Responses of glaciers and glacial lakes to climate variation between 1975 and 2005 in the Rongxer basin of Tibet, China and Nepal

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Abstract This research presents an evaluation of glacier recession and glacial-lake expansion in the Rongxer basin in the Mount Qomolangma National Reserve of central Himalaya. Changes in glacier and glacial-lake surface areas in the Reserve between 1975, 1992 and 2005 have been estimated using remote sensing and GIS techniques that have integrated field data from 2009, 1:50,000 scale topographic maps, ASTER satellite data from 2009, and Landsat MSS/TM images in 1975, 1992 and 2005. By 2005, the glacier surface area had declined from 596.52 to 451.58 km² with a total area loss of 144.94 km², and glacial lakes had increased from 3.55 to 7.87 km², an increase of 121.69 %. The volume of glaciers was reduced by 69.99 km³ from 1975 to 2005. The observed changes in the extent of glaciers are in line with the observed atmospheric warming in the Rongxer basin. Records from the Tingri and Nyalam station have revealed warming during the ablation season since the 1970s at a rate of 0.03 0.04 °C a⁻¹ in the northern and central Rongxer basin. At higher elevations in the study area, represented by the Tingri and Nyalam meteorological stations, the summer warming was accompanied by negative anomalies in annual precipitation since the 1970s, likely enhancing glacier retreat and glacial lake expansion.

Keywords Tibetan Plateau · Rongxer basin · Glaciers · Glacial lakes · Climate change

Introduction

Changes in the extent of glaciers and glacial lakes are among the best natural indicators of global climate change (Haebeli 2005; Kääb et al. 2007). The historical records of these changes go further back in time than most other indicators of glacier response to climate change such as direct mass balance and ice volume measurements. Changes in position of glacier termini and surface area are often relatively well defined and can thus be measured by remote sensing techniques (Kääb et al. 2002). This approach additionally benefits from the increasing availability of satellite data with much improved spatial and temporal coverage. However, not all remotely sensed data are accurate due to the limited vertical resolution and the problem of mixed pixels. Although recent studies have shown that glaciers are generally retreating under the influence of global warming with an accelerating rate (Barry 2006; Solomon and Qinetal 2007; Bolch 2007; Hoelzle et al. 2007; Molnia 2007; Raup et al. 2007), a more generalized conclusion is still precluded due to the lack of more detailed regional data (Raina 2009). Clearly, shrinking glaciers and the associated hydrological changes represent a significant problem for local and regional-scale water budgets and resource management (Barnett et al. 2005). In addition, glacial lakes, which form from melt water, may increase rapidly and overflow, potentially causing outburst floods with disastrous consequences in downstream areas (Richardson and Reynolds 2000; Clayton and Knox 2008; Komori 2008; Liu et al. 2008), including profound impact on the regional ecological and...
environmental systems (Shen et al. 2006; Yao et al. 2010). However, the majority of studies concerned with the recent evolution of glaciers and the assessment of glacial lakes have been conducted in the European Alps, North America and Central Asia, with very few in the Himalaya and Tibetan Plateau (Liu et al. 2002; Barry 2006).

The Tibetan Plateau, located in the south of the central Asian continent and with an average elevation of about 4000 m a.s.l., is known as the roof and the “third pole” of the world. It is the largest glaciated area outside the Greenland and the Polar Regions. According to The Concise Glacier Inventory of China (Shi et al. 2005), there are approximately 36,800 glaciers on the Tibetan Plateau, which occupy an area of about 49,873.44 km² and have a total ice volume of 4,561 kbm³, accounting for 79.5 % of the total number of glaciers, 84 % of the total glaciated area and 81.6 % of the total ice volume in China. A number of studies have been concerned with ice core research (Thompson et al. 1997; Hou et al. 2000; Duan et al. 2007; Geng et al. 2007) and glacier and glacial lake monitoring (Ren et al. 1998, 2004; Yao et al. 2007; Kang et al. 2007; Yang et al. 2008). Since the little ice age (LIA), and especially during the twentieth century, full-scale retreat of glaciers has occurred in the Tibetan Plateau (Ren et al. 1998; Kulikarni and Bahuguna 2002; Pu et al. 2004; Li et al. 2009). In the Mt. Qomolangma region, known as the highest region in the world and located in the Central Himalayas, glaciers deglaciation was intensified as climate tended to be dry and warm (Duan et al. 2002, 2007; Ren et al. 2004; Yang et al. 2006). From 1966 to 1997, the average terminus retreat rates of Mount Qomolangma’s East Rongbuk Glacier, Middle Rongbuk Glacier and Far East Rongbuk Glacier were 8.7, 5.5 and 7.4 m a⁻¹, over the period of 1966 1997, respectively (Ren et al. 1998). Their glaciated area declined by 15.01 km² over the period of 1974 2008 (Ye et al. 2009).

In comparison with most other lakes, the initiation, formation and development of glacial lakes have a much closer relationship with changes in glacier extent and volume, because they are fed from melt water discharge of adjacent or adjoining glaciers (Yao et al. 2010). The dramatic retreat of glaciers may lead to the water-level rise of the glacial lakes in the lower reaches of the rivers, even causing the glacial lake outburst disaster (Harrison et al. 2006). Accordingly, accurate estimation of glacier retreat is important in terms of water resources prediction and planning (Hagg et al. 2007).

The importance of glaciers and glacial lakes for regional water resources and the lack of homogeneity in the rates of glacier retreat require further assessments of glacier behavior on the Tibetan Plateau. This study presents an initial analysis of changes in the extent of glaciers and glacial lakes over the past 30 years in the Rongxer basin between China and Nepal (Fig. 1). Changes in the extent of glaciers have been assessed here by remote sensing techniques and related to observed changes in regional climate. This study addresses the following research questions:

(i) How have the surface area and volume of glaciers and glacial lakes changed in the Rongxer basin over the 1975 2005 period?
(ii) How has climate of the area changed during the period of 1975 2005?
(iii) How are the observed climatic and glacier and glacial lake changes linked?

Research area

The study area is located in the Rongxer basin (29.5°N 86°E to 27.5°N 86.5°E), which mainly lies in the Chinese

![Fig. 1 Location of the Rongxer basin and the study site](image-url)
Responses of glaciers and glacial lakes to climate variation

Table 1 Source of satellite remote sensing data

<table>
<thead>
<tr>
<th>Number</th>
<th>Orbit Path</th>
<th>Date</th>
<th>Sensor</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>151 40</td>
<td>1977 01 07</td>
<td>MSS</td>
<td>57</td>
</tr>
<tr>
<td>2</td>
<td>151 41</td>
<td>1975 10 15</td>
<td>MSS</td>
<td>57</td>
</tr>
<tr>
<td>3</td>
<td>140 40</td>
<td>1992 11 17</td>
<td>TM</td>
<td>28.5</td>
</tr>
<tr>
<td>4</td>
<td>140 41</td>
<td>1992 11 17</td>
<td>TM</td>
<td>28.5</td>
</tr>
<tr>
<td>5</td>
<td>140 40</td>
<td>2005 01 05</td>
<td>TM</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>140 41</td>
<td>2005 11 05</td>
<td>TM</td>
<td>30</td>
</tr>
</tbody>
</table>

national reserve area of the “Mount Qomolangma National Nature Reserve” in Tibet. Its southern part is situated in neighboring Nepal (Fig. 1). The total drainage area of the Rongxer basin is 4,114.6 km², with 1,392.7 km² in China and 2,721.9 km² in Nepal. Rongxer River originates from the Duoka Pula Mountain which elevation is about 5,611 m in the southern-central Himalaya Mountains. From north to south, it extends for 173.3 km across the Mount Qomolangma National Nature Reserve, the Tingri County and the eastern part of Nyalam County in Tibet (China) and the neighboring Dolakha District in Nepal. It has two upper tributaries Rongxer River and Lachpe River in Tibet which join together as Tama Koshi River in Nepal. The Rongxer basin (Tama Koshi basin) is a sub-basin of the Koshi basin of Ganges basin. With an average slope of ~0.04, it is a steep and turbulent river, and its channel and banks are constrained by high mountain flanks. The upper catchment, where most runoff comes from glaciers and glacial lakes, is important for maintaining the volume and quality of water further downstream in Nepal, as it provides water for irrigation. The elevation in the basin ranges from 466 to 7,315 m above sea level (a.s.l.).

The climate of the Rongxer basin is characterized by strong seasonal variations in air temperature and precipitation due to its different altitude north to south. For example, at Tingri and Nyalam meteorological station in the upper reach of the basin, the mean annual temperature and precipitation are 2.95 °C and 296.4 mm, and 3.8 °C and 658.8 mm, respectively. Downstream, however, the mean annual precipitation in Dolakha District is between 2,000 and 2,500 mm, and 250 days a year are frost-free. In addition, biodiversity in the basin is extremely rich, and the ecosystems with vertical characteristics of zonality are mainly composed of mountainous warm-temperate evergreen coniferous forest, deciduous broadleaf forest and alpine sub-frigid tundra.

The Ganges River basin, where the Mount Qomolangma area and the Rongxer basin are located, has the largest glacier size among all flow-out river basins in the Tibetan Plateau, for example, the Brahmaputra, Yangtze and Yellow river basins (Immerzeel et al. 2010). According to the Glacier Inventory in China (Mi et al. 2002), there are 2,192 glaciers in the Ganges River basin, with a total area of 3,609.28 km², a mean area of 1.65 km² and a total ice volume of 329.76 km³. The Mount Qomolangma area is covered with a large number of glaciers and glacial lakes, which in combination account for about 7.67 % of the whole area (Nie et al. 2010). However, over the past 30 years, climate change has significantly affected the retreat of glaciers, and this has had a considerable impact on the number and area of glacial lakes in the area (Wang et al. 2010). Changes in the number and surface areas of glaciers and glacial lakes of this large tributary of the Ganges River, and their relationship with climate variation, will be analyzed.

Data and methods

Mapping changes in glacier surface area

The outlines and termini of glaciers and the extent glacial lakes in the study area were mapped using (1) a series of Landsat MSS (1975) (resolution 60 m) and TM (1992, 2005) (resolution 30 m) (Table 1) and (2) four topographic maps (1:50,000) produced from aerial photographs acquired in 1974 and (3) the DEM (ASTER GDEM, 30 m) published by Japanese Trade and Industry (METI) and American National Aeronautics and Space Administration (NASA) in July, 2009. There are no high-quality TM and MSS images in summer available from the databases of Land Processes Distributed Active Archive Center (LPDAAC) of GLCF and USGS. Instead, the Landsat images in 1975, 1992 and 2005 were obtained for the nearly cloud-free conditions and for October to January, mainly from the database of GLCF (Table 1). Changes to the extent of glaciers were assessed for two periods: (1) between 1975 and 1992 and (2) between 1992 and 2005. These were analyzed with regard to the number, the surface area and the volume of glaciers and glacial lakes, from which the rates of changes in the two periods in the study area were compared.

All images and maps were re-projected to the 1984 WGS UTM zone N45 projection. The Landsat images were geo-corrected and co-registered using ERDAS Imagine 9.2 software with a re-sampled pixel size of 30 m. The ASTER DEM images were used to orthorectify Landsat images in 1975, 1992 and 2005. The registration errors of multi-temporal images were kept within one image pixel. All test results of orthorectification of the global Landsat image from GLCF showed that errors were less than 100 m for Landsat MSS and less than 30 m for Landsat TM (GLCF 2007). Images in 1975 and 1992 were co-registered to Landsat images for 2005 using interactive ground control
points (GCP) of the image geometric correction tool available in ERDAS Imagine 9.2 based on the 1:50,000 topographic maps with a resolution of 30 m. The clearly distinguishable terrain features were used to determine the locations of GCPs. Approximately 30 GCPs were collected and evenly distributed in each pair of images with satisfactory RMSE (a root mean square error) values of less than 30 m.

Earlier assessments have confirmed that human interpretation remains the best tool for extracting detailed information from satellite imagery for glaciers and glacial lakes (Lu et al. 2002; Kulkarni et al. 2007; Rau et al. 2007). However, this method usually lacked location accuracy and created 'salt and pepper' effects that largely constrained their application to our study. Alongside the development of RS techniques, a number of accurate methods for automated mapping of glaciers are available, for example, thresholding of ratio images with Landsat TM band 4/TM band 5 by Paul et al. (2002) and the Normalized Difference Snow Index (NDSI) by Racoviteanu et al. (2008). Due to its robust and time effective advantages compared to single manual digitization, Normalized Difference Snow/Ice Index (NDSII), Normalized Difference Water Index (NDWI) and Normalized Difference Vegetation Index (NDVI) are applied in conjunction with human interpretation to extract the information of glaciers and glacial lakes. The equations for calculating NDSII (Hulka 2008) and NDWI (McFeters 1996) are:

\[
\text{NDSII}_\text{TM} = \frac{(\text{Red} - \text{SWIR})}{(\text{Red} + \text{SWIR})} \quad \text{or} \\
\text{NDSII}_\text{TM} = \frac{(\text{TM3} - \text{TM5})}{(\text{TM3} + \text{TM5})} \\
\text{NDWI}_\text{TM} = \frac{(\text{Green} - \text{NIR})}{(\text{Green} + \text{NIR})} \quad \text{or} \\
\text{NDWI}_\text{TM} = \frac{(\text{TM2} - \text{TM4})}{(\text{TM2} + \text{TM4})}
\]

In this study, the NDSII index was used to differentiate glaciers from snow and to eliminate the impact of shadows (Fig. 2a, b). However, due to the similar NDSII values of glaciers, lakes and rivers, NDWI index was used in conjunction with NDSII index (Fig. 2c). NDWI values of glacial lakes are larger than those of glaciers and rivers and could be used to distinguish glaciers from glacial lakes and other lakes. These were carried out using the modular sector in ERDAS IMAGINE9.2. However, it was difficult to map glaciers by setting a threshold value. Therefore, based on field surveys, typographical maps and images, combined with NDSII and NDWI, manually digitalization was carried out for outline extraction, attributive editing, spatial inspection and correction using ArcGIS software (Fig. 2d). Changes in the extent of glaciers and glacial lakes between 1975, 1992 and 2005 were measured using the 1975 Landsat MSS, 1992 and 2005 Landsat TM to enable a comparison with the results of two periods (Figs. 3, 4; Table 2).

For estimation of the glacier volume changes, Liu et al. (2003) have proposed a scaling relationship between area and volume. The dynamics of glacier volume were calculated by the formula (3):

\[
V = 0.04 	imes S^{1.35}
\]

where \(V\) is the ice volume (unit: km\(^2\)) and \(S\) refers to glacier area (unit: km\(^2\)).

Climatic data

Monthly air temperature and precipitation data from two high altitude meteorological stations, the Tingri (elevation 4,300 m a.s.l.) and Nyalam station (elevation 3,810 m a.s.l.), were used over the 1975–2005 period. The two meteorological stations are standard synoptic stations taking measurements every 6 h. Meteorological records at these two stations are obtained from China Meteorological Administration (CMA).

Prior to analysis, all temperature and precipitation records were standardized by subtracting the mean and dividing by the standard deviation of the time series to ensure comparability of the records (Wilks 1995).

Results

Based on the available satellite remote sensing data in the Rongxer basin, an initial analysis of the variation of glaciers and glacial lakes shows that in 2005 the area of glaciers in the basin was 451.58 km\(^2\), and the area of glacial lakes was 7.87 km\(^2\) (Table 2). These glaciers and glacial lakes were distributed mainly over the northern high altitude region of our study area (Figs. 3, 4).

Glacier changes between 1975, 1992 and 2005

The analysis shows that during the last 30 years, glaciers of the area studied continuously receded (Fig. 3). Between 1975 and 2005, the total surface area of glaciers has decreased by 28.25% from 596.52 to 451.58 km\(^2\) (Table 2). The volume of glaciers has decreased by 70 km\(^3\) from 2,234.44 km\(^3\) in 1975 to 2,164.44 km\(^3\) in the study region.

Changes in terminus location estimated for the two periods are summarized in Fig. 3. The glacier recession intensified between 1992 and 2005. In this period, the total glacier surface area in the study region has decreased by 17.01% of the 1992 value. Between 1975 and 1992, the glacier area reduced by 8.78% of the 1975 value, while in...
Fig. 2 Glacier mapping using the NDSII and manual digitalization combined method: a features of debris covered glaciers, lakes, shadow and snow in the images (1992); b NDSII obtained for differentiating glaciers from snow, cloud and shadows; c NDWI obtained for differentiating glaciers from glacial lakes and rivers; d the colored outlines showing the extent of glaciers for the days indicated in the legend.

the period 1992-2005, the glacier area decreased almost twice the reducing rate based on the area of 1975.

Glacial lakes between 1975, 1992 and 2005

The analysis shows that during the last 30 years, the area and the number of glacial lakes in the study area have continuously increased (Fig. 4). All studied glacial lakes increased in area. Between 1975 and 2005, the total surface area of the glacial lakes increased by 121.69% from 3.55 to 7.87 km² (Table 2). During the same period, the total number of glacial lakes increased from 15 to 28.

Relative to 1975, the glacial lakes in the study region have gained 40.28% of their area between 1975 and 1992, and 58.03% in the 1992-2005 period. The total increase in the surface area of glacial lake was 1.43 km² between 1975 and 1992, and 2.89 km² between 1992 and 2005. The average annual expansion rate was 0.21 km² a⁻¹, which is more than twice the rate observed between 1975 and 1992 (0.08 km² a⁻¹).
Fig. 3 Retreated glacier maps in the study area. Glacier area changes over different periods are shown: a shows the changes from 1975 to 1992; b from 1995 to 2005; c from 1975 to 2005 and d an enlarged drawing from c.

Climatic variation

The glaciers gain and lose mass predominantly in the boreal winter and summer, respectively (Kutuzov and Shahgedanova 2009). Therefore, air temperatures, especially in summer, and precipitation, particularly in winter, are the main factors controlling glacier mass balance (Wang 1995). On the Tibetan Plateau, air temperature and annual precipitation in most regions have shown an increasing tendency over the recent 30 years, whereas maximum evapotranspiration decreased (Liu et al. 1998; Du and Ma 2004; Wu et al. 2005).

A detailed analysis of the mean annual temperature and annual precipitation around the Rongxer basin has shown that the characteristic weather changes have been rising temperatures associated with falling precipitation during the period of 1975–2005 (Fig. 5b). Air temperature rose at an average linear rate of $0.03 \, ^\circ\text{C} \, \text{a}^{-1}$ (sig. <0.05, the fitting equation and fitting coefficients were significant at $p = 0.05$, $R^2 = 39\%$) since 1975, while precipitation tended to decrease with an average linear rate of $1.95 \, \text{mm} \, \text{a}^{-1}$ (sig. >0.05, the fitting equation and fitting coefficients were not significant at $p = 0.05$, $R^2 = 5\%$).

At the Tingri Station and the Nyalam Station, similar trends of air temperature rise were observed between 1975 and 2005 (Table 3), with a higher increasing rate in the second period of 1992–2005 compared with the preceding period of 1975–1992. No strong negative anomalies have been observed in the region since 1975. According to Shrestha et al. (1999), air temperatures measured at the meteorological stations in the low-elevation, southern part of the basin in Middle Mountains and Himalaya regions in Nepal also showed an increasing tendency between 1978 and 1994, which was largely in accordance with the temperature variability observed in the northern part. However, the annual precipitation has been declining over the period of 1975–2005. The decreasing rate was $1.95 \, \text{mm} \, \text{a}^{-1}$ and the lowest record of precipitation was observed in 1992.
Fig. 4 Glacial lake variations during 1975-2005

Table 2 Area of glaciers and glacial lakes in the Rongxer River basin from 1975 to 2005

<table>
<thead>
<tr>
<th>Year</th>
<th>Glacier Area (km²)</th>
<th>Area change (km²)</th>
<th>Area change (%)</th>
<th>Ice volume (m³)</th>
<th>Number</th>
<th>Glacial lake Area (km²)</th>
<th>Area change (km²)</th>
<th>Area change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>595.52</td>
<td>223.44</td>
<td>37.75</td>
<td>15</td>
<td>3.55</td>
<td>144.94</td>
<td>24.30</td>
<td>16.78</td>
</tr>
<tr>
<td>1992</td>
<td>544.16</td>
<td>52.36</td>
<td>9.59</td>
<td>197.37</td>
<td>20</td>
<td>4.98</td>
<td>1.43</td>
<td>30.48</td>
</tr>
<tr>
<td>2005</td>
<td>451.58</td>
<td>92.58</td>
<td>20.43</td>
<td>153.45</td>
<td>28</td>
<td>7.87</td>
<td>2.89</td>
<td>36.87</td>
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<tr>
<td>Total</td>
<td>144.94</td>
<td>24.30</td>
<td>16.78</td>
<td></td>
<td></td>
<td>4.32</td>
<td>121.69</td>
<td>84.78</td>
</tr>
</tbody>
</table>

At the Nyalam station, the annual precipitation is 658.80 mm. The mean annual precipitation was lower in the second period compared with the first period, which was in line with the Tingri station. Similar trends were also characteristic for the northern and southern slopes of Mount Qomolangma in Tibet since 1970s (Yang et al. 2006).

An increase in air temperature during the melting season was observed since 1970s in the Rongxer River basin (Fig. 5a), with an increase rate of 0.02 °C a⁻¹ (sig. <0.05, the fitting equation and fitting coefficients were significant at p = 0.05, R² = 32 %). In the northern glaciated area, at Tingri station, the mean summer temperature increased about 0.53 °C over the period of 1992-2005 compared with that during the period of 1975-1992 (Table 4). During the same periods, mean summer temperature at Nyalam station rose by 0.34 °C over the period of 1992-2005 compared with that during the period of 1975-1992. The increase of the mean summer temperature will obviously accelerate glacier melting. On the contrary, winter precipitation in the northern study area tended to decrease with a rate of 0.35 mm a⁻¹ (sig. >0.05, the fitting equation and fitting coefficients were not significant at p = 0.05, R² = 1 %). The lowest recorded precipitation was 283.08 mm in 1992. The similar trend was observed by Shrestha et al. (2000) in the southern part of the basin in Nepal after 1990. The precipitation in winter at Nyalam station has decreased by 29.04 mm over the second period compared with that during the first period. That was in the opposite to Tingri station, where precipitation increased by 0.31 mm (Fig. 6).

Discussion

The glaciers and glacial lakes in the study show a clear tendency to be changing due to changes in climate and have, therefore, not been in static equilibrium for the period of 1975-2005. These results agree with other studies in other regions on Tibetan Plateau (Ren et al. 1998, 2004; Che et al. 2004, 2005; Chen et al. 2005; Kang et al. 2007; Yao et al. 2007; Wu and Zhu 2008; Yang et al. 2008). Many studies have analyzed glacier retreat and glacial lake expansion since the mid-twentieth century. Our results for glaciers in the Rongxer river basin show that they have lost
Fig. 5 Variations of main climate variables during the period of 1975-2005 in the northern Rongxier basin: a annual mean temperature and precipitation and b mean summer temperature and winter precipitation.

Table 3 Climatic characteristics of average annual temperature and average annual precipitation at Nyalam and Tingri stations during 1975-2005

<table>
<thead>
<tr>
<th>Period</th>
<th>Nyalam station</th>
<th>Tingri station</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average annual temperature (°C)</td>
<td>Average annual precipitation (mm)</td>
</tr>
<tr>
<td>1975-1992</td>
<td>3.48</td>
<td>701.61</td>
</tr>
<tr>
<td>1993-2005</td>
<td>3.92</td>
<td>603.63</td>
</tr>
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</table>

Table 4 Climatic characteristics of average summer temperature and average winter precipitation at Nyalam and Tingri stations during 1975-2005

<table>
<thead>
<tr>
<th>Period</th>
<th>Nyalam station</th>
<th>Tingri station</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average summer temperature (°C)</td>
<td>Average winter precipitation (mm)</td>
</tr>
<tr>
<td>1993-2005</td>
<td>10.43</td>
<td>119.40</td>
</tr>
</tbody>
</table>

144.94 km² of their 1975 area in the 30 years between 1975 and 2005, which equals a loss of 0.78 % a⁻¹. This is in close agreement with variation trend of glaciers in the Mt. Qomolangma region where a glacier retreat rate of 0.52 % a⁻¹ between 1976 and 2006 has been reported (Nie et al. 2010). In the eastern parts of neighboring Mt. Xixabangma region, the Jicong Pu Glacier and Reqiang Glacier in the eastern Mt. Xixabangma have declined between 1977 and 2001 by 7.29 and 22.90 %, respectively (Che et al. 2005). Here, the assessment by Ren et al. (2004) indicates that the loss of glacier area has accelerated with an average retreat rate 6.40 m a⁻¹ since 1980. Compared with other regions, glaciers in the eastern Terskey-Alatoo, inner Tien Shan, located to the north Tibetan Plateau, which developed under a strong warming during the melt season and by negative winter precipitation anomalies in the 1990-1997 period, have been retreating since the end of the LIA and 19 % of ice surface area has been lost between the LIA and 2003 (Kutuzov and Shahgedanova 2009). Glaciers in the higher regions of the eastern Pamir have shown slower retreat rates averaging 7.90 % (Shangguan et al. 2006).

Changes of glacial area result in changes to the size of glacial lakes because the water supply comes mainly from...
the glacier thaw. Glacial lakes in our study area have increased from 1975 to 2005 by 121.69 % from 3.55 to 7.87 km², and the total number has increased from 15 to 28 during the full period. This is in line with the variations of other glacial lakes in the Himalaya area (Wang et al. 2010).

In Poiqu River and Pengqu River, the area of glacial lakes has increased by 47 and 13 %, respectively, which is similar to the areal variations of glacial lakes on east slopes of Mount Xixabangma (Che et al. 2005), Mapam Yumco Basin (Ye et al. 2008). The relation between the changes in lake area and glacier area from 1975 to 2005 is shown in Fig. 7 and Table 2. In the Rongxer basin, the glacial lake area expanded during 1975 1992 and 1992 2005, while the glacier area shrank synchronously. The rates of variation of the lake and glacier areas in the second period were all larger than that in the first period.

The main factors that control glacier mass balance are temperature and precipitation. Climate in this region was affected by South Asian monsoonal circulation and westerly flow. According to research in the Tibetan Plateau (Yao et al. 2000; Li et al. 2006), the annual mean temperature tended to increase in the past 30 years, with a rate of 0.025–0.028 °C a⁻¹. Predictions of climate change using the GCM-HadCM2 model and meteorological records in the Tibetan Plateau, temperature will rise by 2.91 °C by 2099 (Li and Chen 1999). In the meantime, records of the Dasuopu ice core in the Mt. Xixabangma region and Far East Rongbuk ice core in the Mt. Qomolangma region showed that the climate has been in a warm period in recent 100 years in this region (Kang et al. 2000; Duan et al. 2001; Ren et al. 2004).

Accordingly, the increasing temperature mainly accounted for glacier melting, especially in 1990s, and the rapid rise of air temperature intensified the glacier retreat in the Tibetan Plateau (Ren et al. 2004; Yao et al. 2004).

Tingri and Nyalam meteorological stations in the northern part of the Rongxer River basin have shown a warming trend in the study area since 1975 (Fig. 5). An increase in air temperature during melting season at a rate of 0.02–0.03 °C a⁻¹ has been observed at the two regional meteorological stations and also in the neighboring regions (Shrestha et al. 1999). Furthermore, precipitation (winter or annual) tended to decrease in the basin and in the neighboring regions (Shrestha et al. 2000). This combination has created unfavorable conditions for the glaciers, enhancing their retreat. Moreover, as a key indicator of heat, accumulated temperature has tended to increase during the period of 1975 2005 (Fig. 6). An increase of the ≥0 °C accumulated temperature was observed with a rate of 7.31 °C a⁻¹ (at p = 0.05) from 1975 to 2005. The mean value of ≥0 °C accumulated temperature was 1,800.3 °C in the period of 1992 2005, which was much higher than 1,685.5 °C in the period of 1975 1992. This was correlated negatively with glacier surface area, with a correlation coefficient of −0.93 (at p = 0.05). The strong negative correlation further confirmed the importance of atmospheric warming for glacier change in the Rongxer River basin. In general, the air temperature variations confirmed the importance of atmospheric warming for glacier change in the Rongxer basin (Fig. 5; Table 4). This has also been confirmed by Jing et al. (2006) and Aizen et al. (2007) for glaciers monitored in Tien Shan and Liu and Sharma (1988) and Ye et al. (2008) for glacial lakes variations.

Moreover, precipitation tends to decrease in the northern part of the basin and in the neighboring regions (Shrestha et al. 2000). According to the Dasuopu ice core records in the neighboring region (Kang et al. 2000; Duan et al. 2001; Ren et al. 2004), the accumulated amount of ice core tended to decrease in recent 100 years in the Mt. Xixabangma region; however, this showed no obvious variation tendency since 1970s, which indicated that precipitation remained unchanged since 1970s. This agrees with Oerlemans' (2005) conclusion that the sensitivity of glaciers to precipitation change was lower than their sensitivity to temperature change.

Not surprisingly, glacier retreat in the Rongxer River basin is not only a problem to China but also a potential
water crisis for heavily populated South Asia. Continuously rising temperature may result in the disappearance of glaciers in this basin. Although this is a relatively early stage of glacier retreat, melt water may decline substantially in the later stages when intensive and extensive glacier shrinkage occurs (Ren et al. 2004). This could be catastrophic for local and downstream people, and the integrity of ecosystems depending on water availability. Moreover, as a result of the rapid glacier retreat, rock falls, glacier calving and avalanches into a lake can create large tsunami-like that could result in the destruction of property and serious loss of life in mountain terrains. According to Liu et al. (2008), 18 outbursts of floods occurred in 15 glacial lakes in Tibet from 1935 to 1995.

Conclusions

Glaciers in the Rongzex basin, in the Mount Qomolangma region, have been retreating since 1975, and 0.91 % a⁻¹ of surface area has been lost. Our analysis has shown that the total surface area of glacial lakes has increased by 4.32 km² between 1975 and 2005. The same period has been characterized by a strong warming during the summer melt season and negative precipitation anomalies, providing a link between climatic variations and a loss of glacier area. Additionally, the rapid retreat of glaciers seems to have already affected the regional hydrology in the study region through the formation and expansion of glacial lakes. In addition, they present a potential flooding and catastrophic-waste hazard to local communities. In this context, an accurate assessment of potential impacts of glacier retreat and dynamic monitoring of glacial lakes and their impact on water resources is becoming increasingly urgent.

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