99	36.05	34.44	0.64	2226.20	1.24	64.64	0.04	1
	90.64	33.74	29.74	0.27	1056.40	22.48	35.52	0.76	1
Zone 3									
ZigeTangCo	90.87	32.08	228.11	0.36	3507.20	0.00	15.38	0.00	1
DagzêCo	87.52	31.89	270.95	0.08	2053.32	0.00	7.58	0.00	1
GyariogCo	88.34	31.12	483.80	−0.01		0.00		0.00	0
NamCo	*90.60*	*30.74*	*2001.39*	*0.21*	*10718.90*	*196.8*	*5.36*	*0.10*	*1*
RingcoKongma	*89.76*	*30.95*	*242.41*	*0.37*	*3406.70*	*0.00*	*14.05*	*0.00*	*1*
QaguiCo	88.25	31.82	89.19	−0.05		0.00		0.00	0
SilingCo	*88.99*	*31.80*	*2156.77*	*0.63*	*44732.20*	*283.3*	*20.74*	*0.13*	*1*
L1	*88.69*	*32.00*	*78.20*	*0.47*	*4410.60*	*0.00*	*56.40*	*0.00*	*1*
UrruCo	88.00	31.71	363.91	−0.05		0.00		0.00	0
	90.82	31.54	39.33	0.35	348.10	0.00	8.85	0.00	1
Cona	91.47	32.02	210.11	0.02	10510.90	37.85	50.03	0.18	1
	90.49	31.01	48.55	0.15	398.60	0.00	8.21	0.00	1
KyebxangCo	89.98	32.45	171.02	0.49	2698.20	0.00	15.78	0.00	1
	89.79	31.86	27.54	0.43	1474.10	0.00	53.53	0.00	1
	90.34	31.95	34.33	0.30	1019.10	0.00	29.69	0.00	1
MugquCo	89.01	31.05	84.73	0.06		0.00		0.00	0

Table A1. (continued)

Lake	Lon. (°)	Lat. (°)	Lake Area (km^2)	Change Rate (m/yr)	Lake Basin Area (km^2)	Glacier Area in Basin (km^2)	Lake Basin/Lake	Glacier/Lake	Lake Type
ZiguCo	87.90	31.37	75.59	−0.02		0.00		0.00	0
SerbugCo	88.22	32.00	78.27	0.36	2072.30	0.00	26.48	0.00	1
	87.33	31.57	99.22	0.34	2815.90	0.00	28.38	0.00	1
GyarabPunco	87.78	32.20	44.34	0.56	3472.20	10.81	78.31	0.24	1
CoNgoin	88.72	31.57	290.78	−0.01		0.00		0.00	0
Zone 4									
NganglaRingCo	83.08	31.54	499.32	0.19	12509.80	297.84	25.05	0.60	1
RenqingxiubuCo	83.45	31.28	187.27	0.11	2567.60	189.80	13.71	1.01	1
NgangziCo	*87.13*	*31.02*	*438.23*	*0.40*	*7076.50*	*7.92*	*16.15*	*0.02*	*1*
TangraYumCo	*86.61*	*31.07*	*839.15*	*0.27*	*9001.90*	*154.46*	*10.73*	*0.18*	*1*
TarongCo	84.12	31.14	483.57	0.30	16772.70	288.85	34.69	0.60	1
ZhariNamCo	85.61	30.93	982.86	0.15	19985.10	144.33	20.33	0.15	1
DawaCo	84.97	31.24	119.51	0.38	2431.40	34.83	20.35	0.29	1
LagkorCo	84.11	32.02	106.20	0.21	4525.00	33.19	42.61	0.31	1
GopugCo	83.17	31.86	60.72	0.15	2348.30	43.88	38.67	0.72	1
ArgogCo	82.24	30.98	56.68	−0.06	1244.50	13.68	21.96	0.24	1
Zone 5									
	89.05	33.14	83.56	0.89	4222.90	19.61	50.54	0.23	1
Longwei Lake	88.31	33.87	52.16	0.37	1213.10	0.00	23.26	0.00	1
	87.56	34.00	13.60	0.25	907.00	0.00	66.72	0.00	1
	87.79	34.20	16.86	0.00	1037.40	0.00	61.55	0.00	1
	88.24	33.19	77.41	0.59	2730.10	0.00	35.27	0.00	1
CoNyi	87.18	34.55	130.46	0.31	3788.50	97.57	29.04	0.75	1
Margai Caka	86.85	35.10	204.96	0.50	7928.30	70.32	38.68	0.34	1
Suona Lake	86.69	33.92	27.00	0.03	1066.70	6.58	39.51	0.24	1
	86.16	33.02	16.72	−0.11	162.70	0.00	9.73	0.00	1
	86.36	32.20	35.28	0.27	384.90	0.00	10.91	0.00	1
	85.57	33.31	17.99	0.06	96.20	3.77	5.35	0.21	1
ChagboCo	84.19	33.36	45.98	0.18	2070.20	0.00	45.02	0.00	1
	83.84	32.97	18.16	0.17	1386.60	0.00	76.38	0.00	1
Zone 6									
	83.65	34.07	33.69	0.09	374.60	0.00	11.12	0.00	1
	83.56	34.43	12.59	0.04	359.10	0.00	28.53	0.00	1
	80.99	31.58	15.04	0.07		0.00		0.00	0
	80.46	33.42	37.92	0.08		0.00		0.00	0
	80.31	33.10	34.53	0.06	432.10	1.36	12.51	0.04	1
LumajangdongCo	81.61	34.02	361.66	0.33	8496.00	300.85	23.49	0.83	1
BangongCo	79.23	33.68	656.76	0.10	10194.40	63.87	15.52	0.10	1
Yanghu Lake	84.60	35.41	112.96	0.37	4498.50	37.42	39.83	0.33	1
	83.29	32.25	9.78	0.18	95.20	0.00	9.74	0.00	1
	83.21	32.48	35.13	0.21	1095.20	0.00	31.18	0.00	1
	82.78	31.93	14.57	0.16	423.10	0.00	29.04	0.00	1
	82.34	31.64	61.37	0.08	1102.10	2.75	17.96	0.04	1
Heishibei Lake	*82.75*	*35.56*	*101.77*	*0.30*	*1858.50*	*183.18*	*18.26*	*1.80*	*1*
L3	*83.46*	*35.78*	*19.82*	*0.12*	*930.00*	*0.00*	*46.93*	*0.00*	*1*
AruCo	82.39	33.99	104.21	0.03		0.00		0.00	0
MemarCo	*82.31*	*34.22*	*146.44*	*0.48*	*2330.30*	*246.55*	*15.91*	*1.68*	*1*
L2	*82.97*	*33.95*	*40.04*	*0.79*	*3219.40*	*1.13*	*80.41*	*0.03*	*1*
QagongCo	82.33	34.44	25.70	0.39	641.30	0.00	24.95	0.00	1
Luotuo Lake	81.87	34.46	130.58	0.41	2496.50	100.81	19.12	0.77	1
A'ongCo	81.72	32.77	69.47	0.11	2052.30	125.80	29.54	1.81	1
AngshangCo	82.67	33.72	23.79	0.51	408.90	9.09	17.19	0.38	1
JiezeCaka	80.90	33.95	110.82	0.30	2508.50	133.70	22.64	1.21	1
BangdagCo	81.56	34.95	119.36	0.75	3555.30	146.70	29.79	1.23	1
ChemCo	79.78	34.16	117.60	0.19	1809.40	195.38	15.39	1.66	1
AksayqinHu	79.85	35.21	193.32	0.52	8059.20	834.69	41.69	4.32	1
SpanggurTso	78.91	33.53	58.20	0.09	2286.70	11.10	39.29	0.19	1
Tsomoriri	78.31	32.90	145.80	−0.14	2583.40	158.93	17.72	1.09	1
Zone 7									
MapamYumCo	81.47	30.68	413.36	−0.05	7695.10	172.37	18.62	0.42	1
PumaYumCo	90.39	28.57	291.21	−0.03	2585.80	140.34	8.88	0.48	1
YamzhoYumCo	90.69	28.95	681.63	−0.53	7587.40	105.44	11.13	0.15	1
DaggyaiCo	85.72	29.82	117.10	0.17	1765.80	15.96	15.08	0.14	1
PaikuCo	85.59	28.91	273.36	−0.09	3339.90	201.66	12.22	0.74	1
KunggyuCo	82.13	30.64	54.90	−0.08	2036.70	5.62	37.10	0.10	1

Appendix B : The Potential Evaporation, Calculated Following the Penman-Monteith Model

The FAO Penman-Monteith equation was developed from the original Penman-Monteith equation and the equations of aerodynamic and canopy resistance by standardizing and simplifying some metrics based on available observed meteorological variables. The FAO Penman-Monteith equation determines the evapotranspiration from a hypothetical grass reference surface. It provides a standard to which evapotranspiration in different periods of the year or in other regions can be compared and to which the evapotranspiration from different land surface can be related [*Allen et al*., 1998]. The evapotranspiration in mm/month is calculated as follows.

$$ET=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)}$$

where ET is the evapotranspiration, R_n is the net radiation, G is the soil heat flux, e_s is the saturation vapor pressure, e_a is the actual vapor pressure, e_s-e_a is the saturation vapor pressure deficit of the air, T is the air temperature at 2 m height, u_2 is the wind speed at 2 m height, Δ is the slope of the saturation vapor pressure temperature relationship, and γ is the psychrometric constant. These parameters are directly calculated or derived from the average daily maximum and minimum temperature, the monthly average temperature, the monthly average of the daily actual vapor pressure, the monthly average of the daily wind speed data, the actual duration of sunshine hours, the relative humidity data, and other empirical metrics.

Appendix C : The Linear Model of the Rate of Water-Level Change and the Analyzed Factors

Linear model fitting (implemented by the "lm" function of the R software package) is used to examine the potential responses of the lake-level changes to different factors. Two models, with and without the inter-zone variability, are established and expressed as:

$$\text{lm}\ (\text{formula}\ =\ \text{cr}\ \sim\ \text{sc}\ +\ \text{gf}\,), \tag{C1}$$

$$\text{lm}\ (\text{formula}\ =\ \text{cr}\ \sim\ \text{sc}\ +\ \text{gf}\ +\ \text{zf}\,), \tag{C2}$$

where cr is the dependent variable representing the rate of the water-level change of 86 closed lakes, the predicted variable sc is the supply coefficient, the predicted variable gf is the absence or presence of a glacier meltwater supply (binary variable, "1" is a glacier-fed lake and "0" is a non-glacier-fed lake), and zf is the zone code (categorical variable with four levels, 2, 3, 5, and 6).

The generated coefficients are listed in the table.

Table C1. The generated coefficients are listed in the Table below:

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
Model (1)				
(Intercept)	0.1666	0.0489	3.403	0.00103 ***
sc	0.0023	0.0012	1.890	0.06218 *
gf	0.0705	0.0436	1.617	0.10964
Model (2)				
(Intercept)	0.1204	0.0566	2.125	0.0366 **
sc	0.0023	0.0013	1.874	0.0645 *
gf	0.0969	0.0459	2.108	0.0381 **
zf 3	0.1297	0.0641	2.025	0.0462 **
zf 5	0.0237	0.0673	0.352	0.7259
zf 6	0.0171	0.0531	0.322	0.7486

The codes '***', '**', '*' respectively indicate the statistical significance at the 99%, 95%, and 90% confidence levels.

Acknowledgments

This research was funded by the 863 hightech Program of China through grant 2009AA122004, and the Hong Kong Research Grant Council through grant CUHK444612. Their support is gratefully acknowledged. We are also grateful to the National Aeronautics and Space Administration's Earth Observing System Data and Information System, the National Snow and Ice Data Center, and the China Meteorological Data Sharing Service System for providing long-term optical satellite imagery, satellite altimetry data, and meteorological station climate data for this study. We sincerely appreciate the two associate editors' and three reviewers' valuable comments and suggestions, and the editor's efforts in improving this manuscript.

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