Glacier and lake variations in the Yamzhog Yumco basin, southern Tibetan Plateau, from 1980 to 2000 using remote-sensing and GIS technologies

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ABSTRACT. Glacier and lake variations in the Yamzhog Yumco basin in southern Tibet were studied by integrating series of spatial data from topographic maps and Landsat images at three different times: 1980, 1988/90 and 2000. The results indicate that the total glacier area has decreased from 218 km^2 in 1980 to 215 km^2 in 2000, a total reduction of 3 km^2 (i.e. a 1.5% decrease). Glacier recession rates were clearly larger in the 1990s than the 1980s due to the warmer climate. The total lake area decreased by about 67 km^2 during 1980–90 and increased by 32 km^2 during 1990–2000. It is suggested that change of lake area in the basin was rapid and most likely caused primarily by the change in precipitation and evaporation in the basin, and secondarily by the increased water supply from melting glaciers.

INTRODUCTION

Extensive studies have been made on alpine glacier variations in high Asia over the last few decades (e.g. Mayewski and Jeschke, 1979; Fujita and others, 2006), and revealed that glacial retreat has occurred widely and asynchronously across the Tibetan Plateau. Under a warmer climate in the future, melting of glaciers will be accelerated in continental regions (Dyurgerov, 2002). As a result, the hydrological systems may be altered significantly; such hydrological events as floods from glacier lakes may cause hazards in mountain regions. Basins located in different regions will experience different impacts of variability in the climate (Chiew and others, 1995). Studying spatial and temporal covariations of glaciers and lakes will help us understand the impact of climate change within a basin in Tibet (Shi and Ren, 1990).

The Yamzhog Yumco ('co' is the Tibetan word for 'lake') is the largest existing inland lake (Liu, 1995) on the northern foot of the Himalaya in southern Tibet (Fig. 1), located in Nagarzê county at more than 4400 m a.s.l. Terraces on the lake shore are well developed, indicating a larger lake area in the past. There are many lakes around the Yamzhog Yumco, constituting a closed drainage basin (hereafter referred to as the Yamzhog basin) with an area of 8840 km^2. The average annual precipitation was 373 mm at Nagarzê station (4432 m a.s.l. in the northwest of Yamzhog basin) during 1961–75 (Guan and others, 1984). This paper presents areal variations of glaciers and lakes in the Yamzhog basin by means of geographical information system (GIS) and remote-sensing (RS) techniques in order to provide some ideas about the impact of climate change on glaciers and lakes in high-altitude basins on the Tibetan Plateau.

METHODOLOGY

We use four scenes of Landsat images of 137/40 and 138/40 path/row, including Thematic Mapper (TM) on 1 November 1988 and 14 November 1990 (1988/90), i.e. a mosaic image of 2 years to cover the entire basin, and Enhanced TM Plus
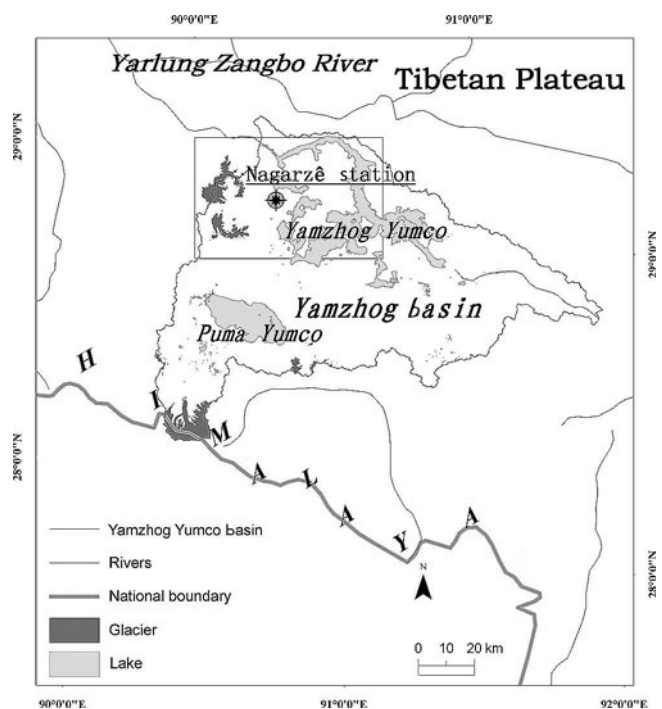
Fig. 1. Map of Yamzhog basin and the surroundings in the Tibetan Plateau. The rectangle indicates the area shown in Figure 2.
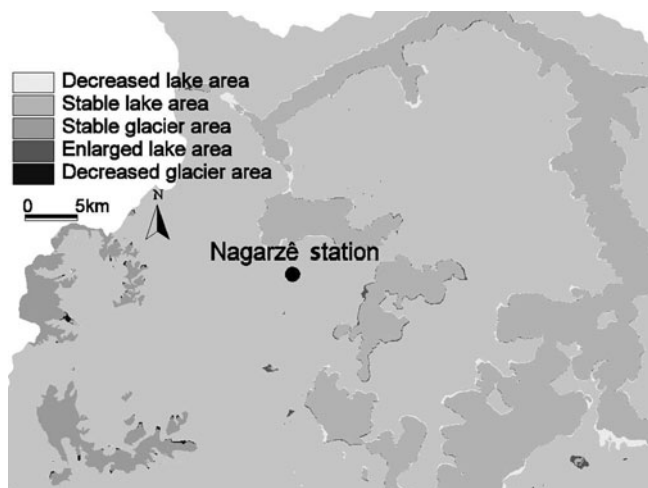
Fig. 2. Variations in areas of glaciers and lakes in Yamzhog basin, 1980–2000.

(ETM+) on 17 November and 28 December 2000. We also use topographic maps at a 1:50 000 scale (about ±25 m accuracy) in 1980 and available digital elevation model (DEM) data (DEM25, cell size: 100 m) which come from digitization of the 1:250 000 topographic map with contour interval of 100 m to ortho-rectify all the digital satellite images. The accuracy of ortho-rectification is within one image pixel. The co-registration errors for all ortho-images to the 1:50 000 scale topographic maps were within one image pixel, i.e. 25 m. Glaciers and lakes on the 1:50 000 scale topographic maps and sequential Landsat images were mapped in the false-color image by on-screen digitizing with manual delineation using Arc/Info software. The accuracy of manual digitization was controlled within one pixel. Changes in the extent of glacier/lakes in the Yamzhog basin were measured with an uncertainty of ±0.015 km^2. For detailed methods of analyses and error estimates, refer to Ye and others (2006b).

It should be noted that all images used were taken in winter (November or December). However, because there was very little winter precipitation in the basin (the average winter precipitation was about 5 mm at Nagarzê station during 1980–2000), there was no substantial seasonal snow cover present to affect the image interpretation.

RESULTS

Calculating glacier and lake areas from classification of digital images in the Yamzhog basin from 1980 to 2000, we determined that the total glacier and lake areas in 1980 were 218 km^2 and 1072 km^2, or 2.5% and 12.1% of the total basin area, respectively. Changes in area of glaciers and lakes from 1980 to 2000, determined using the hybrid-grid method (Ye and others, 2006b), are summarized in Table 1 and Figure 2. The total glacier recession was about 3 km^2 (or 0.15 km^2 a^{-1} on average), and no advancing glaciers were recognized in the basin during this period. Glacier recession accelerated from 0.11 km^2 a^{-1} in the 1980s to 0.18 km^2 a^{-1} in the 1990s (Table 1).

Lake variations in the the Yamzhog basin in the last 20 years were more complicated than glacier variations. From the data shown in Table 1, we know that the lake area decreased by 67.39 km^2 in total (from 1980 to 1988/90 with lake shrinkage amounting to 76.02 km^2 and lake growth to 9.63 km^2), then it increased by 31.58 km^2 in total (from 1988/90 to 2000 with lake shrinkage amounting to 11.13 km^2 and lake growth to 42.71 km^2). About 32.58 km^2 of lake area (about 3.0% of the total lake area in the basin) disappeared during 1980–90 but re-emerged during 1990–2000. It seems that reduction in lake area had greatly decreased (from 4.34 km^2 a^{-1} in the 1980s to 0.71 km^2 a^{-1} in the 1990s) while enlargement rate increased by a factor of almost two (from 0.51 km^2 a^{-1} in the 1980s to 1.01 km^2 a^{-1} in the 1990s). Although lake enlargement in the 1990s did not compensate for the lake reduction in the 1980s, the enlargement trend seems to be in accordance with continuously accelerating glacier recessions in the basin.

DISCUSSION AND CONCLUSIONS

We now examine glacier and lake variations in the context of meteorological data from Nagarzê station during 1980–2000. Figure 3a and b show time series of average summer air temperature (for April through October where monthly mean temperature is above 0°C) and the annual precipitation in the basin (P_a). It is noted that the temperature shows

Table 1. Changes in glacier area and lake area in Yamzhog basin, 1980–2000

Category of variation	Area	Percentage change	Change rate	Percentage change rate
	km^2	%	km^2 a^{-1}	% a^{-1}
Quasi-stable lake area	988.85	7.76	4.16	0.39
Lake that decreased in 1980s but re-emerged in 1990s	32.58	3.04	3.26	0.30
Lake that enlarged in 1980s but decreased in 1990s	4.00	0.37	0.40	0.04
Decreased lake area in 1980s	*43.44*	*4.05*	*4.34*	*0.41*
Decreased lake area in 1990s	*7.13*	*0.71*	*0.71*	*0.07*
Enlarged lake area in 1980s	5.63	0.52	0.56	0.05
Enlarged lake area in 1990s	10.13	1.01	1.01	0.10
Decreased glacier area in 1980s	*1.14*	*0.52*	*0.11*	*0.05*
Decreased glacier area in 1990s	*1.84*	*0.85*	*0.18*	*0.08*
Quasi-stable glacier area	214.96	1.60	0.18	0.08
No change background	7525.51			
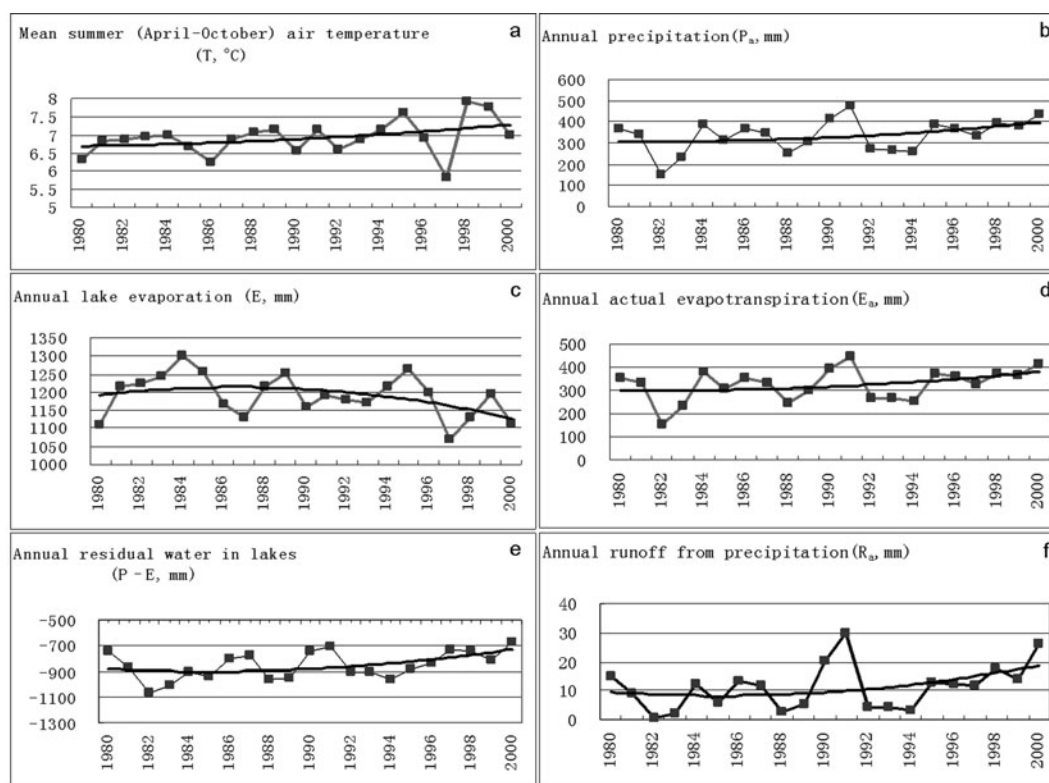
Fig. 3. (a) Mean summer (April–October) air temperature (T, °C); (b) annual precipitation (P_a, mm); (c) annual lake evaporation (E, mm); (d) annual actual evapotranspiration in the basin (E_a, mm); (e) annual residual water in lakes ($P - E$, mm); and (f) annual runoff from precipitation (R_a, mm). Data were obtained at Nagarzê station on the Tibetan Plateau. Solid curves indicate trends fitted by polynomial during the period.

a slight increasing trend and the precipitation a clear increasing trend since 1980.

The hydrological factors involved in lake changes are potentially quite complicated. The water balance of the lake can be described as

$$\Delta W = P + R - E + \delta \qquad (1)$$

$$R = R_a + R_g, \qquad (2)$$

where ΔW is the change of water stored in the lake, P is annual lake precipitation, E is annual lake evaporation (Fig. 3c), which was obtained by multiplying annual evaporation rate measured daily with a 20 cm evaporation pan, by a factor of 0.6, R is the runoff entering the lake consisting of R_g (i.e. runoff from glacier melting) and R_a (i.e. runoff from precipitation, roughly estimated by $R_a = P_a - E_a$) and δ is a factor due to the other effects (e.g. melting water from frozen grounds, human activities, etc.). Actual terrestrial evapotranspiration of the basin (E_a, Fig. 3d) is calculated using P_a, and potential evapotranspiration in the basin (ET) by the Bagrov model (Bagrov, 1953). Owing to the data availability in the study area, we assume $P_a = P$ and ET $= E$. Units of all parameters in Equations (1) and (2) are mm.

Figure 3e indicates that, during the past two decades, $P - E$ (i.e. vertical water flux) for all lakes tended to increase from about –905 mm in the 1980s to –815 mm in the 1990s as a result of an increase in precipitation (Fig. 3b) and a slight decrease in lake evaporation (Fig. 3c). As shown in Figure 3f, the annual runoff from precipitation (R_a) increased from an average of about 8 mm in the 1980s to 14 mm in the 1990s, and it reached 26 mm in 2000.

According to Equation (2), the melting of glaciers may also contribute to changes in the lakes because of increasing runoff from glaciers (R_g). In the Yamzhog basin, the glacier area occupies less than 2.5% and did not change much from 1980 to 2000 (Table 1), so it seems unlikely to have been the primary reason for such a great change in the lake area in the basin (the lake occupies 12% area in the basin). However, it should be noted that the effects of glacier recession on lake changes may manifest differently because of the different lake locations and sizes. For smaller lakes near to the glaciers, glacier recessions may result in more obvious changes in lake area than they do for larger lakes far from the glaciers. This contention was supported by our results shown in Figure 2, where some western smaller lakes tended to enlarge corresponding to more remarkable glacier recessions at the terminus in the western part of the Yamzhog basin. The lake area decreased in the east of the basin, where some smaller lakes have totally disappeared.

Therefore, the lake decrease in the Yamzhog basin in the 1980s was most likely due to the larger negative value of $P - E$ and the decreased value of R_a, whereas the enlargements of lakes in the 1990s may have resulted from the less negative $P - E$ and increased R_a along with the effect of water from enhanced melting of glaciers (R_g). Despite the observations above, the precise reasons for lake shrinkage in the Yamzhog basin have not yet been identified quantitatively because of the shortage of regional in situ hydrological data for the study of water balance in the basin (e.g. runoff from melting glaciers, water-level variations of lakes, etc.). Our work has focused on variations in area of glaciers and

lakes, and (owing to lack of bathymetric data) did not include variations in either lake level or glacier-surface elevation, which would be necessary to extract the information on ice volume and water mass variations.

Our results show that both glacier and lake areas in the Yamzhog basin decreased from 1980 to 2000. Decreases in glacier area during the two decades were not significant; lake areas shrank by 67 km^2 in the 1980s, while almost half of that (33 km^2, about 3% of the total lake area in the basin) re-emerged in the 1990s. This finding indicates that the lake changes occur over a wider range and more rapidly than the glacier changes. The 1.36% (or 0.07% a^{-1}) decrease in glacier area in this basin was not dramatic compared with the 0.18% a^{-1} mean glacier recession across China since the 1960s (Yao and others, 2004) and the 0.31% a^{-1} mean glacier recession in the Naimona'nyi region of the western Himalaya during 1976–2003 (Ye and others, 2006a).

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