Science Bulletin 68 (2023) 489–493

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Short Communication

# Increasing lake water storage on the Inner Tibetan Plateau under climate change

Binghao Jia [a,b], Longhuan Wang [a,c,d,*], Zhenghui Xie [a]

[a] State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
[b] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing 210044, China
[c] Key Lab of Virtual Geographic Environment (Nanjing Normal University), Ministry of Education, Nanjing 210023, China
[d] Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing 210023, China

ARTICLE INFO

*Article history:*
Received 15 November 2022
Received in revised form 9 February 2023
Accepted 10 February 2023
Available online 16 February 2023



Lakes store 20% of surface freshwater resources and are an important link for studying the interactions between the various spheres of the Earth system [1]. There are approximately 1400 lakes larger than 1 $km^2$ on the Tibetan Plateau (TP), with a total area of approximately 50,000 $km^2$, accounting for half of the number and area of lakes in China [2–4]. Most of these lakes are located on the Inner TP (Text S1.1 online), less affected by human activities and respond rapidly to climate and cryosphere changes [5]. With climate warming and wetting, the lakes on the Inner TP have experienced a dramatic expansion [2–6]; drainage reorganization events can occur, which in turn, pose a flood risk to surrounding villages and roads or break existing watersheds, converging into exorheic basins and threatening the ecological environment [7]. Therefore, an effective and accurate estimation of lake water storage (LWS) changes on the Inner TP under climate change is urgently needed.

Estimation of LWS changes requires information regarding lake area and water level changes [2–5,8–11]. Studies derive lake areas based on satellite images focused on large lakes over a short period owing to the influence of high cloud coverage in satellite images across the plateau and the satellite re-entry cycle [8]. Lake water level (LWL) records based on *in situ* measurements are typically available for large lakes, which only record relative water levels and lack data during freeze-up periods [12]. Radar, laser altimeters, and digital elevation models combined with certain empirical relationships have been used to monitor the intra-annual to annual variability of LWL [6,8–11]. These advances in lake volume estimation and measurement technology have improved our understanding of spatiotemporal changes in lake volume on the TP. However, the datasets of these studies were obtained with relatively complex processing and insufficient consideration of other hydrological components. Gravity Recovery and Climate Experiment (GRACE) data can provide quantitative monitoring of terrestrial water storage (TWS) changes, but cannot separate the changes of each hydrological component. Land surface models can provide changes in snow mass, soil water storage, surface water storage, and groundwater storage. However, these models lack an explicit representation of LWS, which describes the hydrological and thermal characteristics of a lake based on the constant ratios of lakes in each grid cell rather than the actual number of lakes [13]. Thus, combining remote sensing data and process-based models is essential for revealing changes in lake systems and understanding LWS changes from a water mass budget perspective [6]. In addition, few studies have been conducted regarding the projected LWS over the Inner TP under climate change.

In this study, we estimated LWS anomalies (LWSA) of 18 lakes (area greater than 300 $km^2$) during 2002–2018 on the Inner TP (Table S1 online) based on GRACE data and a high-resolution land surface model (Text S1.2, S1.3 and S1.5, and Fig. S1 online). Then, we projected future changes of LWSA for an intermediate scenario based on an artificial neural network (ANN) model (Text S1.4 and Fig. S2 online). Our study provides new insights into LWS estimations, yielding a deeper understanding for the development of a land surface model in areas with a dense lake distribution.

The LWSA for 18 lakes on the Inner TP between 2002 and 2018 were calculated based on the water mass budget (Text S1.2 online). The estimated LWSA were then compared with the LWL anomalies (LWLA) derived from multi-source altimetry and remote sensing data [6]. The units of estimated LWSA and satellite derived LWLA are different; the former is represented by equivalent water height and the latter by the elevation of the free surface of a lake. For each

* Corresponding author.
*E-mail address:* wanglh@mail.iap.ac.cn (L. Wang).

https://doi.org/10.1016/j.scib.2023.02.018
2095-9273/

lake, a correlation coefficient was used to examine the accuracy of the LWS estimations (see Text S1.6.1 and Fig. S3 online for more details). At the basin scale, we transformed the units of LWLA into equivalent water height to compare with the LWSA estimations (Text S2.1 online). The average estimated trend of LWSA was 8.1 mm $a^{-1}$, which was consistent with the observed results (7.29 mm $a^{-1}$, Fig. S4 online). The scatter plot of LWSA versus LWLA for 18 lakes from 2002 to 2018 shows that the LWSA estimations for most lakes are in agreement with observations (Fig. 1). The correlation coefficients of all 18 lakes passed the 95% confidence level in the Student's *t*-test (Fig. 1). Though the mass changes of glaciers were considered in this study, the fixed density conversion factor (850 kg $m^{-3}$) used here may introduce biases in the LWSA estimations (Fig. S5 online). Inconsistencies among

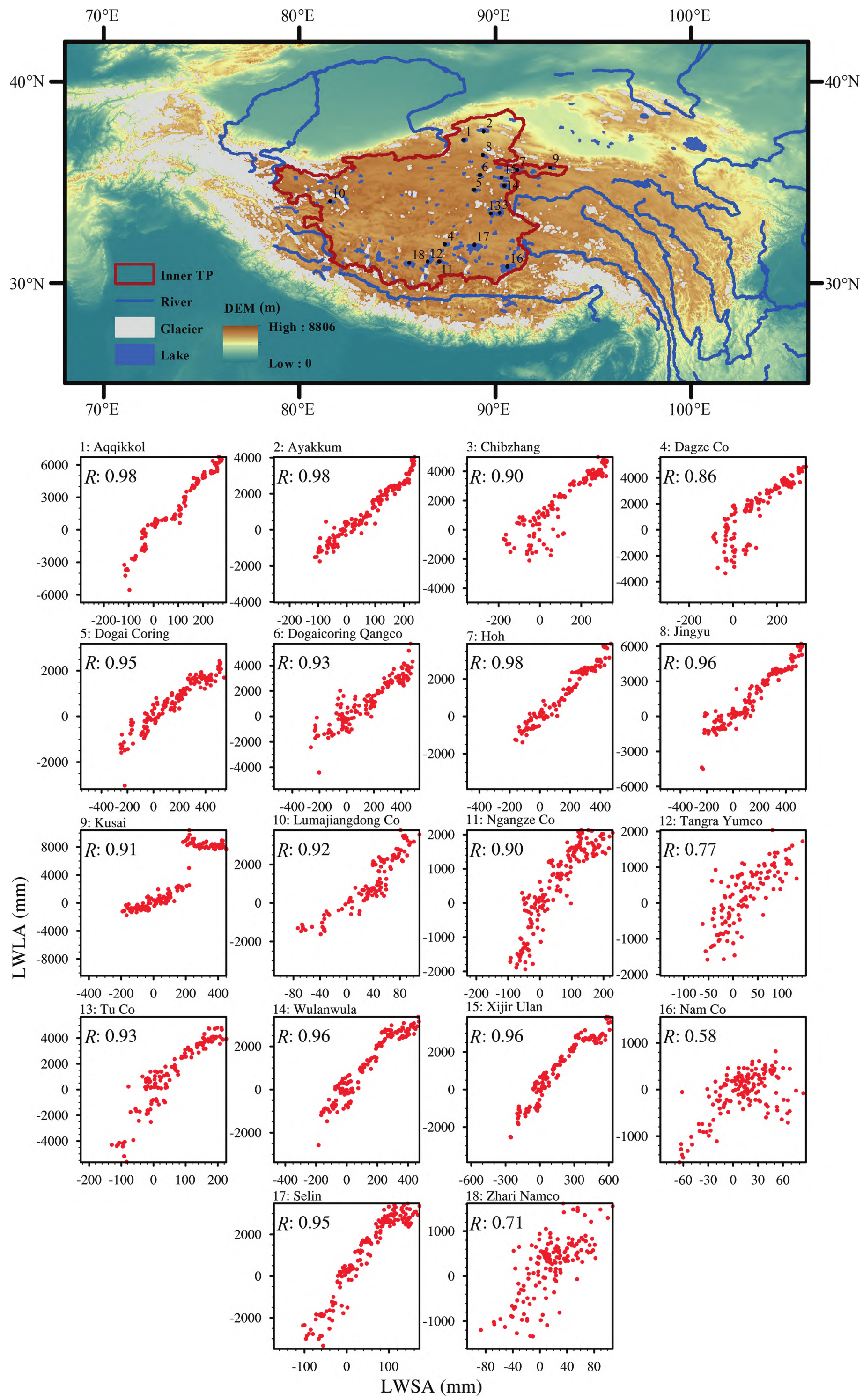



**Fig. 1.** Locations of 18 larger lakes (area >300 $km^2$) on the Inner TP and comparisons of estimated monthly lake water storage anomalies (LWSA) and observed lake water level anomalies (LWLA) during 2002–2018. The number in the upper left corner is the correlation coefficient (*R*) between LWSA and LWLA of each lake. All correlation coefficients passed the 95% confidence level in the Student's *t*-test.

different data resolution types and uncertainties from the land surface modeling (Text S2.2 online) may also lead to lower correlations for Tangra Yumco (0.77), Nam Co (0.58), and Zhari Namco (0.71). All other lakes have high correlations ($\geq$0.86). Moreover, the lake area on the Inner TP has dramatically changed during the study periods [3]; we further compare the LWSA with the lake water volume anomalies (LWVA) derived from Ref. [6]. Similar results (Fig. S3 online) indicate the reasonability of the estimated LWSA in this study. Thus, our estimation results can be used to identify regional changes in lakes for areas with limited available data and can be helpful when monitoring water resource changes.

LWS increases rapidly on the Inner TP, with an average growth rate of 26.92 mm $a^{-1}$. Most increasing lakes have an annual rate of change exceeding 12 mm $a^{-1}$ (Fig. S6 online), with the fastest rising lake being Lake Dogai Coring and Xijir Ulan (more than 44 mm $a^{-1}$). The simulation-based changes in LWS in this study were consistent with the trends in previously reported datasets based on satellite stereo, multispectral images, and multiple altimetric missions [3,5,6], indicating the reliability of the simulation results (see Text S2.1 online for more details). We grouped these 18 lakes into three subregions based on their geographical locations and changes in LWS (Fig. S6a online). Sub-region NW is located in the northern Ali region of the TP, surrounded by the Kunlun, Karakorum, and Ladakh mountains, as well as several glaciers. The lakes in this region have the slightest variation among all subregions, with an average annual rate of 8.65 mm $a^{-1}$. Sub-region N, located in Cocosia, includes 11 lakes, the highest number among the five sub-regions. All lakes in this sub-region exhibit a significant increasing trend in LWS, with an average annual rate of 35.19 mm $a^{-1}$. Subregion S, located in the southern Nagqu region of the TP, is surrounded by the Nyingchi Tanggula and Tanggula Mountains and includes six lakes. The LWS in this subregion has an increasing trend, with an average annual change rate of 12.77 mm $a^{-1}$. The discrepancy of LWSA trends can also be explained by the changes in TWS and subsurface water from the perspective of the water mass budget (Figs. S7 and S8 online). Results show that the 18 lakes in this study are characterized by an increase in surface water (the sum of LWSA, glacier, snow, and canopy water storage) and a decrease in subsurface water (the sum of soil and groundwater storage), and LWSA dominated the surface water changes. Subsurface water decreased for both subregions S and N, while the contrasting trend of TWSA caused the difference in LWSA in these two subregions (see Text S2.2 online for more details).

Increased LWS on the Inner TP is mainly related to precipitation. The precipitation variability is consistent with the temporal characteristic of monthly LWSA (Figs. S7 and S8 online). The average increase rate of precipitation for the 18 lakes from 2002 to 2018 and the standardized cumulative precipitation are highly compatible with changes in LWS (correlation coefficient is 0.99, Fig. S9 online), illustrating the critical role of precipitation on LWS. Previous studies have also shown that the variation of LWS on the Inner TP is mainly driven by precipitation [5,14]. In addition, glacial meltwater due to warming also affects LWS. Studies have been conducted to classify lakes into glacier-fed and non-glacier fed based on whether the lake receives glacial flow from a glacier terminus [5]. For the 18 lakes in this study, the change in LWS in 2002–2018 was 8.1 mm $a^{-1}$, and the glacier loss was $-1.27$ mm $a^{-1}$. Thus, the relative contribution of glacier loss to the increase in LWS from 2002 to 2018 is $\sim$16%. Owing to the different study periods and the lake boundaries used, the estimated contribution of glaciers to lakes can vary. The results of the contribution of glacier loss to the LWS increase in this study are within a reasonable range (10%–30% in previous studies) [5,14].

Atmospheric dynamic and warming induced solid water mass loss (for example, accelerated glacial melting), and liquid water mass gain (for example, LWS increased rapidly) changed the balance between liquid and solid water resources among different reservoirs. For the Inner TP with a dense distribution of lakes, it is worth exploring whether this imbalance will increase or stabilize in the future. An ANN model was used for 18 lakes on the Inner TP to project the LWSA under an intermediate scenario (see Text S1.4 online for more details). Considering the climatic mechanisms of historical LWSA changes, precipitation should be the primary driver of LWSA increase, while temperature and radiation are the other two variables that may lead to glacier and evapotranspiration changes and influence LWSA. The input variables of the ANN model were derived from the bias-corrected precipitation, temperature, and surface shortwave radiation. The bias correction improved the accuracy of the inputs, contributing to a higher temporal correlation and lower root mean square error (see Text S1.6.2 and Fig. S10 online for more details). This ANN model can accurately reproduce the LWSA on the Inner TP during the historical period (2002–2018), and the Kling-Gupta efficiency (KGE) value between the ANN results and estimated LWSA is greater than 0.94 for 17 lakes (Fig. S11 online) while the other is 0.88 (Zhari Namco). Then, we used the trained model for future prediction. We assumed the nonlinear relationship between input and output in the historical period could be applied to a business-as-usual scenario in the future. Thus, we focused on the Shared Socio-economic Pathways (SSPs) and the Representative Concentration Pathway (RCP) under a low population growth and emissions scenario (SSP2-RCP4.5, abbreviated as SSP245). For moderate scenario SSP 245, the LWS on the Inner TP increases through the mid-twenty-first century (Fig. 2). However, the increasing rate slows, particularly in the next decade (2019–2035) with a rate of 5 mm $a^{-1}$ (Fig. 2 and Fig. S12 online). Even if the growth increases in 2036–2060, the changes in the next 40 years roughly equal the changes in the last 20. In brief, the increasing rate of LWS by the mid-twenty-first century for an intermediate scenario is predicted to decrease to 40% of that of recent decades. The projected LWSA is relatively consistent with the precipitation variability. The change points of precipitation (intersection of the red and blue lines in Fig. S13 online) based on the Mann-Kendall test show that 50% of the lakes have change points in 2030–2040, which may lead to a jump point around 2036 (Fig. S12 online). This prediction is supported by the projection of TWS, which indicates that the TWS will be relatively stable on the Inner TP over the next 40 years [15]. Similarly, recent studies indicate that the glacial runoff should reach a peak in around 2042 and then show a slowly increasing trend (see Text S2.3 online for more details).

Lakes located on the Inner TP are rarely affected by human activities and influenced by climate and cryosphere changes. We estimated LWS for 18 lakes on the Inner TP with an area of more than 300 $km^2$ using GRACE, glacier mass change data, and high-resolution land surface simulations (Fig. S1 online). The LWSA estimated in this study are consistent with the LWLA derived from multi-source altimetry and remote sensing data (Fig. 1). In the past decade, the LWS expanded rapidly with a rate of 26.92 mm $a^{-1}$ from 2002 to 2018 (Fig. S6 online). The increasing rate of LWS by the mid-twenty-first century for an intermediate scenario is predicted to decrease to 40% of that in recent decades (Fig. 2). This prediction is supported by the TWS and glacial runoff projections on the Inner TP. With climate warming and humidification on the Inner TP, adaption and management policies are needed to avoid the threat of increased LWS and protect lives under climate change. Our study provides new insights into the estimation of LWS, yielding a deeper understanding of the development of a land surface model in areas with dense lake distribution.

## Conflict of interest

The authors declare that they have no conflict of interest.

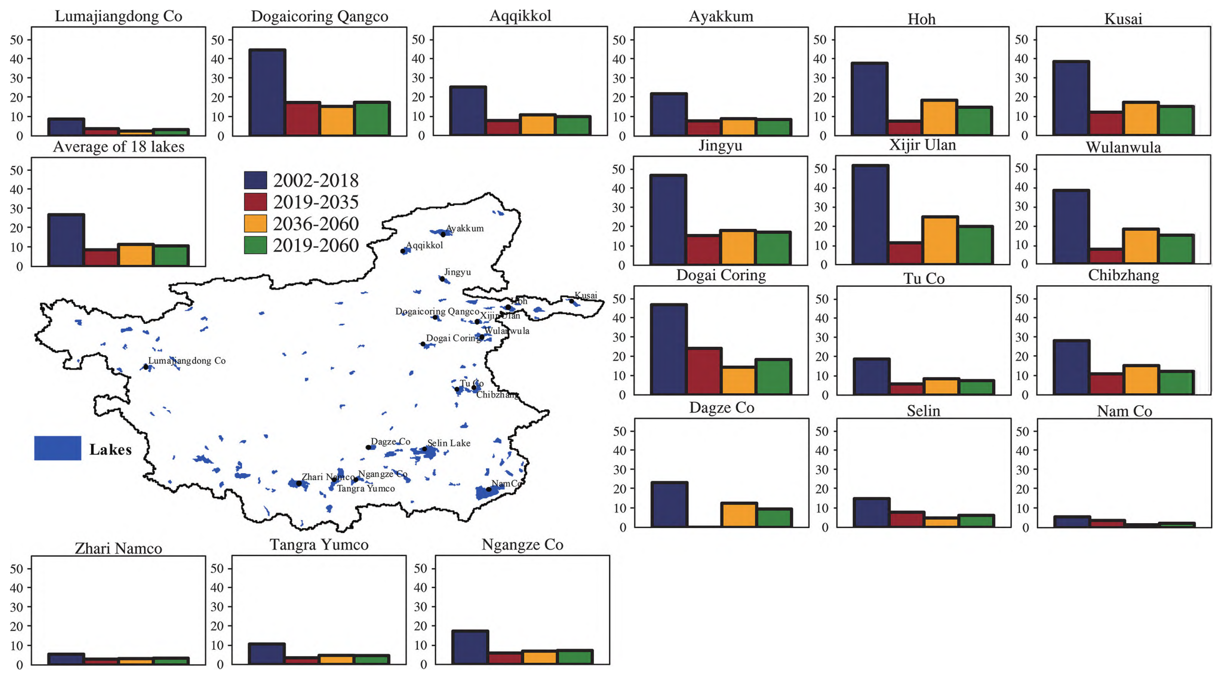



**Fig. 2.** Trends (mm $a^{-1}$) of LWSA for 18 lakes (area >300 $km^2$) on the Inner TP and their average values during 2002–2018, 2019–2035, 2036–2060, and 2019–2060.

## Acknowledgments

This work was supported by the Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK0206), the Strategic Priority Research Program of Chinese Academy of Sciences (XDA20100300), the National Natural Science Foundation of China (42205176), the Youth Innovation Promotion Association of Chinese Academy of Sciences (2021073), the National Key Scientific and Technological Infrastructure Project "Earth System Science Numerical Simulator Facility" (EarthLab), and the Open Fund Project of Key Lab of Virtual Geographic Environment (Nanjing Normal University), Ministry of Education (2021VGE04). We would like to thank the editor and four anonymous reviewers for their constructive and thoughtful comments.

## Author contributions

Binghao Jia and Longhuan Wang designed the research and text organization. Binghao Jia wrote and revised the manuscript. Binghao Jia and Longhuan Wang performed the research and analyzed data. Binghao Jia, Longhuan Wang, and Zhenghui Xie participated in the results and discussion.

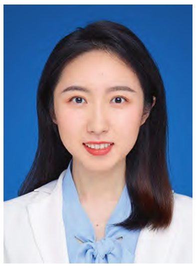
## Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2023.02.018.

## References

[1] Wang W, Lee X, Xiao W, et al. Global lake evaporation accelerated by changes in surface energy allocation in a warmer climate. Nat Geosci 2018;11:410–4.
[2] Zhang GQ, Chen WF, Xie HJ. Tibetan Plateau's lake level and volume changes from NASA's ICESat/ICESat-2 and Landsat missions. Geophys Res Lett 2019;46:13107–18.
[3] Zhang GQ, Luo W, Chen WF, et al. A robust but variable lake expansion on the Tibetan Plateau. Sci Bull 2019;64:1306–9.
[4] Luo SX, Song CQ, Zhan PF, et al. Refined estimation of lake water level and storage changes on the Tibetan Plateau from ICESat/ICESat-2. Catena 2021;200:105177.
[5] Zhang GQ, Bolch T, Chen WF, et al. Comprehensive estimation of lake volume changes on the Tibetan Plateau during 1976–2019 and basin-wide glacier contribution. Sci Total Environ 2021;772:145463.
[6] Li XD, Long D, Huang Q, et al. High-temporal-resolution water level and storage change data sets for lakes on the Tibetan Plateau during 2000–2017 using multiple altimetric missions and Landsat-derived lake shoreline positions. Earth Syst Sci Data 2019;11:1603–27.
[7] Liu K, Ke L, Wang J, et al. Ongoing drainage reorganization driven by rapid lake growths on the Tibetan Plateau. Geophys Res Lett 2021;48:e2021GL095795.
[8] Zhang B, Wu YH, Zhu LP, et al. Estimation and trend detection of water storage at Nam Co Lake, central Tibetan Plateau. J Hydrol 2011;405:161–70.
[9] Song CQ, Huang B, Ke L. Modeling and analysis of lake water storage changes on the Tibetan Plateau using multi-mission satellite data. Remote Sens Environ 2013;135:25–35.
[10] Zhang GQ, Yao TD, Xie HJ, et al. Increased mass over the Tibetan Plateau: from lakes or glaciers? Geophys Res Lett 2013;40:2125–30.
[11] Zhang GQ, Yao TD, Shum C, et al. Lake volume and groundwater storage variations in Tibetan Plateau's endorheic basin. Geophys Res Lett 2017;44:5550–60.
[12] Lei YB, Yao TD, Yang K, et al. Lake seasonality across the Tibetan Plateau and their varying relationship with regional mass changes and local hydrology. Geophys Res Lett 2017;44:892–900.
[13] Lawrence DM, Fisher RA, Koven CD, et al. The Community Land Model Version 5: description of new features, benchmarking, and impact of forcing uncertainty. J Adv Model Earth Syst 2019;11:4245–87.
[14] Chen W, Liu Y, Zhang GQ, et al. What controls lake contraction and then expansion in Tibetan Plateau's endorheic basin over the past half century? Geophys Res Lett 2022;49:e2022GL101200.
[15] Li XY, Long D, Scanlon BR, et al. Climate change threatens terrestrial water storage over the Tibetan Plateau. Nat Clim Chang 2022;801:807.

Binghao Jia is a professor of the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) at the Institute of Atmospheric Physics, Chinese Academy of Sciences. His research interest focuses on land surface ecohydrological process and satellite-based data assimilation.



Longhuan Wang works as a postdoctoral fellow of the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) at the Institute of Atmospheric Physics, Chinese Academy of Sciences. Her research interest focuses on the development and application of land surface hydrological model.