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A half-century of changes in China's lakes: Global warming or human influence?

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[1] Lake size is sensitive to both climate change and human activities, and therefore serves as an excellent indicator to assess environmental changes. Using a large volume of various datasets, we provide a first complete picture of changes in China's lakes between 1960s–1980s and 2005–2006. Dramatic changes are found in both lake number and lake size; of these, 243 lakes vanished mainly in the northern provinces (and autonomous regions) and also in some southern provinces while 60 new lakes appeared mainly on the Tibetan Plateau and neighboring provinces. Limited evidence suggested that these geographically unbalanced changes might be associated primarily with climate change in North China and human activities in South China, yet targeted regional studies are required to confirm this preliminary observation. **Citation:** Ma, R., H. Duan, C. Hu, X. Feng, A. Li, W. Ju, J. Jiang, and G. Yang (2010), A half-century of changes in China's lakes: Global warming or human influence?, *Geophys. Res. Lett.*, *37*, L24106, doi:10.1029/2010GL045514.

1. Introduction

[2] Lakes are affected by both climate change and human activities, therefore serving as important indicators of climate/anthropogenic forcing and regional responses. China has a large number of lakes with rich cultural, ecological, and economic importance. These include a large group of lakes in the Tibetan Plateau known as "the roof of the world" and "the third pole".

[3] China's first nationwide lake investigation consisted of multiple surveys between the 1960s and 1980s, which showed 2,928 lakes with an area of >1 km^2, covering a total area of 91,020 km^2 [*Wang and Dou*, 1998; *Ministry of Water Resources of the People's Republic of China* (*MWR*), 1998]. Over recent decades, human activities and climate change have driven complex physical and ecological changes to China's inland water bodies, yet information on such changes is scattered and incomplete. Here, using a large volume of geographical datasets from various sources and extensive efforts to calibrate and validate the data products, we examine variations in the number and size of China's lakes (>1 km^2 in this study) between 1960s–1980s and 2005–2006, with the latter period representing the most recent status after rapid development and industrialization since the 1980's. Our objective is to provide the first comprehensive view of decadal-scale lake changes, which may be used to examine how climate change and human activities may have affected lakes in the entire China.

2. Data and Methods

[4] Data used for 2005–2006 mainly included: (1) CBERS CCD satellite images (20 m pixel resolution, n = 10494, 2004–2008); (2) Landsat TM/ETM+ satellite images (30 m resolution, n = 510, 1999–2000); (3) digitalized maps (n = 6843, 1960–1980) with scales of 1:100 000 (30 m resolution, n = 3946) and 1:50 000 (15 m resolution, n = 2897); (4) a digitalized topographic map in 2000 (1:250 000 or 75 m resolution) of inland water distribution (rivers, lakes, and reservoirs, etc.). In addition, information from Google-Earth, hydro-meteorological records, published literature and field investigations were used to help delineate lake boundaries. A series of semi-objective tests (see auxiliary material) was conducted to assure the quality of this heterogeneous dataset (>24,000 images/maps in total), including screening clouds and excluding reservoirs and data where anomalous rainfall or drought conditions could induce errors in assessing changes.[1] All images were geo-rectified to an Albers Equivalent Conical Projection, with RMS uncertainties <1.5 pixel.

[5] Topography, dry/wet conditions, and administrative provinces were used to define 5 geographic zones [*Wang and Dou*, 1998] (Figure 1). The TPL and IMXL zones are generally considered as parts of internal drainage systems with enclosed lagoons or salt lakes in arid or semiarid climate. Located in the Asian monsoon climate zone, the other three zones (NPML, YGPL, EPL) are characterized by abundant rainfall with out-flowing freshwater lakes, and these zones belong to external drainage systems. For each of the 5 zones, lake boundaries were determined using a set of universal rules and zone-specific rules during the periods where water levels were stable [*Ma et al.*, 2010]. Other measures, including literature review, field survey, and interviews with local experts were used to quality control and validate the results. The final definitive lake boundaries were delineated and used to calculate lake areas, and then compared with historical baseline data to determine changes. These baseline data include the *Chinese Lake Catalogue*

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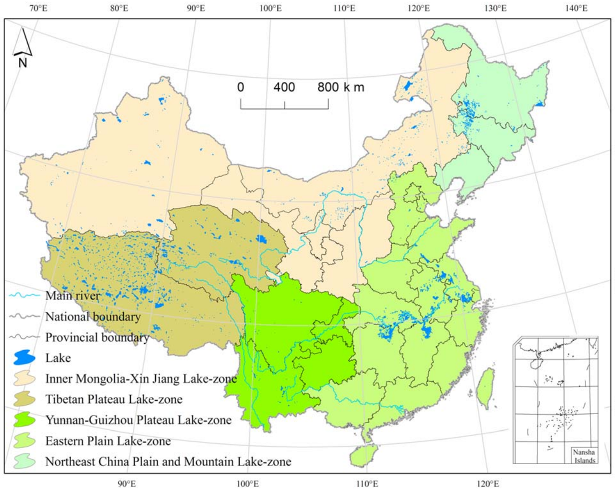

Figure 1. Five geographic lake zones in China [*Ma et al.*, 2010]. These are [*Wang and Dou*, 1998] (1) the Tibetan Plateau Lake Zone (TPL) covering Qinghai Province and Tibet Autonomous Region; (2) the Yunnan-Guizhou Plateau Lake Zone (YGPL) covering Yunnan, Guizhou and Sichuan provinces and Chongqing Municipality; (3) the Inner Mongolia-Xinjiang Lake Zone (IMXL), covering Inner Mongolia, Xinjiang Uygur and Ningxia Hui autonomous regions, and Gansu, Shaanxi and Shanxi provinces, (4) the Northeast Plain and Mountain Lake Zone (NPML) covering Liaoning, Jilin and Heilongjiang provinces, and (5) the Eastern Plain Lake Zone (EPL) covering Shanghai, Beijing and Tianjin Municipalities, Hong Kong and Macao special administrative regions, and Taiwan, Jiangxi, Hunan, Hubei, Anhui, Henan, Shandong, Zhejiang, Jiangsu, Hainan, Fujian, Guangdong and Guangxi provinces. The inset in the lower right corner shows the Nansha Islands of China.

[*Wang and Dou*, 1998], *Code for China Lakes Name* (*No. SL261-98*) [*MWR*, 1998], *Lake Resources in China* [*Wang*, 1989], *Water Resources of Lakes in China* [*Wang*, 1987], and the 1964 topographic maps (1:100 000).

3. Results

[6] Dramatic changes are found in both lake number and lake size between 1960s–1980s and 2005–2006. Total number of lakes (area >1 km^2) decreased from 2928 to 2693 (by 8%). Of the 2693 present lakes, there are 39%, 24%, 19%, 16%, and 2% in the 5 lake zones (TPL, EPL, IMXL, NPML, and YGPL), respectively. The 8% decline is the net effect of vanished lakes, lakes shrunk to <1 km^2 (not used in our statistics), lakes enlarged to >1 km^2, newly formed lakes, and newly discovered lakes. Associated with this decline is the 12527 km^2 or 13% reduction in surface area. 60 new lakes (558 km^2) appeared and 243 lakes (7983 km^2) vanished in the last 50 years, respectively. To facilitate an analysis of these trends, we categorized all lakes into five classes: (A) >1000 km^2, (B) 500–1000 km^2, (C) 100–500 km^2, (D) 10–100 km^2 and (E) 1–10 km^2. In summary, there are 254 lakes downgraded in class (1 from A to B, 1 from A to C, 1 from B to D, 8 from C to D, 3 from C to E, 40 from D to E, 4 from D to <1 km^2, 196 from E to <1 km^2) and 98 lakes upgraded (1 from B to A, 1 from C to B,14 from D to C, 2 from E to C, 80 from E to D).

[7] Geographically, there is a clear difference in lake changes between North China and South China. Most of the 254 shrunk lakes and 243 vanished lakes are in the IMXL and EPL zones (Figure 2a). Most enlarged and new lakes, in contrast, are in the TPL zone. Correspondingly, similar changes in lake areas (decreased, vanished, increased, or area from new lakes) are also found in these zones (Figure 2b). The class-downgraded lakes are largely restricted to the northern provinces (and autonomous regions) in the IMXL and to a smaller extent in the middle and lower reaches of the Yangtze River in the EPL. The Inner Mongolia Autonomous Region had 79 lakes downgraded in class. Large reductions in lake areas also occurred in Heilongjiang (30), Xinjiang (26), Hubei (24), Qinghai (16), Tibet (15), and Jilin (15) in the north as well as in Jiangsu (10), Anhui (9), Hunan (8) in the south. A similar geographical distribution was also observed on the reduction in lake numbers. Half of the vanished lakes were in the northern autonomous regions of Xinjiang (62) and Inner Mongolia (59) in the IMXL. A large reduction in lake number also occurred in Hubei (55), Jiangsu (11), Anhui (10), Jiangxi (10), Hunan (9) and Hebei (9) in the middle and lower reaches of the Yangtze River and also in the EPL. Most of these vanished lakes had original sizes of <10 km^2, while the largest, the Lop Nur (Xinjiang), had an original surface area of 5500 km^2. At present, the maximal size of these downgraded lakes, after shrinking, is 930 km^2, followed by 139 km^2.

[8] The uneven geographic distributions of changes in lake number and lake size appear to be driven by both climate change and human activities. The shrunk and vanished lakes mainly occurred in North China and in the middle and lower reaches of the Yangtze River (Figures 3a and 3b). North China, especially Xinjiang and Inner Mongolia with much lower GDP than in South China (e.g., a GDP of RMB 4.0×10^{11} in Xinjiang in 2009 but 33.5×10^{11} in Jiangsu), is characterized by an arid and sub-arid climate (232.5 mm annual precipitation in 1961–1990 [*Yang et al.*, 2003]) and high annual total solar radiation (5384 MJ/m^2 between 1961–2000 [*Xie and Wang*, 2007]). Air-temperature records indicate a warming trend beginning in the 1950s with an abrupt change in the mid- and late-1980s, resulting in an average annual increase of 0.0221°C for 1951–2000 [*Guo et al.*, 2005], accompanied with mean annual potential evaporation of 2205.6 mm during 1961–1990 [*Yang et al.*, 2003]. In addition, agriculture in the arid and sub-arid areas such as Xinjiang mainly benefits from irrigation [*Zhang et al.*, 2006] and the effective irrigated land area has been continuously increasing [*Liu et al.*, 2006]. The irrigation water comes from those endorheic lakes or upper reaches of their inflow rivers. For example, Taitema Lake (Xinjiang), a typical endorheic lake, is located at the end of the Tarim River, which is the only inflow water source for this lake since 1952 when a dam was established in the upper reach. After 1952, agriculture activities in the upper and middle reaches of the Tarim River resulted in annual runoff reduced from 49.8×10^8 m^3 in 1957 to 1.65×10^8 m^3 in 1977 at Alaer, without effective runoff at Yingsu near the Taitema Lake. These activities completely dried Taitem Lake in 1977 [*Wang and Dou*, 1998]. In 2001, water was transported from Bosten Lake to Taitema Lake through the Tarim River [*China Water Resources Newspaper*, 2002]. As a result, Taitema Lake appeared again with a surface area of about 98 km^2. Therefore, human (agricultural) activities

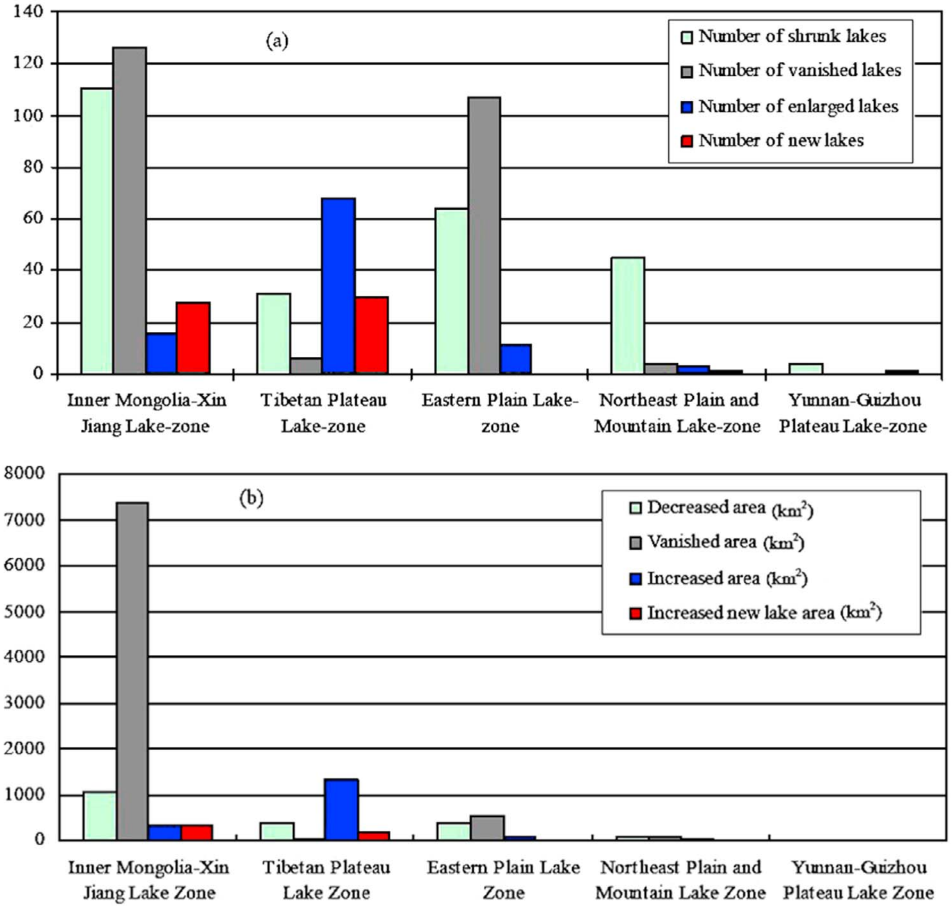

Figure 2. (a) Changes in lake numbers in the 5 lake zones; (b) changes in lake areas in the 5 lake zones. There are no vanished or enlarged lakes in YGPL.

may have also played a role in affecting lake changes. In contrast, in the humid South China, annual warming (0.008°C) was much weaker than in Northeast China (0.046°C) in the past 50 years [*Wang et al.*, 2003], while the effectively irrigated land area has been continuously decreasing [*Liu et al.*, 2006]. The loss of lake area in South China is therefore likely to be attributable to lake reclamation, expansion of lake-side development and enclosures, as shown in the satellite images and field surveys. For example, the provinces around the middle and lower reaches of the Yangtze River, with an annual precipitation of 1300 mm [*Mei and Yang*, 2005] and an annual warming of 0.018°C in the past 50 years [*Wang et al.*, 2003], have experienced significant economic growth (33.8% per year GDP) over the last decade, associated with over-exploitation of lake resources. The number of vanished lakes in this area accounts for 40% of the total loss in China. Of this loss, 95% is due to the reclamation or expansion of lake-side development and enclosures. Among the lakes in this area, 251 lakes (1285 km^2) are still being enclosed and reclaimed, accounting for 42% (6% in area) of the total lakes. About half of the 251 lakes are in Hubei (120), followed by Jiangsu (45), Hunan (41), Anhui (25), Jiangxi (11), Zhejiang (7), and Shanghai (2).

[9] New lakes and enlarged lakes were mainly confined to the plateau subfrigid zone in the western provinces and autonomous regions, where modifications in lake size can be linked to changes in snow and ice cover. Increases in lake size mainly occurred on the Tibetan Plateau and in the northern Inner Mongolia and Xinjiang (Figure 3c). New lakes (>1 km^2) also appeared in the Tibet Autonomous Region and Inner Mongolia (Figure 3d). These changes may be linked to climate change over the past three decades, when the areas at altitudes above 4,000 m have warmed 0.3°C per decade, which is twice the rate of observed global warming [*Xu et al.*, 2009]. Similarly, glaciers on the Tibetan Plateau have been melting at an accelerating, alarming rate over the past decade [*Xu et al.*, 2009; *Yao et al.*, 2004], leading to increases of water resources [*Yao et al.*, 2004; *Kehrwald et al.*, 2008] and consequently resulting in increases in the number and size of glacially fed lakes in Tibet, especially in valleys, marshes, glacier tips and intermountain hollows. For example, Selin Co (88.99°E, 31.81°N) [*Bian et al.*, 2010], the largest salt water lake in Tibet at present, is located in the glacier-rich Northern Tibet. With abnormal warming since the 1980s, there appears a decreasing trend in annual snow accumulation and accelerated glaciers melting, leading to increased lake area of Selin Co (Figure 4). Increased surface ponding or small lakes in the warming permafrost environments was driven primarily by slumping and collapsed terrain features that were subsequently filled with water [*Smith et al.*, 2005]. In contrast to this regional

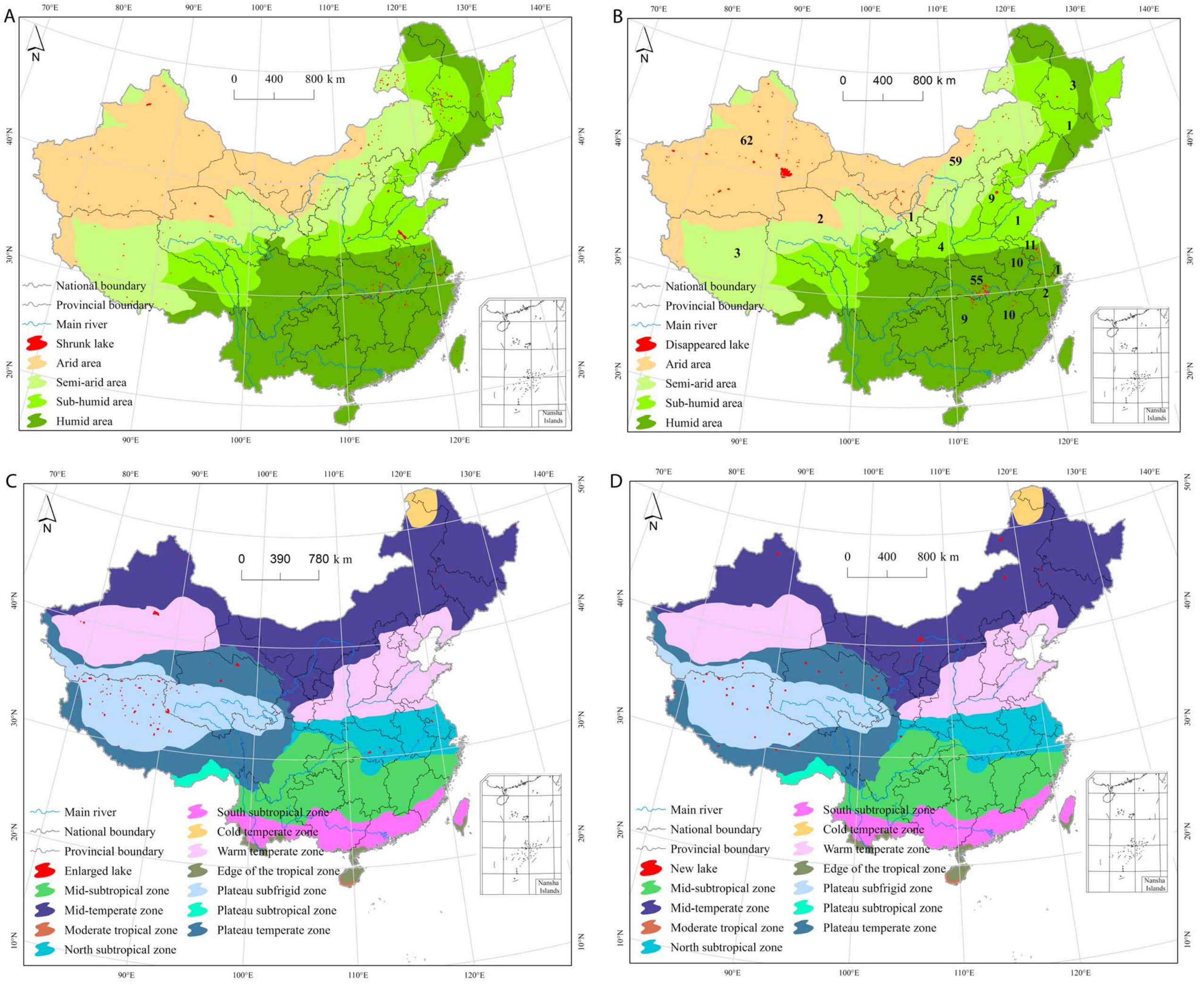

Figure 3. Spatial distribution of (a) downgraded lakes in size, (b) vanished lakes (c) enlarged lakes in size, and (d) new lakes between 1950s–1980s and 2005–2006. The inset in the lower right corner shows the Nansha Islands of China.

setting, new lakes in Inner Mongolia were located in the oasis areas where groundwater was attributed to the formation of new lakes. The groundwater may come from: (a) local rainfall [*Yang*, 2006], (b) the surrounding Yabulai Mountain through a phreatic aquifer [*Gates et al.*, 2008], (c) some remote regions, for example, ice-snow melt water from the Qilian Mountains, lake water in the Tibetan Plateau through deep fracture zone [*Chen et al.*, 2004], or Heihe River leakage in the Jinta-Dingxin Basin along the west-east Altyn Tagh fault [*Ding and Wang*, 2007].

[10] We want to emphasize that the findings that the geographically unbalanced changes in lake numbers and sizes might be attributed to different reasons (i.e., climate change in North China and human activities in South China) are based on limited evidence and therefore preliminary. Indeed, as shown above, human activities such as agricultural irrigation also played a role in affecting the lakes in North China. Likewise, localized weather events affecting lake size in South China might also be due to climate variability. Due to data availability, the study here only used data in 2005 and 2006 to represent the current decadal-scale status (number and sizes) of lakes. This simplification might induce some short-term uncertainties for areas where lake dynamics is very sensitive to climate variability. However, these potential uncertainties may have little effect on the objective of this work, which is to provide a large picture of the current situation of China's lakes as well as their cumulated changes in the past half century, which may be used to assess future changes. The exact reasons of the changes at any regional scale, on the other hand, still require targeted research to reveal.

4. Conclusions

[11] Over the last half century, dramatic changes occurred to China's 2928 lakes (>1 km^2 in size), where 243 lakes vanished, 60 new lakes appeared, 254 lakes were downgraded in class, and 98 lakes were upgraded in class. These observed changes are geographically unbalanced. Limited environmental data suggested that such unbalanced changes might be primarily attributed to climate change in North China and human activities in South China, respectively. However, targeted regional studies are required to confirm this preliminary observation. With China's continuous economic growth since the 1980s, these changes are expected to continue in the coming decades. The results

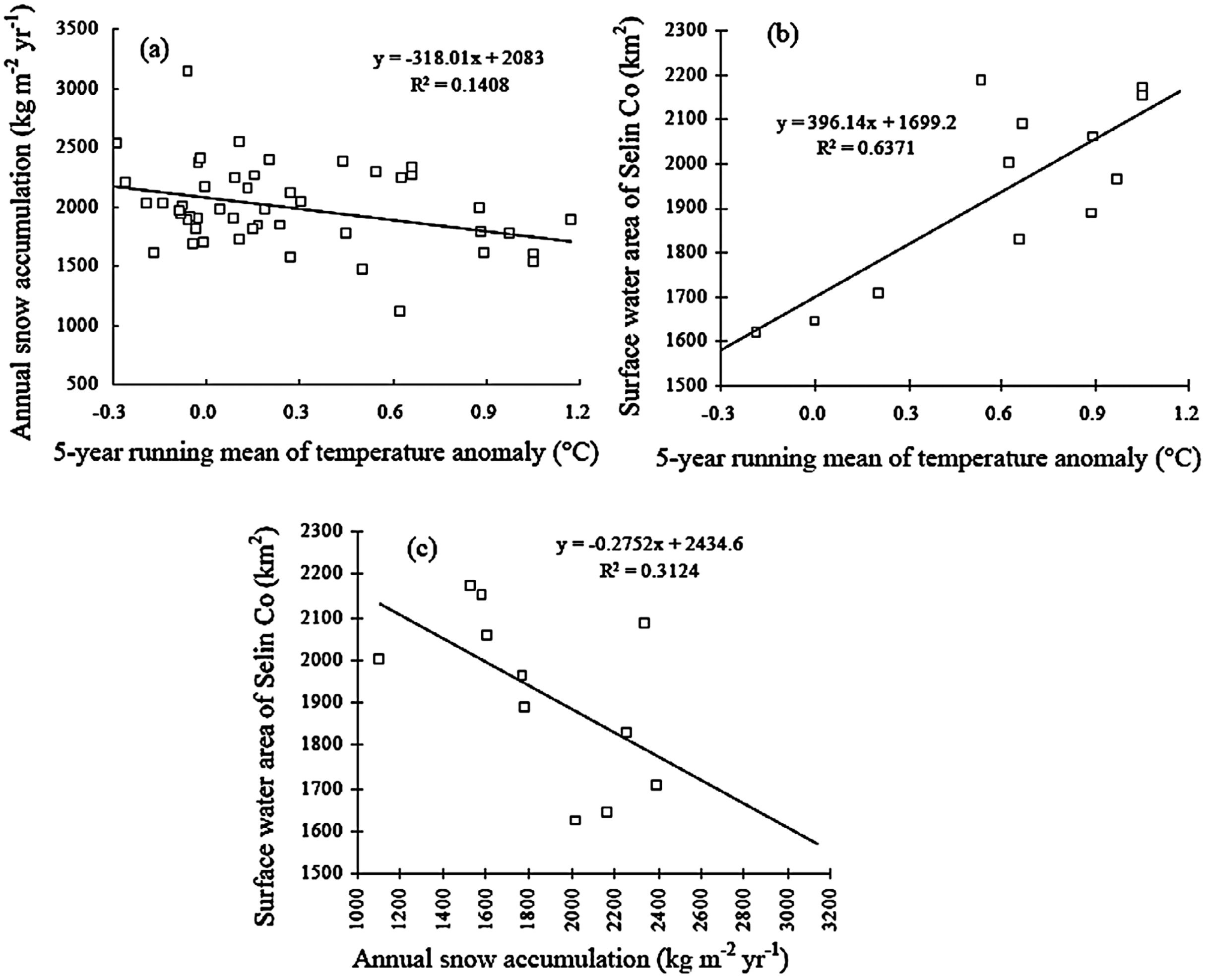

Figure 4. (a) Annual snow accumulation during 1956–2006 [*Xu et al.*, 2009] and (b) lake size of Selin Co [*Bian et al.*, 2010] are highly correlated with 5-year running mean of temperature anomaly; (c) lake size of Selin Co [*Bian et al.*, 2010] is also highly correlated to the annual snow accumulation [*Xu et al.*, 2009].

shown here provide the first complete view of lake changes in the entire China, which may serve as baseline data to perform periodic re-assessment of lakes in order to understand the water environment of China in a changing climate.

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