



## Short Communication

## A robust but variable lake expansion on the Tibetan Plateau

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Lakes on the Tibetan Plateau (TP) are an indicator and sentinel of climatic changes [1]. We extended lake area changes on the TP from 2010 [2] to 2018, and provided a long and dense lake observations between the 1970s and 2018. We found that the number of lakes, with area larger than 1 km<sup>2</sup>, has increased to ~1,400 in 2018 from ~1,000 in the 1970s. The total area of these lakes decreased between the 1970s and ~1995, and then showed a robust increase, with the exception of a slight decrease in 2015. This expansion of the lakes on the highest plateau in the world is a response to a hydrological cycle intensified by recent climate changes [3].

The TP in central Asia, defined here as land with elevation greater than 2,500 m a.s.l. [4], has an area of  $\sim 3 \times 10^6$  km<sup>2</sup>. It has a mean elevation of approximately 4,000 m a.s.l. and is composed of twelve great river basins (Fig. 1a). The TP and its surroundings are sometimes referred to as the “Third Pole of the Earth” after the Arctic and Antarctic, or as the “Water Tower of Asia”; a reference to the water resources contained in its great rivers, glaciers and lakes. Half of China’s total number and area of lakes are in the TP, and these lakes are currently undergoing a natural evolution driven by climate and cryosphere changes [5,6].

Lake changes on the TP have attracted a great deal of attention from hydrological, atmospheric and cryospheric researchers, and an expanding area, rising levels and increasing water volumes have been observed from space [7]. Landsat series satellites and radar/laser altimetry have been successful tools for monitoring lake area and level changes, respectively. These observations indirectly imply how climate and cryosphere changes have occurred on the plateau. An inventory of lakes revealed that there were ~1,200 lakes, with area greater than 1 km<sup>2</sup>, in the TP in 2010, with a total area of  $\sim 4.7 \times 10^4$  km<sup>2</sup> [2]. There was a slight decrease of the total lake area between the 1970s and ~1990, but a rapid increase in

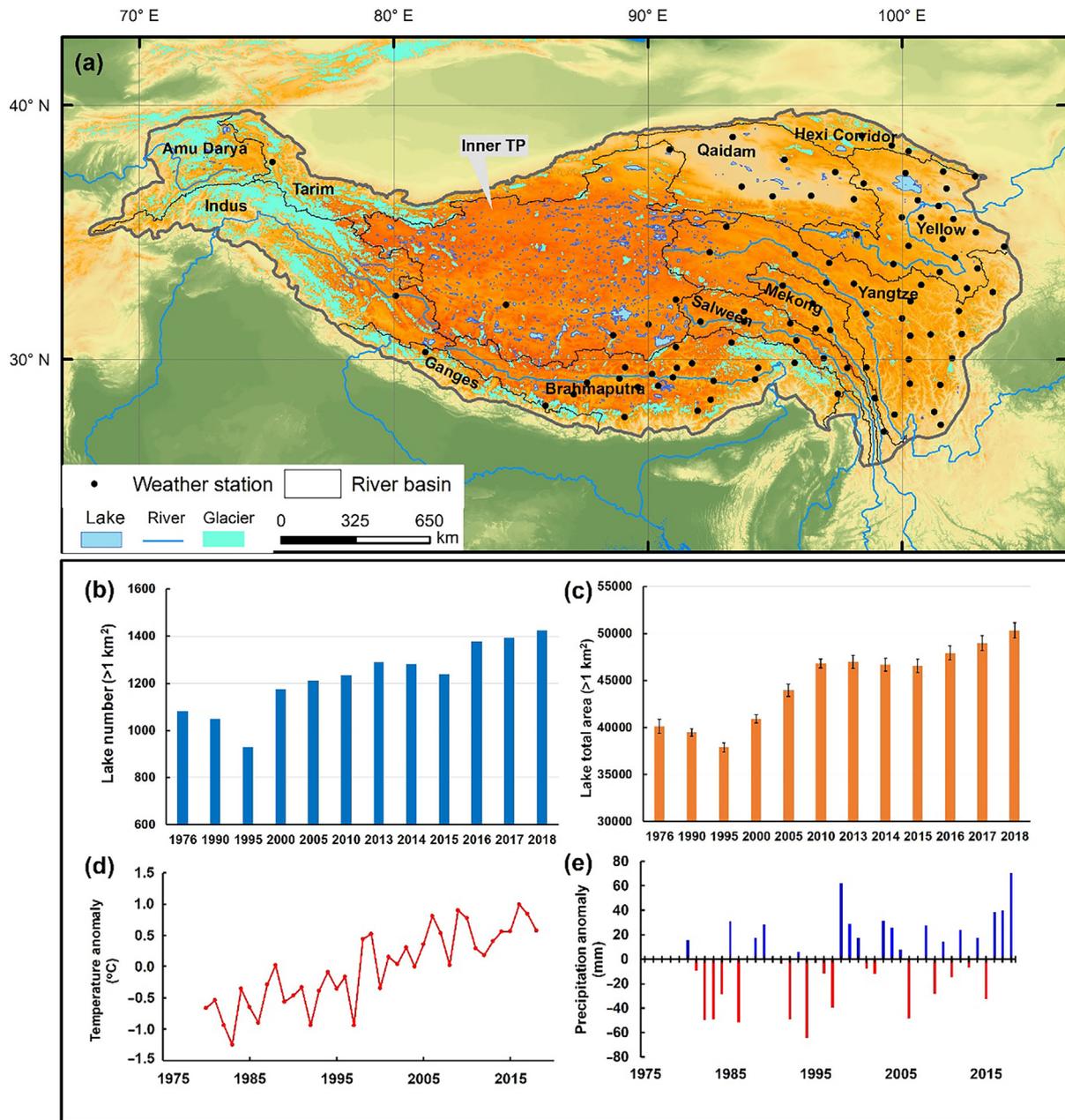
area in the period 2000–2010. Many other studies have also examined lake area change in the TP (e.g., [8]), but in these previous studies the TP’s boundary is limited to the Qinghai-Tibet Plateau, the temporal coverage of the data used is sparse [2,8]. Moreover, the mapping of lakes (with areas larger than 1 km<sup>2</sup>), for the entire TP, finished in ~2010 [2]. To fully examine the trends, variabilities and causes of long-term lake evolution from the 1970s until the present, it is necessary to define a consistent TP boundary, and to use a temporally dense set of images.

In this study, lakes with area greater than 1 km<sup>2</sup> were delineated from Landsat MSS/TM/ETM+/OLI data for the 1970s (1972–1976, but mostly 1976), ~1990, ~1995, ~2000, ~2005, ~2010, and 2013–2018. The lake boundaries in the 1970s, ~1990, ~2000 and ~2010 were derived from a study which employed visual interpretation [2]. The other lake data sets were delineated by using the popular Normalized Difference Water Index (NDWI), which is derived from Landsat data as the ratio of the green and near-infrared bands. To calculate NDWI, the digital number of the original Landsat images was first converted into top-of-atmosphere reflectance by radiometric calibration. An optimal threshold determined by the Otsu method was applied to separate each water body from non-water features. To ensure that each lake boundary was delineated with a high degree of accuracy, visual checking against the original Landsat images and manual editing of incorrect lake boundaries were also employed.

The intra-annual variation of lake area can introduce uncertainty for long-term lake change studies. Ideally, all images used should be from the same month (usually ~October for the TP), but in practice, this ideal is precluded by the limited availability of cloud-free optical Landsat images. Before 2013, to try to minimize such seasonal variability, intervals of 5-years were used, but inevitably some images from other months still had to be included when no available data existed for the priority month of

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**Fig. 1.** Lake distribution on the TP and changes in their number and area. (a) Spatial distributions of lakes, glaciers, major rivers, and weather stations. (b)–(e) Time series of lake number and area, and temperature ( $T$ ) and precipitation ( $P$ ) changes between the 1970s and 2018. The uncertainty in the lake area measurements was estimated as the lake perimeter length multiplied by half the pixel size.

October. After 2013, the availability of the high-quality Landsat 8 data enabled annual lake mapping to be achieved. Lake mapping is also subject to other uncertainties caused by factors such as turbid water, images acquired in lake freezing or ice breakup periods, and lakes with associated salt pan areas. Careful visual checking ensured that the vectored lake outlines closely matched the original Landsat images.

The number of lakes (>1 km<sup>2</sup> in area) was 1,080 in ~1976, but decreased to 930 in ~1995 (Fig. 1b). In ~2000, the number of such lakes increased to 1,174, and then remained relatively stable with just a slight increase. 1,424 lakes (>1 km<sup>2</sup>) were identified in 2018. An increase in lake number mainly results from lake expansion, i.e. a lake increases in size from less than 1 km<sup>2</sup> to more than 1 km<sup>2</sup>.

Entirely new lakes do sometimes appear, but only rarely, and they make only a small contribution to the increased numbers [2,5].

The total area of lakes (>1 km<sup>2</sup>) in the TP was  $4.0 \times 10^4 \pm 766.5$  km<sup>2</sup> in ~1976 (Fig. 1c). There was a decrease in the total area of  $-5.6\%$  from the 1970s to ~1995. Subsequently, there was a clear upwards trend from  $4.1 \times 10^4 \pm 443.7$  km<sup>2</sup> in ~2000 to  $5.0 \times 10^4 \pm 791.4$  km<sup>2</sup> in 2018 (+22.9%), although there was a decrease in 2015 ( $4.7 \times 10^4 \pm 693.6$  km<sup>2</sup>). Overall, between the 1970s and 2018, there was an increase of 25.4% in the total lake area, but the trend was not monotonic.

Temperature observations from 95 China Meteorological Administration (CMA) stations on the TP for the period 1980 to 2018, revealed a warming rate of  $0.04 \pm 0.005$  °C/a ( $P < 0.0001$ )

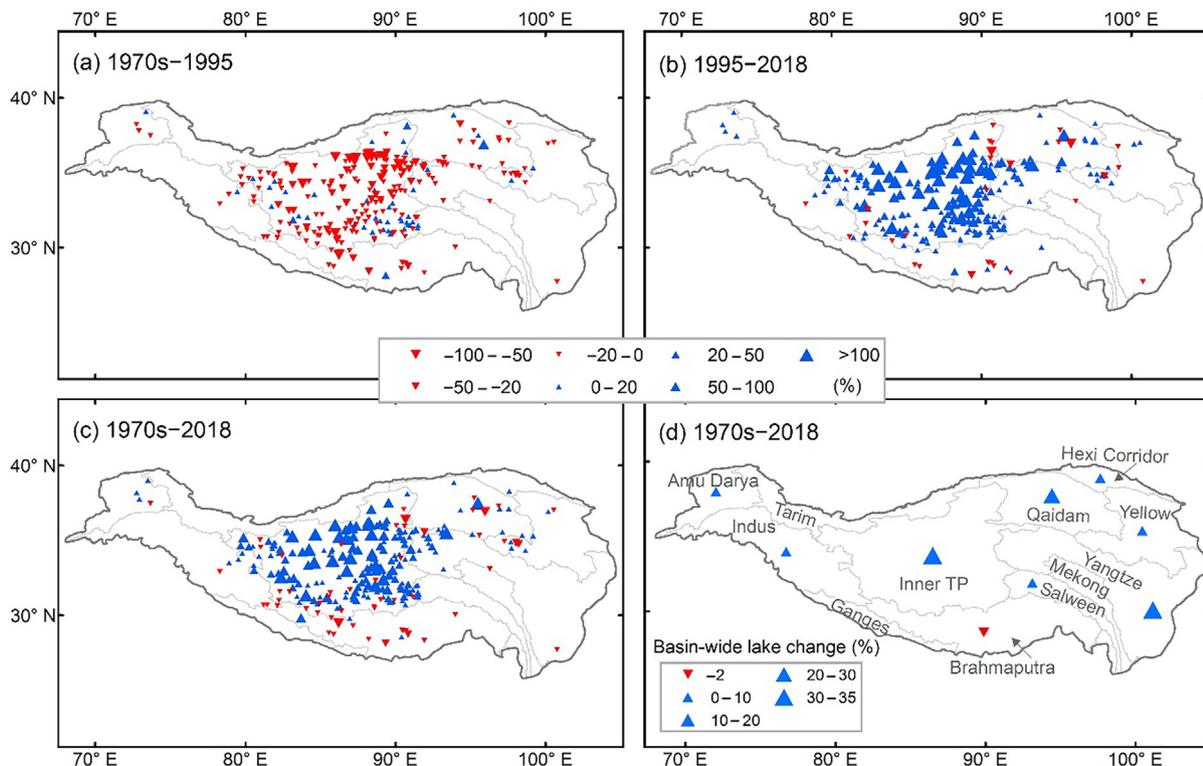
(Fig. 1d). Precipitation also had a generally increasing trend, especially after 1998 (Fig. 1e). Overall, the precipitation variation is well matched with lake area expansion, for example, low precipitation in ~1995 and 2015 coincides with small lake area, whereas high precipitation in 2016–2018 coincides with large lake area. However, lake area does not always show such a consistent correlation with precipitation dynamics. The precipitation data used here is the mean annual precipitation from all the stations in the TP, and so this discrepancy may be attributable to spatial variations in precipitation.

The spatial patterns of lake area changes (Fig. 2) show that the majority of lakes shrank between the 1970s and 1995. However, a contrasting pattern occurred in 1995–2018, with most of the lakes expanding in area. Over the entire period of the 1970s–2018, lake expansion was the dominant behavior, with only a small number of lakes in the southern and northeastern TP shrinking in area. Basin-based lake area change (Fig. 2d) indicates that, for the period 1970s–2018, all of the great basins had a total increased lake area, with the exception of the Brahmaputra River basin in the southern TP which had a ~2% shrinkage.

The observed trend of lake area evolution in the TP is consistent with the increasing precipitation observed in data from meteorological stations and in global precipitation data sets [9]. However, the limited number of weather stations in the region, and uncertainties in global precipitation products for the TP, have hindered the quantitative evaluation of lake water balance on the TP. The CMA stations on the TP are mostly located in the east of the region, at relatively low altitudes, while the lakes are dominantly situated in the western Inner TP, a region containing only five CMA stations. The Terrestrial Water Storage observations from the Gravity Recovery and Climate Experiment (GRACE) and other satellite

observations, have shown that increased precipitation has played a dominant role in driving water storage gains, and consequently lake boundary expansion in the Inner TP [9]. However, it is still a challenge to make quantitative evaluations for individual lake basins across the TP from climate and cryosphere contributions [9,10].

The climate of the TP is becoming warmer and wetter. The warming rate of the TP, as determined from station observations, is two times greater than the global rate of change of mean surface temperature. Precipitation in the TP, derived from station measurements, and from the Global Precipitation Climatology Centre (GPCC) data, also presents an overall increasing trend [5]. Enhancements to water vapor transport and the local hydrological cycle have resulted in increased precipitation, which has further driven lake expansion. Modelling, based the current climate and projected future climate scenarios, suggests that this pattern could continue over the period 2015 to 2035 [11]. Most of the precipitation increase has been driven by moisture transport from the western and southwestern TP by the Westerlies and the Indian monsoon respectively [12]. Several inflection points (1997/1998, 2015/2016) in the trend of lake development may be related to large-scale atmospheric circulation anomalies [13]. For example, the shrinkage of lakes in 2015 is associated with the strong 2015/2016 El Niño event [14]. For a better understanding of the lake water balance and its driving mechanisms, the teleconnections among various large-scale circulation systems need further exploration. The combination of multi-mission satellite data, such as optical (e.g., MODIS [15], Landsat, Sentinel-2), altimetry (ICESat-1 and -2, Cryosat-2), and Synthetic Aperture Radar (Sentinel-1, Chinese Gaofen-3) and the upcoming Surface Water and Ocean Topography (SWOT), will improve the ability to examine



**Fig. 2.** Spatial patterns of lake area changes on the TP for lakes of area greater than 20 km<sup>2</sup>. (a) Lake area change between the 1970s and 1995. (b) Lake area change between 1995 and 2018. (c) Lake area change between the 1970s and 2018. (d) Basin-wide lake area change between the 1970s and 2018. The Mekong, Ganges and Tarim River basins were excluded from the figure, as they had small total lake areas (<100 km<sup>2</sup>) in the 1970s or in 2018.

intra- and inter-annual changes in lake area and the estimation of lake water balance on the TP. The data sets presented here provide a baseline for further lake studies, and will be available at <http://data.tpdc.ac.cn/zh-hans/>.

### Conflict of interest

The authors declare that they have no conflict of interest.

### Author contributions

G. Zhang designed the study and led the writing of the manuscript. All authors contributed to the data processing and analysis of results.

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