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Response of Lakes to Climate Change in Xainza Basin Tibetan Plateau Using Multi-Mission Satellite Data from 1976 to 2008

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Abstract: Changes in the lake areas of Xainza basin in the past 33 years (1976 to 2008) were studied using Landsat data from Multispectral Scanners (1973-1977), Thematic Mapper (1989-1992, 2007-2009), and Enhanced Thematic Mapper Plus (1999-2002). The results indicated that lakes in the study area evidently expanded from 1976 to 2008, with total expansion of 1512.64 km^2. The mean annual air temperature presented an upward trend with certain fluctuations from 1966 to 2008. The air temperature rise rates in the cold season (0.31°C/10a) were higher than those in the hot season (0.24°C/10a), in the Xainza station example. Precipitation exhibited evident seasonal differences. Mean annual precipitation in hot season is 281.48 mm and cold season is 32.66 mm from 1966 to 2008 in study area. Precipitation in the hot season was the major contributor to the increase in annual precipitation. Grey relational analysis (GRA) was used to study the response of lake areas to climatic factors. The mean air temperature and precipitation were selected as compared series, and the lake areas were regarded as the reference series. The grey relational grade (GRG) between compared series and reference series were calculated through GRA. The results indicated that changes in lake areas were mainly affected by climatic factors in the hot season. Lakes in this region were classified into three grades, namely, Grades I, II, and III according to the recharge source and elevation. The GRGs of each series varied for different grade lakes: the area of Grade III lakes were the most relevant to the hot season factors, the GRGs of precipitation and air temperature were 0.7570 and 0.6606; followed by the Grade II lakes; Grade I lakes were more sensitive to the air temperature.

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Introduction

Lakes and reservoirs comprise only about 3% of the earth's total land surface area (Downing et al.

2006), yet they play a pivotal role as sentinels, integrators, and regulators of climate change (Williamson et al. 2009a, 2009b). The important point of that was once the subject of a special issue of Limnology and Oceanography in 2009. With special natural conditions, the Tibetan Plateau has formed unique and fragile ecosystems, which are sensitive and vulnerable to climate change (Tang et al. 1998; Feng et al. 1998; Su et al. 1999). Therefore, the Tibetan Plateau has attracted considerable attention in global change studies. The lakes in the Tibetan Plateau are rarely disturbed by human activities because most of these lakes are closed inland lakes without outsource water recharge and are located in remote areas. The change in lake area was caused by the natural environment, such that this change can be considered a sensitive indicator (Ding et al. 2006; Zhang et al. 2012). Recent studies showed that in the context of global climate change, Tibetan Plateau was characterized by rising air temperature, more precipitation, and less evaporation (Wu et al. 2005; Du et al. 2008). For instance, the mean annual air temperature shows an upward trend of Tibetan Plateau from 1971 to 2008, with a rate between 0.22°C-0.49°C /10a; and the annual utilizable precipitation overall increased significantly at a rate of 19.6 mm/10a in the eastern region in Qiangtang Plateau of northern Tibetan Plateau (Jiang et al. 2012); the potential evapotranspiration decreases at a rate of 13.1 mm/10a during 1961-2000 (Chen et al. 2006). Meanwhile, plateau lakes have undergone relevant changes. Then, do lakes contain valid indicators that are appropriate for climate change? Previous studies have suggested a suite of response variables (e.g., water temperature, water level, ice phenology, chemical variables, dissolved organic carbon, biota.) that can act as effective indicators of climate change. Water level, as one of the indicators, is a good indicator of climate change because it reflects the dynamic balance between water input (precipitation, runoff) and water loss (evaporation), and the timing of the ice-free season on timescales ranging from hours to centuries (Adrian et al. 2009). Lake area has the corresponding relationship with lake level (water level). The change of lake area indirectly reflects the change of water level. Thus, the lake area can act as an indicator of climate change. Remote sensing (RS) is particularly promising for inferring lake temperatures, water levels, and algal dynamics (Hampton. 2013). RS technique also provides useful tool for long-term and broad spatial coverage lake studies.

Currently, the studies on the response of lakes to climate change mainly focused on regional spatial variations in the whole Tibetan Plateau (Zhang et al. 2008; Li 2012; Jiang et al. 2012), eco-security monitoring of the Sanjiangyuan region (headwaters of Yangtze River, Yellow River, and Lancang River) (Li et al. 2008; Li et al. 2010), as well as overall changes in the large river basin and individual large lakes (Zhang et al., 2012). Numerous studies have been conducted on Namco Basin and Ranwuhu Basin in southeastern Tibet (Chen et al. 2009; Zhu et al. 2010; Xin et al. 2009) and Yamzho Basin and Anglaren Co Basin in south Tibet (Chu et al. 2012; Zhang et al. 2012). However, study on watershed in central Tibet is lacking. In addition, most of these studies focused on qualitative investigations with limited quantitative research. So, how lakes in different topography type of the same watershed are responding to climate change? Can we determine the response relationship between lakes and climate changes with the quantitative method? What kind of climate factor is the dominant factor of the lake change?

In this study, Xainza watershed, located at the central region of Tibet, China was studied using four Landsat data series (1976 to 2008) and meteorological data (1966 to 2008) of Xainza Station, Baingoin Station, and Amdo Station nearby. Both of overall changes in the whole river basin and individual grades were considered. The GRGs between changes in lakes and climatic factors were studied using GRA to explore the quantitative relationship between lake areas and climatic factors.

1 Study Area

The study area (30°-32°58′N, 87°-90°46′E) mainly covers Xainza County, north Baingoin County, and part of Nyima County (Figure 1) with total area of 68,000 km² and average altitude of 4500 m in the lake basin of central Tibetan Plateau. This region is located in the cold arid-semi arid plateau monsoon climate zone.

Numerous rivers and inland lakes can be found in this basin. Over 200 lakes of various sizes are distributed in the study area. The major lakes include: Siling Co, Dagze Co, Geren Co, Qingxiang Co, Ondar Co, Zigui Co, Yagen Co, and Ren Co. Major rivers include Za'gya Zangbo and Bogcang Zangbo. At an altitude of 5600 m and beyond, snow covers the mountain throughout the year. The modern glaciers developed well. Meltwater is an important water supply for the lakes in this region.

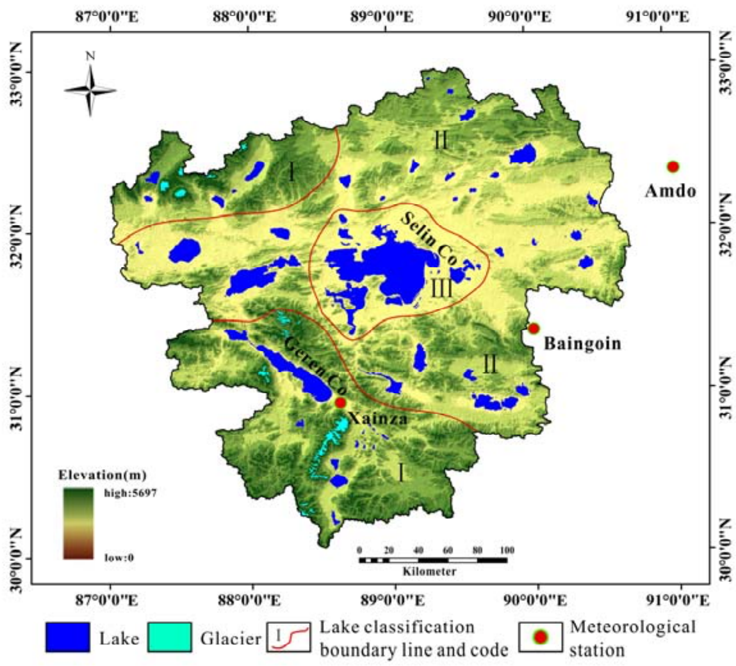

Figure 1 Location of study areas and meteorological stations in China.

2 Data and Methods

2.1 Data Source

The Landsat series of satellites provides the longest continuous record of satellite-based observations. The Landsat sensors include the Landsat 5 Thematic Mapper (TM), the Landsat 7 Enhanced Thematic Mapper Plus (ETM^+), and the Landsat 1–5 Multispectral Scanners (MSS). The high value of the data from Landsat can be partly attributed to long-term repeat coverage (1972 up to the present) and relatively high spatial resolution (30 m for TM and ETM^+ and 80 m for MSS). Both Landsat 5 and Landsat 7 are still functioning, although both have substantially exceeded their planned design lives (Chen et al. 2011). Ten images that were relevant to the study areas were analyzed. The details are shown in Table 1.

Table 1 Details of four series of remote sensing images

Path/Row	MSS (1976)	TM (1990)	ETM+ (2000)	TM (2008)
138/037	1976-12	1992-08	2002-05	2008-06
138/038	1976-12	1992-08	2001-06	2008-06
139/037	1973-06	1990-05	2000-10	2007-09
139/038	1977-02	1990-06	1999-09	2008-06
139/039	1976-12	1989-11	2000-11	2009-06
140/037	1976-12	1992-09	1999-08	2008-08
140/038	1976-12	1992-09	2000-10	2008-10
140/039	1976-12	1992-09	2000-10	2008-10
141/037	1976-12	1990-11	2001-09	2008-10
141/038	1977-01	1990-11	2001-09	2009-06

Notes: MSS, Multispectral Scanner; TM, Thematic Mapper; ETM^+, Enhanced Thematic Mapper plus. The row track number of MSS image (1976) should be plus 10. For example, the correct track row number of P138R037 should be P148R037.

The DEM (Digital Elevation Model) data used to delineate watershed of study area came from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM. The Ministry of Economy, Trade, and Industry (METI) of Japan and NASA released the ASTER global DEM (GDEM) in June 2009. ASTER GDEM was produced by the automated processing of the complete ASTER archive from 2000 to 2007, which contains more than 1.5 million scenes. The ASTER GDEM has a horizontal resolution of 1 arc-second (30 m) and covers the earth's surface between 83°N and 83°S (Frey and Paul 2012). For this study, the ASTER GDEM tiles N30E087, N30E088, N30E089, N30E090, N31E087, N31E088, N31E089, N31E090, N32E087, N32E088, N32E089, and N32E090 were used.

Meteorological stations in northern Tibet are very limited. Only Xainza, Baingoin, and Amdo stations are distributed in the study area (Figure 1). Mean monthly air temperature and monthly precipitation data of these three stations from 1996 to 2008 were used.

2.2 Method

2.2.1 Preprocess of remote sensing data

The Landsat images were calibrated to reflectance by using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes module, which was integrated in the ENVI (The Environment for Visualizing Images) image processing system.

The third band of Landsat MSS and the fourth band of TM and ETM^+ were sensitive to water bodies, such that false color composite images were produced from the false color of MSS 3/2/1 TM and ETM^+ 4/3/2. ETM^+ images (2000) were used as reference images. Images taken at other periods were calibrated under the Universal Transverse Mercator (UTM) coordinate system, zone 45N, based on the "image to image" model (Root-mean-square Error (RMSE)<0.5 pixels in both x and y directions). The remote sensing images of the study area were then produced through a geometric mosaic. The boundaries of lakes were identified by visual interpretation. The areas of lakes in different years were calculated using ArcGIS 9.3.

2.2.2 Watershed delineation

First, the ASTER GDEM datasets were reprojected to the UTM-WGS84 coordinate system, zone 45. The GDEM scenes were then incorporated into one DEM image. The catchment basin was delineated using ArcGIS 9.3. The conditional tool (Spatial Analyst Tool extension) was also used to make corrections. Negative elevation values were removed from the DEMs. Subsequently, automated extraction was performed using the Hydrology Spatial Analyst Tool. Two secondary raster products were obtained for DEM input: Flow direction and Flow length. The extracted drainages were classified into stream order and refined to purge excess vectors. All stream vectors were converted into ArcGIS shapefile format. The watershed polygons were extracted using the Watershed IDRISI algorithm (Mantelli et al. 2011).

2.2.3 Processing of climate data

The climate trend was represented by liner equation, i.e.,

$$y=a_0+a_1t \tag{1}$$

where y is meteorological element, t is time, a_0 is a constant, a_1 is linear trend term, and $a_1\times10$ denotes the tendency rate of climate per 10a.

Studies have shown that Xainza region had evident seasonal water and heat distribution (Da. 2011). In this study, monthly air temperatures not lower than 0°C were regarded as the hot season (Wu et al. 2007). According to the mean monthly air temperature records of these three stations from 1966 to 2008, October to April (mean air temperature is -5.22°C at Xainza station) could be regarded as the cold seasons, and May to September (mean air temperature is 7.57°C at Xainza station) was the hot season. The annual and seasonal meteorological series were established through arithmetic average.

2.2.4 Grey relational analysis

The problems on uncertainty existing commonly in nature and thinking, the ones in myriad sample can be solved by probability and statistics ways, the ones in kenning uncertainty can be dealt with by fuzzy mathematics. However, there also exists another category on uncertainty in less data little sample, incomplete information and devoid of experience, which is just suitable to be dealt with by grey system theory (GST). The less data uncertainty, usually, behave as a limited series. Every series stands for one of factors. In order to analyze the status of factors, it is necessary to model the relationship among series. It is the so-called grey relational analysis (GRA) (Deng 2005). The response of lake area to climate change is just the system which in less data little sample and incomplete information. GRA was used to study the relational grade between lake areas and climatic factors in Xainza region over the most 30 years to determine the main factors affecting lake areas. The basic idea of GRA is based on the geometric similarity of curves. The curves of two series are more similar, the series are more relevant, and vice versa (Liu et al. 2010). Grey relational grade (GRG) is the measure between reference and compared series. The so-called reference series is the object to study, such as the changes in lake area of this manuscript. And the so-called compared series refer to the factors of lake area change, such as the climate elements. The basic principle of GRA is as follows (Liu et al. 2010; Zhou et al. 2012):

Let the reference series be

$$X_0=[X_0(1),X_0(2),\ldots,X_0(n)] \tag{2}$$

The compared series is

$$X_i = [X_i(1), X_i(2), \ldots, X_i(n)], i = 1,2,\ldots,m \quad (3)$$

The GRG between compared series X_i and reference series X_O is

$$r(x_0(k),x_i(k)) = \frac{\min\limits_i \min\limits_k |x_0(k)-x_i(k)| + \xi \max\limits_i \max\limits_k |x_0(k)-x_i(k)|}{|x_0(k)-x_i(k)| + \xi \max\limits_i \max\limits_k |x_0(k)-x_i(k)|} \quad (4)$$

$$\gamma(X_0, X_i) = \frac{1}{n}\sum_{k=1}^{n} r(x_0(k),x_i(k))) \quad (5)$$

where $r(x_0(k),x_i(k))$ is the GRG of X_i to X_O at k, ζ is the distinguishing coefficient, ζ is 0.1 in this work, and $\min\limits_k |x_0(k)-x_i(k)|$ represents the minimum differences between series X_O and series X_i at k. $\min\limits_i \min\limits_k |x_0(k)-x_i(k)|$ represents the minimum of minimum differences. $\max\limits_k |x_0(k)-x_i(k)|$ is the maximum difference between series X_O and series X_i at a corresponding point, whereas $\max\limits_i \max\limits_k |x_0(k)-x_i(k)|$ is the maximum value of maximum differences. Once the GRG $\gamma(X_0, X_i)$ is determined, it can be used to identify how close the reference and compared series are.

3 Lake Change and Analysis

3.1 Overall change

From 1976 to 2008, lake area in the study area has evidently expanded by 1512.64 km². The enlargement rate of the lake area was 11.38%, with a rate of 31.57 km²·y⁻¹ from 1976 to 1990. To 2000, the lake area was enlarged by 852.18 km² at a rate of 34.09 km²·y⁻¹. To 2008, the lakes enlarged by 36.36%, reaching 45.84 km²·y⁻¹. The most rapid expansion occurred during the period from 2000 to 2008. Compared with the total area in the last 30 years, the area increased significantly by approximately 36.36%.

3.2 Grade lake analysis

As previously mentioned, the main evident trend exhibited by lakes was area enlargement. However, the trends are significantly different. For example, Siling Co, which is located downstream of the catchment basin, expanded evidently by approximately 625.33 km² from 1976 to 2008 (Table 2), whereas Geren Co, located upstream of the catchment basin, has undergone “expansion–shrinkage–expansion” from 1976 to 2008 (Table 2), such that the areas of Geren Co presented slight fluctuations. Therefore, even within the same catchment, the differences in terrain and landscape could cause an unbalanced distribution of water and heat, thus resulting in various changes in lake areas.

Table 2 Area change of three grades of typical lakes from 1976 to 2008 (km²,%)

Year	Lake 1	Lake 2	Lake 3	Lake 4
1976	58.83	475.59	431.79	1641.24
1990	68.72	473.66	431.98	1714.32
2000	69.27	482.28	457.39	1810.12
2008	68.72	475.82	436.14	2266.57
Area[1]	9.89	0.23	4.35	625.33
Change[2]	16.81%	0.05%	1.01%	38.10%

Notes: Lake1, Yochags Co (Grade I); Lake 2, Geren Co (Grade I); Lake 3, Wuru Co (Grade II); Lake 4, Siling Co (Grade III). [1] means Total expansion area. [2] means change rate.

To study the area change of different lakes in catchment comprehensively, lakes were divided into Grades I, II, and III based on terrain elevation and water supply conditions (Figure 1). Grade I represented lakes located upstream of the catchment, mainly supplied by glacial meltwater. Grade III refers to lakes located downstream of the catchment, mainly supplied by meteoric water. Grade II represented lakes between Grades I and III, located in the middle of the catchment, and mainly supplied by meteoric water and surface runoff. When water supply was sufficient, a progressive supply relationship was established, such that Grade III can be supplied by Grade II, and Grade II can be supplied by Grade I.

Figure 2 visually demonstrates the trend of area change of different grade lakes from 1976 to 2008. The tendency rate of overall lake area change from 1976 to 2008 was 491.66 km²/10a, which indicated a significant changing rate. The Grade III lakes had the highest enlargement rate at 256.28 km²/10a, followed by Grade II, at a tendency rate of 207.56 km²/10a. The Grade I lakes had the smallest tendency rate of 27.789 km²/10a.

Table 3 quantitatively demonstrates the area change of different grade of lakes from 1976 to 2008. Different grades have different change rate and the period of biggest area expansion. For Grade Ⅰ lakes, the fluctuation range of change rate is not big, at a rate of 2.54% to 3.91%. Grade II lakes have a biggest mean change rate at 14.00%. In the period of 1976 to 1990, Grade I lakes and Grade II lakes reached the biggest area expansion. The period of 2000 to 2008 is the biggest area expansion period for Grade III lakes.

4 Results and Discussions

4.1 Climate change

4.1.1 Changes in Air Temperature

The inter-annual variations of air temperature in Xainza, Baingoin, and Amdo stations from 1966 to 2008 are given in Figure 3. Overall, all stations showed similar warming trends at 0.3, 0.43, and 0.34°C/10a, of which Baingoin station has undergone the greatest air temperature rise. The mean annual air temperatures of Xainza and Baingoin stations were significantly higher than that of Amdo station. The interannual variations of Xainza and Baingoin stations were relatively smaller, with Xainza station having the highest mean annual air temperature. In addition, two fluctuations were observed in 1983 and 1997. All three stations experienced the lowest air temperature within this period. However, the air temperature rose rapidly and has exhibited warming trends since then. Xainza, Baingoin, and Amdo stations, with latitudes of 30°57′N, 31°23′N, and 32°21′N and elevations of 4663, 4728, and 4705 m respectively presented consistent changes in air temperature with Tibetan Plateau, but also indicated spatial variations caused by differences in river basin, latitudes, and elevations.

According to the classification of cold and hot seasons, the mean air temperatures of the cold and hot seasons at Xainza station were used as the air temperature at different seasons for the whole study area to prepare the trend diagram for 1966 to 2008 (Figure 4). The results indicated that the air temperature rise rates in the cold season (0.31°C/10a) were higher than those in the hot season (0.24°C/10a).

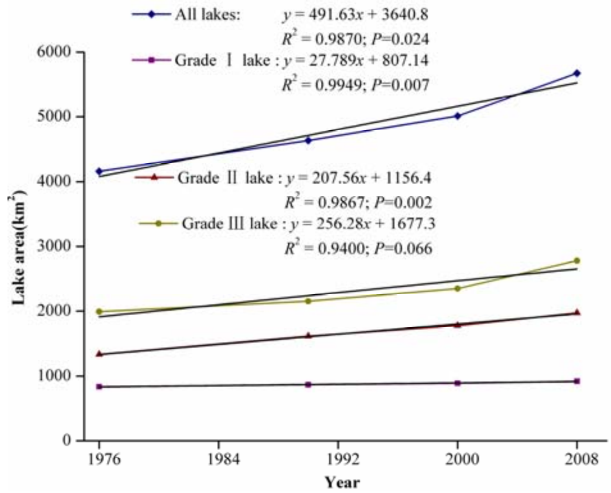

Figure 2 Area change trends of different lakes from 1976 to 2008.

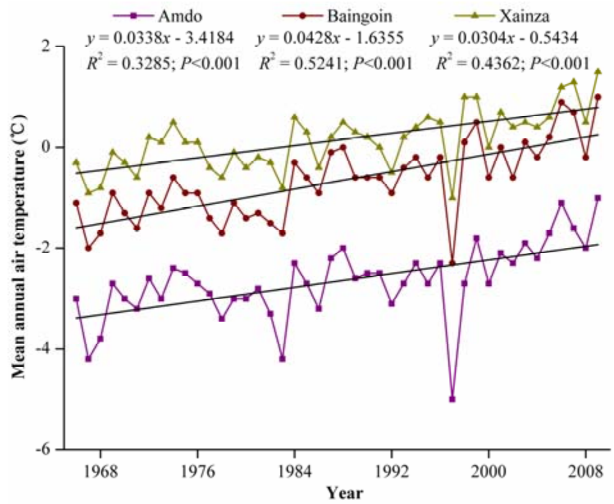

Figure 3 Mean annual air temperature at Xainza station, Baingoin station and Amdo station from 1966 to 2008.

Table 3 Area changes of Grade I, II, III lakes from 1976 to 2008

Year	Lake area(km²)			Lake area change (km²)			Change rate (%)		
	I	II	III	I	II	III	I	II	III
1976	833.51	1335.25	1991.62						
1990	866.08	1614.98	2152.84	32.57	279.73	161.22	3.91%	20.95%	8.09%
2000	888.04	1778.07	2346.23	21.96	163.09	193.39	2.54%	10.10%	8.98%
2008	918.82	1972.74	2781.44	30.78	194.67	435.21	3.47%	10.95%	18.55%

4.1.2 Changes in Precipitation

With certain fluctuations, the precipitations at Xainza, Baingoin, and Amdo stations from 1966 to 2008 showed slight upward trends (Figure 5) at a growth rate of 23.15, 28.62, and 14.26 mm/10a, respectively. Amdo station had the most precipitation among these stations, whereas Xainza station has experienced the greatest precipitation growth. All three stations exhibited evident seasonal variations in precipitation. Rainfall in summer was dominant but with large fluctuations ranging from 200 mm to 500 mm. Precipitations in winter were generally not more than 20 mm with minimal fluctuations.

The records at Xainza station indicated that precipitation rise in the hot season (23.73 mm/10a) was seven times faster than that in the cold season (3.77 mm/10a) (Figure 6). The increase in annual precipitation in the river basin was significantly relevant to the increase in the hot season.

4.2 Glacier changes

The glacier area sharply shrinks as high as 115.99 km^2 during nearly 30 years accounting for 45.83% of the total statistical area of 1976 at 3.51 $km^2 \cdot y^{-1}$. During 1976-1990, the glacier area decreases by 42.52% at 7.17 $km^2 \cdot y^{-1}$; during 1990-2000, the glacier area expands by 46.65% at 6.17 $km^2 \cdot y^{-1}$. During 2000-2008, the glacier area retreats by 76.24 km^2 at 8.47 $km^2 \cdot y^{-1}$. The change trend in time sequence is a model of ‘decreasing-increasing-decreasing’. Seen from space, the glacier changes are mainly at the snout. Jiagang glacier, the largest glacier in the study area, shrinks by 37.39 km^2 accounting for 35.5% during 1976-2008.

4.3 Response of Lakes to Climate Change

4.3.1 Overall Response

There are three meteorological stations of Xainza, Baingoin, and Amdo distributed around the study area. All the stations showed similar trends of the air temperature and precipitation. But the size of the air temperature and precipitation values differed slightly caused by differences in river basin, latitudes, and elevations. Only Xainza station located in the study area, in order to facilitate research, this paper chooses Xainza meteorological station data to analyze the response between lake changes and climate changes.

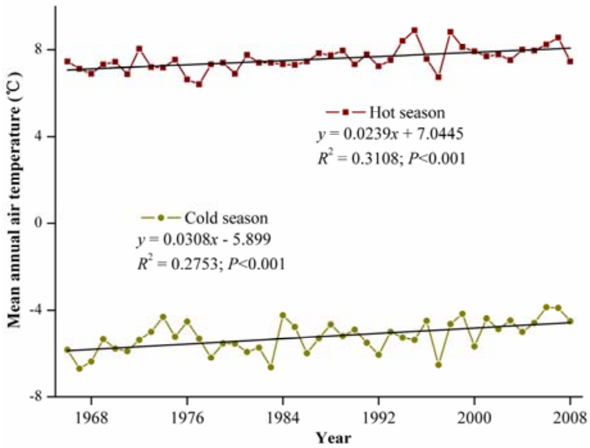

Figure 4 Mean annual air temperature in the cold and hot seasons at Xainza station from 1966 to 2008.

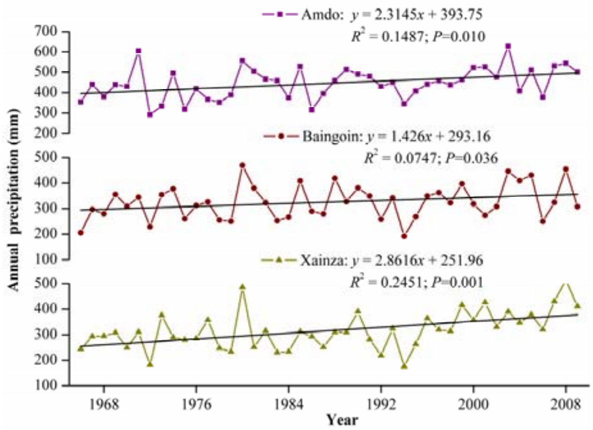

Figure 5 Precipitation at Xainza, Baingoin, and Amdo stations from 1966 to 2008.

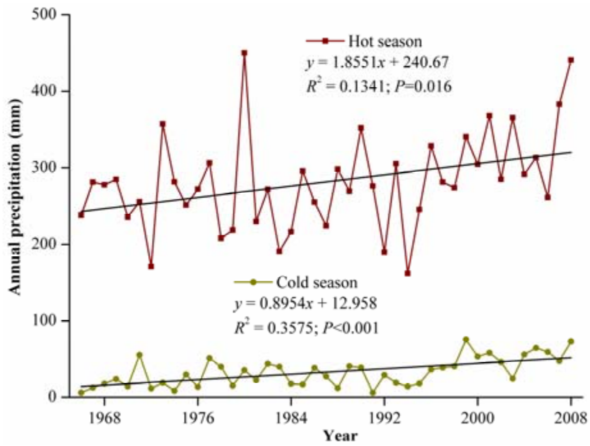

Figure 6 Precipitation in the cold and hot seasons at Xainza station from 1966 to 2008.

Considering the time series of the images, the mean air temperature and precipitation at Xainza station from 1976 to 1977, 1990 to 1992, 1999 to 2001, and 2007 to 2008 were selected as compared series, and the lake areas were regarded as the reference series (X_o, km^2) for GRA. The values of each series are given in Table 4.

The GRGs between lake areas and climatic factors during the four phases are given by

$\gamma(X_o,X_1)$ =0.7635, $\gamma(X_o,X_2)$=0.5922, $\gamma(X_o,X_3)$=0.6469, $\gamma(X_o,X_4)$=0.4520, $\gamma(X_o,X_5)$=0.3521

In descending order,

$$\gamma(X_o,X_1) > \gamma(X_o,X_3) > \gamma(X_o,X_2) > \gamma(X_o,X_4) > \gamma(X_o,X_5) \quad (6)$$

The results showed that among all the factors, mean air temperature and precipitation in the hot season were the two most dominant factors affecting lake areas.

4.3.2 Response of grade lakes

The areas of lakes with various grades were regarded as the reference series (Table 5). Similarly, mean air temperature and precipitation in the hot and cold seasons (Table 4) were the compared series for GRA to study the response of lakes with different grades to various climatic factors.

The results (Table 6) indicate that the GRGs of climatic factors varied for lakes with different grades. For Grade I lakes, air temperature (X_1 and X_2) was the major sensitive factor on the expansion of lake area. Meanwhile, glacial area decreased from 253.07 km^2 to 137.08 km^2 from 1976 to 2008 as result of continuous warming from 1976 to 2008. The shrinking glaciers and meltwater provided more recharges for the expansion of Grade I lakes. Meanwhile, the large Grade I lakes, such as Geren Co, continuously discharged into Grade II lakes. Therefore, although obtaining continuous supplies from meltwater, the expansion of Grade I lakes were steady and slight.

For Grade III lakes, mean precipitations in the hot season (X_3) were the major contributor to their expansion. The lake areas (2008) accounted for 36.2% of the Grade III lake study area, precipitation recharged lakes straightforwardly

Table 4 Series value of GRA

X	**1976**	**1990**	**2000**	**2008**
X_o: Lake areas (km^2)	4160.37	4633.89	5012.55	5673.01
X_1: Hot season mean air temperature (°C)	7.18	7.48	7.95	7.96
X_2: Cold season mean air temperature (°C)	-5.47	-5.48	-5.04	-4.39
X_3: Hot season precipitation (mm)	267.52	262.99	289.33	342.52
X_4: Cold season precipitation (mm)	21.74	28.04	39.85	54.05
X_5: Glacier areas (km^2)	253.07	145.46	213.32	137.08

Table 5 Reference series (*X*) of grade lakes (km^2)

Grade lakes	***X***	**Lake area (km^2)**			
		1976	**1990**	**2000**	**2008**
Grade I	X_0^1	833.51	866.08	888.04	918.82
Grade II	X_0^2	1335.25	1614.98	1778.07	1972.74
Grade III	X_0^3	1991.62	2152.84	2346.23	2781.44

Table 6 GRGs between grade lakes and compared series

Grade lakes	**$\gamma(X_o,X_1)$**	**$\gamma(X_o,X_2)$**	**$\gamma(X_o,X_3)$**	**$\gamma(X_o,X_4)$**	**$\gamma(X_o,X_5)$**
Grade I	**0.5616**	**0.5627**	0.5363	0.5172	0.3933
Grade II	**0.5716**	0.4582	**0.5664**	0.4242	0.3450
Grade III	**0.6606**	0.5327	**0.7570**	0.4990	0.3597

Notes: $\gamma(X_o,X_1)$, the GRG between hot season mean air temperature (°C) and lake areas (km^2); $\gamma(X_o,X_2)$, the GRG between cold season mean air temperature (°C) and lake areas (km^2); $\gamma(X_o,X_3)$, the GRG between hot season precipitation (mm) and lake areas (km^2); $\gamma(X_o,X_4)$, the GRG between cold season precipitation (mm) and lake areas (km^2); $\gamma(X_o,X_5)$, the GRG between glacier areas (km^2) and lake areas (km^2)

with minimal losses from runoff. Meanwhile, the annual evaporation has been decreasing gradually (the annual evaporation in the Tibetan Plateau decreases at 13.1 mm/10a) (Chen et al. 2006). Coupled with the rise in precipitation in the hot season over the last 40 years, the areas of Grade III lakes have been expanding. The mean air temperature in the hot season (X_1) was the second contributor to the expansion of Grade III lakes. On one hand, the permafrost around Grade III lakes was low-lying and thus had high water content. With air temperature rising, the permafrost melted to recharge lakes in the form of groundwater. On the other hand, the rising air temperature and increasing rainfall were interconnected, causing the Tibetan Plateau to develop a warm and humid climate.

Mean air temperature (X_1) and precipitation (X_3) in the hot season were two major factors affecting the changes in Grade II lakes. The recharges of Grade II lakes mainly depended on precipitation, surface runoff, and meltwater from permafrost. In the early periods, Grade III lakes were medium sized with numerous small lakes. The direct recharge from precipitation was relatively less. The indirect recharge greatly suffered from evaporation and leakage. The surface runoff was mainly from precipitation and discharge of Grade I lakes. Grade II lakes are located in the central of catchment, and their elevation were higher than that of Grade III lakes, such that the permafrost melted relatively slowly. Therefore, Grade II lakes expanded more slowly than Grade III lakes. The climatic factors in the hot season were the major factors affecting the expansion of all lakes regardless of grade, which was consistent with the overall response.

5 Conclusions

The response of lakes to climate is a complex crossfeed mechanism involving the physical, chemical, and biological lake properties. RS Lake area detecting is a fast, broad spatial coverage, long-term, and economical way to study the lake respond to climate-related changes. GRA is a useful tool to study the relationships of having incomplete running mechanism, lacking of behavior data, devoid of experience in treatment, being naked to inherent connotation. The meteorological data were divided into two groups according to the monthly air temperatures, namely cold season and hot season. GRA was carried out in response to the lake area change with climate change. The overall response results show that, the temperature rise and precipitation increase in hot season are the main factors of lake area expansion in Xainza watershed from 1976 to 2008. At the same time, due to the different hydrographic features, the lake area has different changes within the same watershed. So the point of view of lake classification is put forward. The response of grade lake area to climate shows that the GRGs of the climate series varied for different grade lake. The GRGs of air temperature and precipitation in the hot season to lake area have a clear rule: Grade III lakes maximum, Grade II lakes followed, Grade I lakes minimum. And the other compared series with a slight difference in different grade lakes.

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