Asymmetric changes in the cooling capacity of China’s lakes

Zikang Xing, Yunliang Li, Yufeng Dai, Jianhui Wei, Enlou Zhang, Harald Kunstmann

Angaben zur Veröffentlichung / Publication details:

Xing, Zikang, Yunliang Li, Yufeng Dai, Jianhui Wei, Enlou Zhang, and Harald Kunstmann. 2026. “Asymmetric changes in the cooling capacity of China’s lakes.” *Geophysical Research Letters* 53 (5): e2025GL120047. https://doi.org/10.1029/2025gl120047.

AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters®

RESEARCH LETTER
10.1029/2025GL120047

Asymmetric Changes in the Cooling Capacity of China's Lakes

Zikang Xing[1], Yunliang Li[1], Yufeng Dai[2], Jianhui Wei[3], Enlou Zhang[1], and Harald Kunstmann[3,4,5]

[1]State Key Laboratory of Lake and Watershed Science for Water Security, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China, [2]State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, [3]Institute of Meteorology and Climate Research (IMKIFU), Karlsruhe Institute of Technology, Campus Alpin, Garmisch-Partenkirchen, Germany, [4]Institute of Geography, University of Augsburg, Augsburg, Germany, [5]Centre for Climate Resilience, University of Augsburg, Augsburg, Germany

Key Points:

- China's lakes cool summer daytime air temperature by 0.46°C/10 km, with effects extending over 27 km from their shorelines
- Lake cooling strengthened on the Tibetan Plateau but weakened in eastern plains, revealing divergent climate responses
- Lake surface albedo, depth, and surrounding topography dominate the spatial and temporal variations in lake cooling capacity

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

Y. Li,
yunliangli@niglas.ac.cn

Citation:

Xing, Z., Li, Y., Dai, Y., Wei, J., Zhang, E., & Kunstmann, H. (2026). Asymmetric changes in the cooling capacity of China's lakes. *Geophysical Research Letters*, *53*, e2025GL120047. https://doi.org/10.1029/2025GL120047

Received 16 OCT 2025
Accepted 12 FEB 2026

Author Contributions:

Conceptualization: Zikang Xing, Yunliang Li
Funding acquisition: Enlou Zhang
Methodology: Zikang Xing
Project administration: Yunliang Li, Enlou Zhang, Harald Kunstmann
Resources: Yunliang Li, Yufeng Dai
Software: Zikang Xing
Supervision: Yunliang Li, Yufeng Dai, Jianhui Wei, Harald Kunstmann
Validation: Zikang Xing
Visualization: Zikang Xing
Writing – original draft: Zikang Xing
Writing – review & editing: Yunliang Li, Jianhui Wei

Abstract

Lakes significantly influence local climate, yet a systematic assessment of their cooling effect across diverse regions remains limited. This study develops a multi-metric (spatial extent, magnitude, and efficiency) framework to evaluate the spatiotemporal patterns of Lake Cooling Capacity (LCC) for 265 major Chinese lakes from 1980 to 2022. Results show that Chinese lakes exert substantial cooling on summer daytime maximum temperatures, with a mean extent of 27.5 km, a magnitude of 1.03°C, and an efficiency of 0.46°C/10 km. LCC efficiency shows spatially asymmetric trends, intensifying on the Tibetan Plateau but weakening in the eastern plains. Random forests analysis reveals that albedo is the dominant driver of temporal variability, while depth and surrounding topography are the primary spatial controls. These findings underscore the critical role of lakes in mitigating regional heat extremes and highlight the necessity of incorporating lake-climate feedback into climate adaptation.

Plain Language Summary

Lakes act like natural air conditioners for their surrounding areas, absorbing heat during the day and cooling the air nearby. In China, where lakes are changing rapidly due to climate change and human activities, we studied how this cooling effect works across the country. Using weather data, we found that lakes can lower summer afternoon temperatures by about 0.46°C for every 10 km closer to the water, with this cooling influence reaching up to 27.5 km away. Interestingly, lakes on the Tibetan Plateau are becoming better at cooling over time, while lakes in eastern China are losing this ability. These differences are mainly driven by changes in how much sunlight the lake surfaces reflect and the shape of the lakes themselves. Our research shows that protecting lakes helps maintain their natural cooling role, which is especially important as heatwaves become more common.

1. Introduction

In a warming world, the increasing frequency and intensity of heat extremes pose severe threats to ecosystems, water security, and human society (Tian et al., 2024; W. Wang et al., 2024). Among natural landscape features that can mitigate such extremes, lakes play a vital but often underappreciated role by acting as natural cooling islands through evaporative cooling and thermal inertia (Xing et al., 2026). Quantifying the spatiotemporal patterns and drivers of lake cooling capacity (LCC) is therefore essential not only for advancing fundamental knowledge of land-atmosphere interactions, but also for informing climate-resilient landscape planning and water resource management (Gao et al., 2025; Yan et al., 2024).

The LCC, defined as the modulation of near-surface air temperature resulting from lake-atmosphere interactions, serves as a fundamental metric for quantifying this climate regulation function. LCC most profoundly reduces daytime maximum temperatures (T_2max) through the absorption of incoming solar radiation and suppression of turbulent heat fluxes during peak insolation periods (Rouse et al., 2008; Scott & Huff, 1996). As rising extreme temperatures intensify global threats under climate change (Hua et al., 2023; W. Wang et al., 2024), their cooling role becomes increasingly vital, exemplified by severe heatwaves such as the 2022 Yangtze River event (Jiang et al., 2023).

China's diverse lacustrine system, encompassing lakes from the rapidly expanding Tibetan Plateau (Qiu et al., 2023) to the shrinking Eastern Plains (Tao et al., 2020), provides a unique natural laboratory to investigate how lake-climate interactions vary across contrasting environmental and anthropogenic gradients. However, existing assessments of LCC remain fragmented, typically focusing on individual lakes or regions (Liang et al., 2012; Wang et al., 2015). A systematic, nationwide quantification of LCC that encompasses its spatial extent, intensity, and efficiency is lacking, which hinders a holistic understanding of lakes' role in regional climate regulation under changing conditions.

To bridge this gap, key challenges must be addressed. First, a consistent multi-metric framework is needed to quantify and compare the spatial footprint, magnitude, and efficiency of LCC across diverse lakes. Second, the temporal trends of LCC over recent decades of rapid warming and lake surface change remain unquantified at the national scale. Third, the relative importance of climatic versus geomorphic drivers in controlling the observed spatial and temporal variations in LCC require systematic attribution (Du et al., 2016). To tackle these research questions, we integrate high-resolution reanalysis, in situ observations, and machine learning to map LCC dynamics for 265 major Chinese lakes from 1980 to 2022. Our objectives are to: (a) develop and apply a multi-metric framework for LCC assessment; (b) reveal the spatiotemporal trends of LCC across major lake regions; and (c) attribute the divergent LCC patterns to key environmental drivers.

2. Materials and Methods

2.1. Data Acquisition

This study analyzes summer (June–August) daytime maximum near-surface air temperature (T_2max) across China from 1980 to 2022. The primary data set is the ERA5-Land reanalysis (0.1° spatial resolution; Muñoz-Sabater et al., 2021), selected for its FLake parameterization scheme that explicitly resolves lake-atmosphere interactions. Lake boundaries were sourced from the HydroLAKES database (Messager et al., 2016), which inventories both natural lakes and artificial reservoirs. From this database, we retained 265 water bodies (63839.47 km^2) with a surface area >50 km^2 to ensure a detectable LCC signal given the resolution of ERA5-Land. Among these, 219 are natural lakes and 46 are reservoirs. Based on spatial clustering and geographical features, these lakes are classified into five subregions for intercomparison, that is, the North-east Plain Lake Region (NEP), Inner Mongolia-Xinjiang Lake Region (IMXJ), Tibetan Plateau Lake Region (TP), Eastern Plain Lake Region (EP), and Yunnan-Guizhou Plateau Lake Region (YGP; G. Zhang et al., 2019). Auxiliary data sets included the SRTM digital elevation model (30 m resolution; K. Liu et al., 2024) to correct elevation-induced temperature biases using a 6.5°C/km lapse rate, and GLC_FCS30-2020 land cover data (30 m; Zhang et al., 2021) to exclude urban areas, dense forests, and other waterbodies from analysis zones.

2.2. Concentric Zone Model Framework

We developed a spatial framework to detect lake-induced T_2max signals. For each lake, 10 non-overlapping concentric belts (10-km width, 0–100 km radius) were generated using geodesic buffering (Figure S1c in Supporting Information S1). Land cover data then masked pixels classified as urban, forest, or non-lake waterbodies within belts to minimize confounding effects (Figure S2 in Supporting Information S1). Mean elevation per belt was computed from SRTM DEM, and T_2max values were adjusted using the environmental lapse rate to account for topographic differences. This correction minimizes elevation-induced temperature variations and helps isolate the lake-specific cooling signal. Multi-year summer mean T_2max (1980–2022) was calculated for each belt, generating distance-temperature gradient curves (Figure S1d in Supporting Information S1).

2.3. LCC Metrics

We focused on daytime maximum temperature (T_2max) because of its direct relevance to extreme heat and its more pronounced LCC signal relative to daily mean temperatures. The LCC was quantified through three dedicated metrics (see Figure S1d in Supporting Information S1): (a) **LCC extent** (buffer range), representing the distance from the lake edge to the first statistically significant breakpoint in the T_2max gradient curve, identified using Pettitt non-parametric change-point detection (Pettitt, 1979) (see Text S1 in Supporting Information S1 for details); (b) **LCC magnitude**, defined as the T_2max difference between the lake surface and the LCC extent location; and (c) **LCC efficiency**, calculated as the rate of T_2max reduction per unit distance (10 km), derived from the ratio of LCC-magnitude to LCC-extent. The derived LCC efficiency was systematically validated against in situ observations from over 1,400 meteorological stations, demonstrating strong agreement in spatial gradient patterns (see Text S2 and Figure S3 in Supporting Information S1).

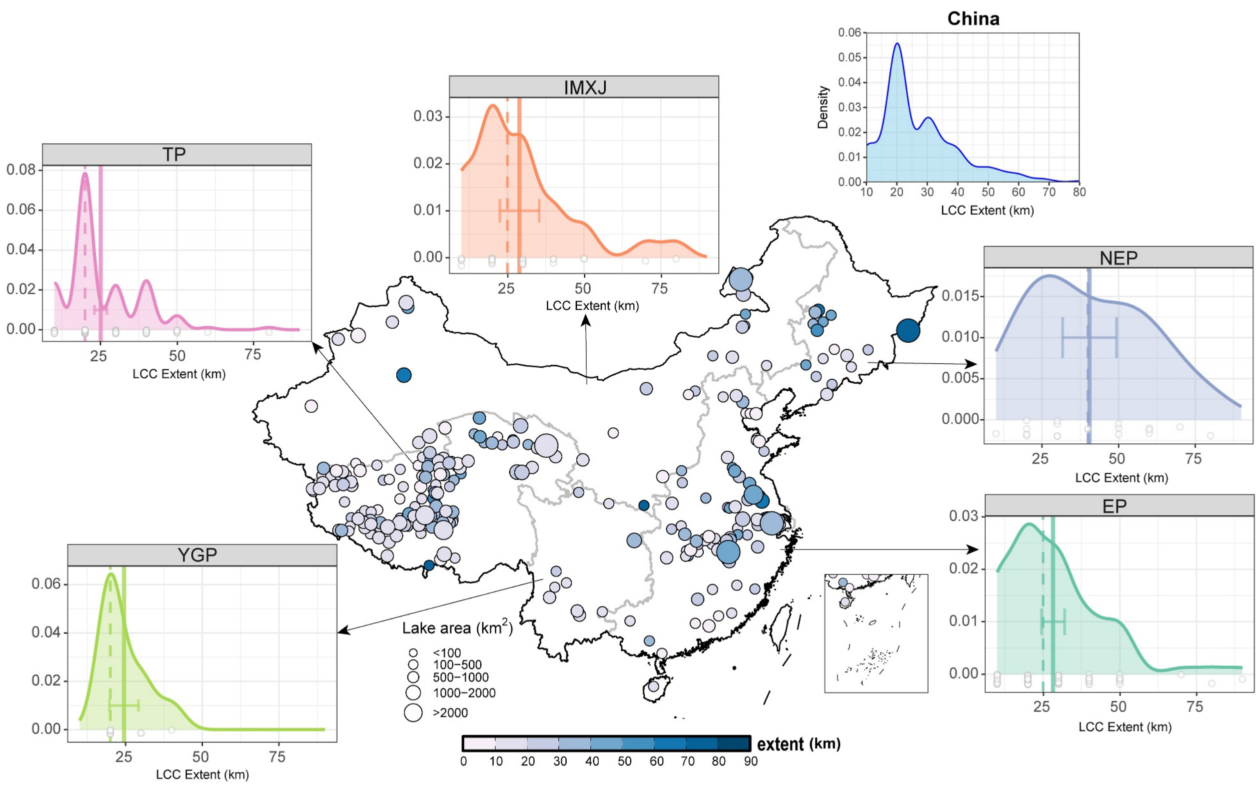

Figure 1. Distribution of LCC extent across China's lake regions. The central plot shows LCC extent for 265 Chinese lakes, with connecting lines to six probability density plots representing five lake regions and national aggregate distributions. The solid vertical lines indicate means, dashed vertical lines represent medians, and I-shaped error bars show 95% confidence intervals.

2.4. Statistical and Attribution Analysis

Long-term trends in annual LCC (1980–2022) were assessed using Sen's slope estimator (Wilcox, 2005), with significance ($p < 0.05$) evaluated via the Mann-Kendall test. To attribute LCC variations, random forests models (BREIMAN, 2001) were implemented. The potential temporal drivers of LCC including 26 climatic variables (e.g., albedo, net solar radiation, evaporation) from ERA5-Land averaged over each lake, and spatial drivers consisting of 13 static geomorphic parameters (e.g., area, depth, lakeshore slope) from HydroLAKES (see detailed list in Table S1 of Supporting Information S1). For temporal attribution, separate model was trained for each lake using annual data (43 years). For spatial attribution, a single model was trained using all 265 lakes. All models were configured with 1000 trees, and variable importance was quantified by the percent increase in mean squared error (%IncMSE) upon permutation. Detailed model setups, parameter choices, and validation procedures are provided in Text S1 and Text S2 of Supporting Information S1.

3. Results

3.1. Spatial Patterns of Lake Cooling on Daytime Maximum Temperature

Chinese lakes significantly reduce summer daytime maximum temperatures, with nationally averaged LCC characterized by an extent of 27.5 ± 14.9 km (Figure 1), a magnitude of 1.03 ± 0.84°C, and an efficiency of 0.46 ± 0.44°C/10 km (Figure 2, For detailed statistical information, see Table S2 in Supporting Information S1). The spatial distribution of lake cooling exhibits strong regional heterogeneity: lakes in the NEP and EP show the most extensive cooling footprints, exceeding 40 km in major water bodies such as Poyang Lake and Taihu Lake. In contrast, Tibetan Plateau lakes, despite their large surface areas, produce more localized cooling, with a median LCC extent below 25 km. These spatial patterns are consistently captured by the distance–temperature gradient curves from the concentric zone model across all 265 lakes (Figure S4 in Supporting Information S1), which uniformly indicate declining T_2max toward lake centers.

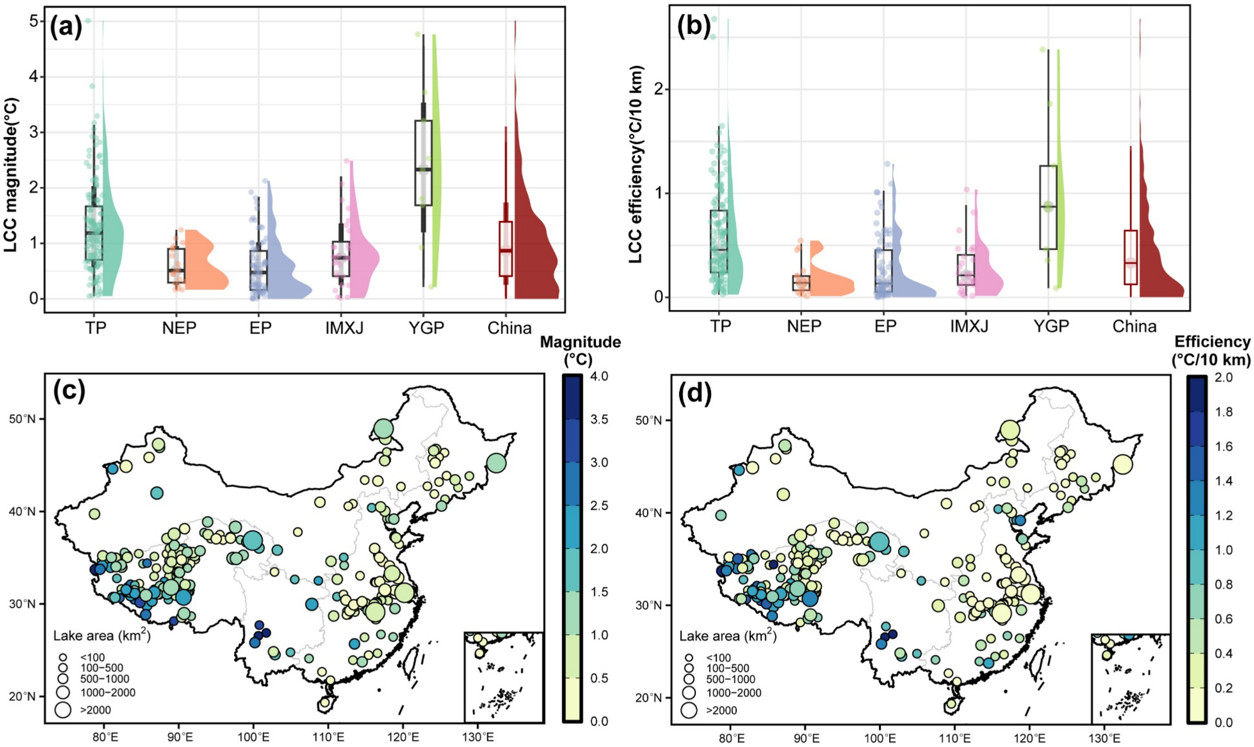

Figure 2. National-scale patterns of LCC across China. Raincloud plots display the distribution of (a) LCC magnitude and (b) LCC efficiency for five lake regions and the national aggregate. Spatial distribution of mean (c) LCC magnitude and (d) LCC efficiency during the study period reveals distinct regional characteristics.

LCC magnitude displays a similar spatial structure, with the highest values in the YGP (2.37°C) and TP (1.29°C), and lower values in the NEP (0.59°C) and EP (0.60°C). Combined with extent, LCC efficiency is highest in the YGP (1.01°C/10 km) and TP (0.59°C/10 km), and lowest in the NEP (0.18°C/10 km). Although magnitude and efficiency share broadly similar spatial patterns, efficiency exhibits stronger heterogeneity, likely because it integrates information from both cooling intensity and spatial extent, offering a more comprehensive measure of lake thermal regulation. Comparison between the 219 natural lakes and 46 large reservoirs showed minimal differences in cooling effects (Figure S5 in Supporting Information S1). The mean LCC extent of natural lakes was 3.3 km larger than that of reservoirs, while differences in LCC magnitude and efficiency were negligible.

3.2. Divergent Trends in Cooling Efficiency Across Regions

LCC efficiency across China has intensified over the past four decades, with a nationally increasing trend of 8.06×10^{-5}°C/10 km·decade^{-1} during 1980–2022 (Figure 3). This trend, however, exhibits pronounced spatial heterogeneity linked to elevation: high-altitude lakes on the Tibetan Plateau enhanced their cooling role, led by Qinghai Lake (0.02°C/10 km·decade^{-1}), whereas low-altitude lakes in the Eastern Plain experienced declines, exemplified by Poyang Lake (−0.01°C/10 km·decade^{-1}). Of the 94 lakes with statistically significant trends, 57% (54 lakes) increased in efficiency while 43% (40 lakes) decreased, reflecting divergent lake-specific responses to climate change rather than uniform behavior.

3.3. Drivers of Temporal and Spatial Variability

Random forests analysis identified distinct controls on both temporal and spatial patterns of lake cooling effectiveness (Figure 4). For temporal variability (Figures 4a and 4b), albedo emerged as the predominant driver, controlling LCC variations in 31% of lakes nationally. This was particularly evident in the EP, NEP, and TP (32% of lakes). Soil water content (11%), radiation processes (surface net thermal radiation, 9%), and evaporation processes (potential evaporation, 8%) represent additional important climatic controls.

A significant positive correlation exists between lake albedo and LCC efficiency across China's lakes (Figure S6a in Supporting Information S1). This relationship is particularly significant for lakes on the TP (Figure S6c in

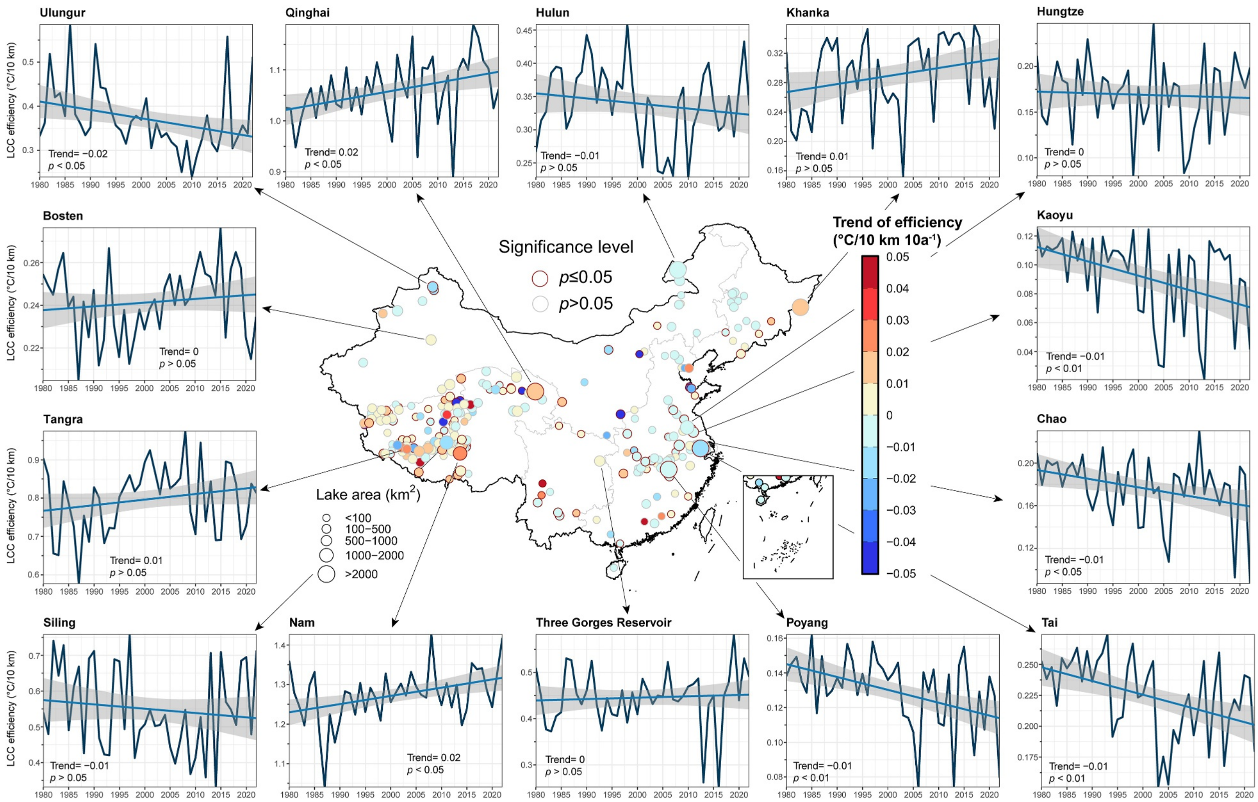

Figure 3. Temporal trends in LCC efficiency across China. The central plot shows the trend magnitude and statistical significance of LCC efficiency for 265 studied lakes. Surrounding panels display the time series and linear regression curves of LCC efficiency for the 14 largest lakes, arranged geographically.

Supporting Information S1). Concurrently, multi-year trends reveal a widespread and significant decrease in albedo for TP lakes (Figure S6b in Supporting Information S1). This declining albedo trend is likely associated with the rapid expansion of TP lakes, which may alter surface properties and water composition.

Figures 4c–4e further reveals the dominant drivers of inter-lake variability in LCC. Surface pressure emerged as the primary control on LCC extent and a significant predictor of both magnitude and efficiency. Geographic location (longitude/latitude) also contributed substantially to spatial heterogeneity in cooling extent. For LCC efficiency, lakeshore topography and lake morphology dominated, with mean depth, longitude, and near-shore slope (100 m buffer, slope_100) identified as the three most important geomorphic determinants. Lake elevation additionally played a significant role in shaping LCC patterns.

Lake area, average depth, and total volume are all positively correlated with both LCC magnitude and LCC efficiency, with lake depth exhibiting a stronger and more significant influence on LCC (Figure S7 in Supporting Information S1). Deeper lakes, indicative of greater water storage capacity, enhanced heat storage capacity and cooling efficiency. Longitudinal gradients reflected a clear west-east decline in LCC efficiency. Steeper near-shore slopes (typical of mountain lakes) were associated with higher LCC efficiency, likely due to constrained atmospheric mixing. In contrast, gentle littoral zones promoted greater heat exchange and stronger lake–atmosphere coupling. Morphological factors overall outweighed climatic variables in explaining efficiency patterns, with 9 of 11 statistically significant predictors ($p < 0.05$) relating to physical lake attributes. Among meteorological variables, surface pressure and 2 m air temperature significantly influenced LCC magnitude and efficiency, underscoring the role of regional climate background in modulating lake cooling performance.

To integrate our spatial, temporal, and driver analyses, we propose that China's lakes can be conceptualized into four characteristic types of cooling response based on the two most influential drivers identified: surface albedo and lake depth (Figures S8–S10 in Supporting Information S1). Lakes were classified into four categories using median albedo and depth thresholds: high albedo-deep lake (HA-DL), high albedo-shallow lake (HA-SL), low albedo-deep lake (LA-DL), and low albedo-shallow lake (LA-SL). Among these, HA-DL lakes exhibit the

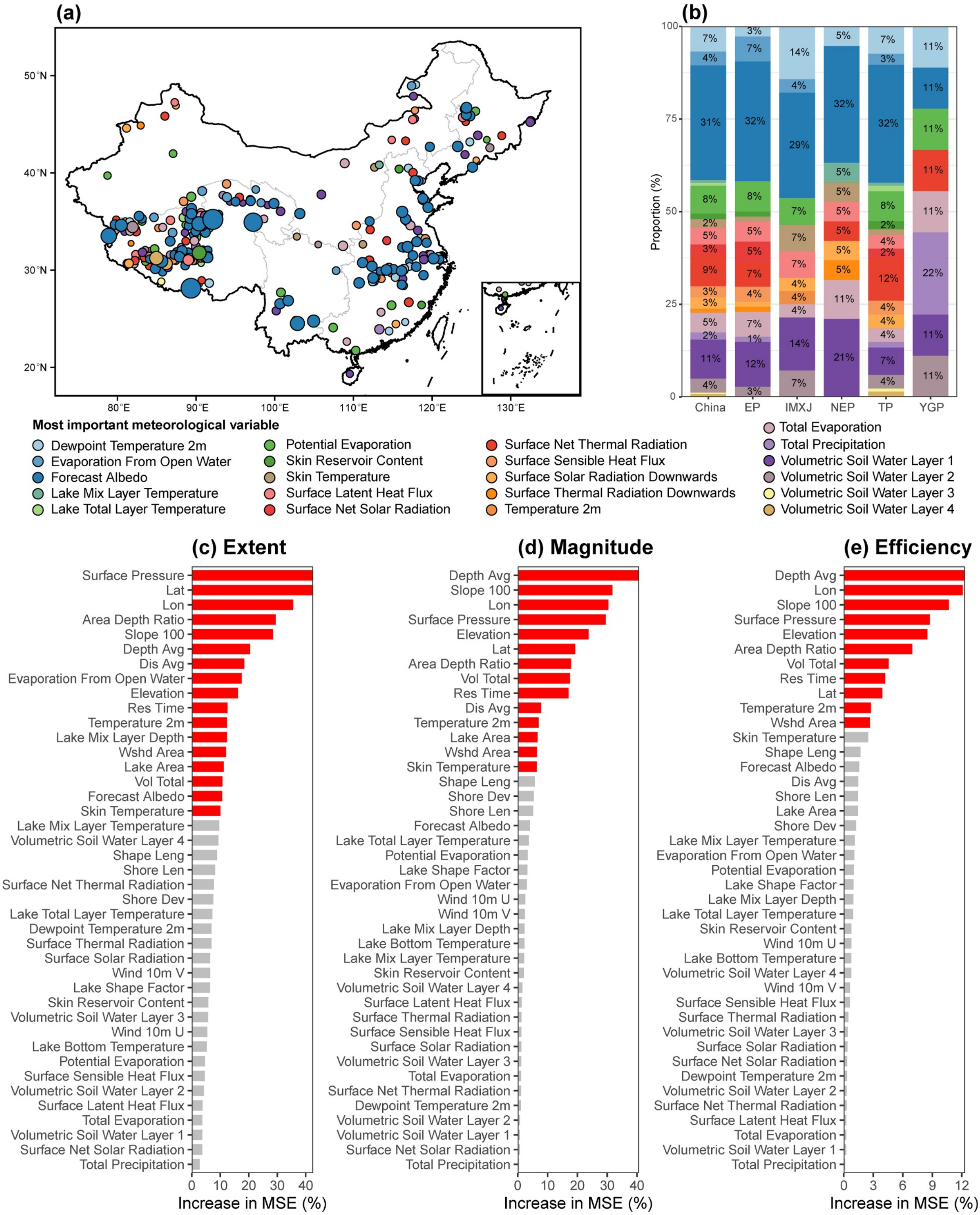

Figure 4. Control factors on LCC identified through random forests models. (a) Key meteorological drivers and their importance (quantified by increase in MSE) for LCC efficiency across lakes. (b) Proportional distribution of primary meteorological factors by lake region. (c–e) Importance of environmental predictors (including lake geomorphometry and climate variables) for LCC (c) extent, (d) magnitude, and (e) efficiency across China. Red bars denote statistically significant predictors ($p < 0.05$).

highest median LCC efficiency (Figure S10 in Supporting Information S1) and are predominantly located in the western TP (Figure S9 in Supporting Information S1). LA-DL lakes, which also show relatively high cooling efficiency, are mainly distributed in the eastern TP, YGP, and parts of the EP. In contrast, LA-SL lakes, characterized by the lowest median LCC efficiency, are concentrated in the EP, especially within the Yangtze River mid-lower reaches. This typology not only synthesizes the key drivers of LCC variability but also highlights how combinations of albedo and depth shape the spatial patterning of lake cooling effectiveness across China's major lake regions.

4. Discussion

4.1. Climate Regulation Capacity of China's Lakes

This study presents comprehensive assessment of LCC across China, using a multi-indicator framework that quantifies the extent, magnitude, and efficiency of lake-induced temperature regulation. Our tri-metric approach reveals that Chinese lakes exert substantial cooling on summer daytime maximum temperatures, with a mean LCC extent of 27.5 km, a magnitude of 1.03°C, and an efficiency of 0.46°C/10 km. This integrated characterization demonstrates that lakes provide crucial mitigation of regional heat extremes. Notably, the efficiency metric enabled the novel identification of the Eastern Plain lakes as the most effective climate regulators, despite their generally smaller sizes compared to Tibetan lakes. This finding suggests that lake morphology and local topography outweigh absolute lake size in controlling the spatial influence of lake effects, a nuance previously obscured by single-metric approaches. While the cooling magnitude aligns with prior regional studies (Bryan et al., 2015; Zhu et al., 2018), our multi-dimensional assessment reveals how cooling capacity varies in structure, not just in magnitude, across diverse lake regions.

The pronounced regional heterogeneity in LCC extent, particularly the smaller values observed on the TP compared to the NEP, may also be linked to fundamental differences in geomorphology. On the TP, many large lakes reside in isolated, high-elevation basins bounded by mountain ranges (Chen et al., 2022). When applying a fixed 0–100 km concentric buffer, these zones can extend beyond the immediate topographic basin, incorporating adjacent areas that may belong to separate climatic regimes. This could lead to the detection of an earlier temperature gradient breakpoint, resulting in a smaller estimated LCC extent. In contrast, the vast, flat landscapes of the northeastern and eastern plains allow lake-influenced air masses to advent farther with less topographic disruption, facilitating a more extensive spatial footprint.

The divergent trends in cooling efficiency between high-altitude Tibetan lakes and low-altitude Eastern Plain lakes reveal complex responses to climate change. Tibetan lakes' enhanced cooling capacity coincides with documented lake expansion (Guo et al., 2021; Xu et al., 2024), suggesting that increased water volume amplifies their climate regulation function. This amplification likely operates through multiple pathways: increased evaporative cooling due to larger surface area, enhanced albedo from glacier-fed sediment inputs, and greater thermal inertia from deeper waters (Lee et al., 2023). Conversely, Eastern Plain lakes' diminished cooling capacity occurs alongside widespread lake shrinkage, indicating that water loss reduces their ability to moderate local climate.

4.2. Mechanistic Insights From Driver Analysis

Our random forests models reveal that albedo variations dominate the temporal variability in lake cooling capacity (LCC), highlighting the central role of surface energy balance in mediating lake-atmosphere interactions. Mechanistically, albedo fluctuations (driven by water area changes, sediment influx, or ice-cover dynamics) directly regulate solar energy absorption, thereby modulating the lake's thermal storage and subsequent cooling effects (Hou et al., 2025). The secondary importance of evaporation and radiation-related variables in our analysis further underscores the critical role of surface energy partitioning. While albedo regulates solar energy input, evaporation acts as the primary heat dissipation pathway, converting absorbed radiation into latent heat flux and thereby modulating the intensity of daytime cooling (Vanderkelen et al., 2020).

Spatially, the primacy of topographic and morphometric factors reveals that lake dimensions and surrounding terrain constrain the expression of climate effects (Qin et al., 2023). Lake depth emerged as a key driver of LCC efficiency heterogeneity, with deeper lakes enhancing heat storage capacity and sustaining stronger LCC. Steeper surrounding topography appears to enhance cooling efficiency by restricting cold air drainage and prolonging lake-air interaction. For LCC extent, surface pressure was identified as the primary determinant, governing the horizontal propagation scale of lake effects through its control on atmospheric boundary layer structure. Lower surface pressure promotes deeper vertical mixing, enabling lake-modified air masses to spread farther downwind, whereas higher pressure conditions suppress vertical development and constrain lake effects to nearer shores.

The driver importance analysis provides a mechanistic foundation for the key spatial patterns described earlier. The dominant role of albedo in governing temporal variability directly explains the enhanced cooling efficiency observed on the TP. The significant positive albedo-LCC relationship for TP lakes coupled with their widespread albedo decline, suggests that ongoing lake expansion is a key modulator of their cooling capacity (Qiu et al., 2023). Furthermore, the identified importance of both lake area and depth points to the integrated role of total lake water storage (Su et al., 2020). Greater water volume confers higher thermal inertia, enabling a lake to absorb more solar energy, thereby sustaining a stronger land-lake temperature gradient and a more robust cooling effect (Subin et al., 2012). This storage-induced mechanism offers a unified explanation for the divergent regional trends: significant water volume increase on the TP enhances thermal inertia and supports strengthening LCC, whereas widespread lake shrinkage and shallowing in the EP reduce water storage and weaken cooling efficiency.

The classification scheme based on albedo and lake depth provides a transferable framework for characterizing LCC in other global regions. The dominant drivers identified in this study, surface energy regulation (governed by albedo) and heat storage capacity (determined by depth), represent fundamental physical properties of lakes that are relevant across diverse climatic and geographic settings. For example, in high-latitude or glacial-fed lakes, elevated albedo due to prolonged ice cover or meltwater inputs could enhance cooling efficiency, mirroring the behavior of high-albedo deep lakes on the Tibetan Plateau (Wen et al., 2015). Similarly, shallow lakes with low albedo in arid or semi-arid regions may exhibit minimal cooling capacity, comparable to the low-albedo shallow lakes in eastern China (Gu et al., 2016). This physically grounded typology offers a scalable approach to synthesize cross-regional patterns, prioritize lakes for climate-adaptive management, and improve the representation of lake effects in earth system models.

To further assess the robustness of LCC under varying meteorological backgrounds, we conducted a supplemental analysis examining the influence of precipitation on LCC (Figures S11 and S12 in Supporting Information S1). By comparing distance-T_2max gradients and LCC metrics between rainy (days with total precipitation $\geq$1 mm, including the following 1–2 days) and non rainy days across all lake regions, we found that precipitation generally lowers near shore daytime temperatures, yet its effect on spatial cooling patterns remains limited (Figure S11 in Supporting Information S1). Nationally, rainfall slightly reduced LCC extent and magnitude, leading to a modest and statistically non significant decrease in cooling efficiency (Figure S12 in Supporting Information S1). The most pronounced precipitation mediated suppression of LCC occurred on the TP, whereas other regions showed weaker responses. These results suggest that while precipitation contributes to surface cooling, its influence does not fundamentally alter the lake dominated thermal regulation patterns identified in our main analysis.

4.3. Implications, Limitations and Future Scope

The spatial and temporal patterns of lake cooling efficiency have important implications for climate change adaptation. Regions experiencing both lake shrinkage and reduced cooling capacity, particularly the Eastern Plain, face compound challenges of diminishing water resources and weakening natural climate regulation. This dual threat exacerbates vulnerability to heat extremes in precisely those regions with high population density and agricultural importance (Li et al., 2025). Conversely, the enhanced cooling capacity of expanding Tibetan lakes may provide some mitigation to warming trends in these sensitive high-altitude ecosystems (Qiu et al., 2025). Our findings suggest that lake conservation and restoration could serve as effective climate adaptation strategies, particularly in regions where maintaining lake ecosystems helps preserve their climate regulation services (Cheng et al., 2023).

The increasing prevalence of lake heatwaves presents a potential threat to lake-induced climate regulation (Yang et al., 2025). A severe lake heatwave elevates lake surface temperature, thereby reducing the critical land-water temperature gradient that drives evaporative and sensible heat fluxes (Woolway et al., 2021). This process likely suppresses the LCC during the event. Should such events increase in frequency or intensity under climate change, a sustained reduction in seasonal or annual mean LCC could occur, particularly for shallow lakes with lower thermal inertia (Qin et al., 2023). Future research must integrate lake thermal dynamics with near-surface climate analysis to evaluate the resilience of LCC under compound heat extremes.

While our concentric zone approach effectively quantifies lake cooling extent, it simplifies complex spatial patterns that higher-resolution climate models could better resolve. Future work should integrate 3D atmospheric modeling with seasonal tracking to unravel how lake-atmosphere interactions evolve under climate variability.

5. Conclusions

This study provides a quantitative assessment of lake cooling capacity across China's 265 major lakes through three key metrics: spatial extent, intensity, and efficiency. Results show that lakes exert substantial summer daytime cooling, with a mean extent of 27.5 km, a magnitude of 1.03°C, and an efficiency of 0.46°C/10 km. Spatially, lake's cooling is most efficient in the Yunnan-Guizhou Plateau and weakest in the northeastern plains. Temporally, 57% of lakes have significantly increased cooling efficiency since 1980, though trends diverge regionally, which is strengthening on the Tibetan Plateau but weakening in eastern plain. These patterns are primarily controlled by surface albedo and lake morphology, emphasizing the role of both climatic and geomorphic factors. The findings highlight the importance of incorporating lake-climate interactions into regional climate adaptation and lake conservation strategies.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The ERA5-Land data used in this study is available at Muñoz Sabater (2019). The DEM data is available at OpenTopography (2013). The GLC_FCS30-2020 data is available at L. Liu et al. (2023). The in situ air temperature data can be accessed through China Meteorological Data Service Centre at https://data.cma.cn/data/detail/dataCode/A.0012.0001.S011.html ("China Surface Meteorological Observation Data," 2025). The HydroLAKES data set is available at https://www.hydrosheds.org/pages/hydrolakes ("HydroLAKES," 2016).

Acknowledgments
This work was supported by the National Key Research and Development Program of China (2022YFF0801104), the National Natural Science Foundation of China (42071036, 42401049), the China Postdoctoral Science Foundation (2024M763367), the Science Foundation of Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (NIGLAS2022GS08), the Jiangxi "Double Thousand Plan" (jxsq2023101105), the Jiangxi Provincial Natural Science Foundation (20252BAC200244), the Youth Innovation Promotion Association of the Chinese Academy of Sciences (2022067), and the German Research Foundation (DFG) through funding of the AccHydro project (KU 2090/11-1).

References

Breiman, L. (2001). Random forests. *Machine Learning*, *45*(1), 5–32. https://doi.org/10.1023/a:1010933404324

Bryan, A. M., Steiner, A. L., & Posselt, D. J. (2015). Regional modeling of surface-atmosphere interactions and their impact on Great Lakes hydroclimate. *Journal of Geophysical Research: Atmospheres*, *120*(3), 1044–1064. https://doi.org/10.1002/2014jd022316

Chen, T., Song, C., Fan, C., Cheng, J., Duan, X., Wang, L., et al. (2022). A comprehensive data set of physical and human-dimensional attributes for China's lake basins. *Scientific Data*, *9*(1), 519. https://doi.org/10.1038/s41597-022-01649-z

Cheng, Y., Bartesaghi-Koc, C., Tian, Y., Shen, L., Teng, M., Liu, H., et al. (2023). Where and how to cool through blue infrastructure? Large lake groups to ameliorate urban overheating in a typical inland multi-lake megacity. *Sustainable Cities and Society*, *98*, 104869. https://doi.org/10.1016/j.scs.2023.104869

China Surface Meteorological Observation Data. (2025). Retrieved from https://data.cma.cn/data/detail/dataCode/A.0012.0001.html

Du, H., Song, X., Jiang, H., Kan, Z., Wang, Z., & Cai, Y. (2016). Research on the cooling island effects of water body: A case study of Shanghai, China. *Ecological Indicators*, *67*, 31–38. https://doi.org/10.1016/j.ecolind.2016.02.040

Gao, X., Yan, Z., Bao, L., Li, X., Gao, L., & Yu, L. (2025). Satellite observation reveals wetland-induced local cooling moderated by regional climate gradients. *Science of Remote Sensing*, *12*, 100292. https://doi.org/10.1016/j.srs.2025.100292

Gu, H., Ma, Z., & Li, M. (2016). Effect of a large and very shallow lake on local summer precipitation over the Lake Taihu basin in China. *Journal of Geophysical Research: Atmospheres*, *121*(15), 8832–8848. https://doi.org/10.1002/2015JD024098

Guo, Y., Song, C., Zhang, J., Wang, L., & Sun, L. (2021). Influence of wetland reclamation on land-surface energy exchange and evapotranspiration in the Sanjiang plain, Northeast China. *Agricultural and Forest Meteorology*, *296*, 108214. https://doi.org/10.1016/j.agrformet.2020.108214

Hou, Z., Zhang, L., Peng, J., Forzieri, G., Jia, A., Xiao, Z., et al. (2025). Radiative forcing reduced by early twenty-first century increase in land albedo. *Nature*, *641*(8065), 1162–1171. https://doi.org/10.1038/s41586-025-08987-z

Hua, W., Dai, A., Qin, M., Hu, Y., & Cui, Y. (2023). How unexpected was the 2022 summertime heat extremes in the middle reaches of the Yangtze River? *Geophysical Research Letters*, *50*(16), e2023GL104269. https://doi.org/10.1029/2023GL104269

HydroLAKES. (2016). Retrieved from https://www.hydrosheds.org/products/hydrolakes

Jiang, J., Liu, Y., Mao, J., & Wu, G. (2023). Extreme heatwave over Eastern China in summer 2022: The role of three oceans and local soil moisture feedback. *Environmental Research Letters*, *18*(4), 044025. https://doi.org/10.1088/1748-9326/acc5fb

Lee, H., Ganbat, G., Jin, H.-G., Seo, J. M., Moon, S., Bok, H., & Baik, J.-J. (2023). Effects of Lake Baikal on summertime precipitation climatology over the Lake surface. *Geophysical Research Letters*, *50*(10), e2023GL103426. https://doi.org/10.1029/2023GL103426

Li, Z., Zhao, X., Fan, X., Lu, Y., Zhao, L., & Wu, A. (2025). Diminishing cooling effects of China's largest freshwater lake due to shrinking water surfaces. *Ecological Indicators*, *178*, 114097. https://doi.org/10.1016/j.ecolind.2025.114097

Liang, X.-Z., Xu, M., Yuan, X., Ling, T., Choi, H., Zhang, F., et al. (2012). Regional climate-weather research and forecasting model. *Bulletin of the American Meteorological Society*, *93*(9), 1363–1387. https://doi.org/10.1175/bams-d-11-00180.1

Liu, K., Song, C., Zhao, S., Wang, J., Chen, T., Zhan, P., et al. (2024). Mapping inundated bathymetry for estimating lake water storage changes from SRTM DEM: A global investigation. *Remote Sensing of Environment*, *301*, 113960. https://doi.org/10.1016/j.rse.2023.113960

Liu, L., Zhang, X., & Zhao, T. (2023). GLC_FCS30D: The first global 30-m land-cover dynamic monitoring product with fine classification system from 1985 to 2022 [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.8239305

Messager, M. L., Lehner, B., Grill, G., Nedeva, I., & Schmitt, O. (2016). Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nature Communications*, *7*(1), 13603. https://doi.org/10.1038/ncomms13603

Muñoz Sabater, J. (2019). ERA5-Land hourly data from 1950 to present [Dataset]. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. https://doi.org/10.24381/cds.e2161bac

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., et al. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349–4383. https://doi.org/10.5194/essd-13-4349-2021

OpenTopography. (2013). Shuttle Radar Topography Mission (SRTM) Global [Dataset]. *OpenTopography*. https://doi.org/10.5069/G9445JDF

Pettitt, A. N. (1979). A non-parametric approach to the change-point problem. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, *28*(2), 126–135. https://doi.org/10.2307/2346729

Qin, J., Xing, Y., Liu, J., Nakhaei, P., Hamamy, W., Li, B., et al. (2023). Modelling analysis of the potential impact of large reservoir on heatwave events. *Ecological Indicators*, *154*, 110841. https://doi.org/10.1016/j.ecolind.2023.110841

Qiu, Y., Chen, J., Chen, D., Li, W., & Xiong, L. (2023). Lake-Area expansion alters downwind precipitation patterns on the Tibetan Plateau: Insights from the Most dramatically expanded Lake. *Journal of Geophysical Research: Atmospheres*, *128*(15), e2023JD039274. https://doi.org/10.1029/2023JD039274

Qiu, Y., Chen, J., Chen, D., Woolway, R. I., Luo, H., & Xiong, L. (2025). Dipolar response of precipitation to lake expansion on the Tibetan Plateau. *Journal of Hydrology*, *660*, 133532. https://doi.org/10.1016/j.jhydrol.2025.133532

Rouse, W. R., Blanken, P. D., Duguay, C. R., Oswald, C. J., & Schertzer, W. M. (2008). Climate-Lake interactions. In M. Woo (Ed.), *Cold Region atmospheric and hydrologic studies. The mackenzie GEWEX experience* (pp. 139–160). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-75136-6_8

Scott, R. W., & Huff, F. A. (1996). Impacts of the Great Lakes on regional climate conditions. *Journal of Great Lakes Research*, *22*(4), 845–863. https://doi.org/10.1016/s0380-1330(96)71006-7

Su, D., Wen, L., Gao, X., Leppäranta, M., Song, X., Shi, Q., & Kirillin, G. (2020). Effects of the largest Lake of the Tibetan Plateau on the regional climate. *Journal of Geophysical Research: Atmospheres*, *125*(22), e2020JD033396. https://doi.org/10.1029/2020JD033396

Subin, Z. M., Murphy, L. N., Li, F., Bonfils, C., & Riley, W. J. (2012). Boreal lakes moderate seasonal and diurnal temperature variation and perturb atmospheric circulation: Analyses in the Community Earth System Model 1 (CESM1). *Tellus A: Dynamic Meteorology and Oceanography*, *64*(1), 15639. https://doi.org/10.3402/tellusa.v64i0.15639

Tao, S., Fang, J., Ma, S., Cai, Q., Xiong, X., Tian, D., et al. (2020). Changes in China's lakes: Climate and human impacts. *National Science Review*, *7*(1), 132–140. https://doi.org/10.1093/nsr/nwz103

Tian, Y., Kleidon, A., Lesk, C., Zhou, S., Luo, X., Ghausi, S. A., et al. (2024). Characterizing heatwaves based on land surface energy budget. *Communications Earth & Environment*, *5*(1), 617. https://doi.org/10.1038/s43247-024-01784-y

Vanderkelen, I., Van Lipzig, N. P. M., Lawrence, D. M., Droppers, B., Golub, M., Gosling, S. N., et al. (2020). Global heat uptake by inland waters. *Geophysical Research Letters*, *47*(12), e2020GL087867. https://doi.org/10.1029/2020gl087867

Wang, B., Ma, Y., Chen, X., Ma, W., Su, Z., & Menenti, M. (2015). Observation and simulation of lake-air heat and water transfer processes in a high-altitude shallow lake on the Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, *120*(24), 12327–12344. https://doi.org/10.1002/2015jd023863

Wang, W., Shi, K., Wang, X., Zhang, Y., Qin, B., Zhang, Y., & Woolway, R. I. (2024). The impact of extreme heat on lake warming in China. *Nature Communications*, *15*(1), 70. https://doi.org/10.5281/zenodo.10214063

Wen, L., Lv, S., Li, Z., Zhao, L., & Nagabhatla, N. (2015). Impacts of the two biggest Lakes on local temperature and precipitation in the Yellow River source region of the Tibetan Plateau. *Advances in Meteorology*, *2015*(1), 248031. https://doi.org/10.1155/2015/248031

Wilcox, R. R. (2005). Theil–Sen estimator. In *Introduction to robust estimation and hypothesis testing* (pp. 423–427). Academic Press.

Woolway, R. I., Jennings, E., Shatwell, T., Golub, M., Pierson, D. C., & Maberly, S. C. (2021). Lake heatwaves under climate change. *Nature*, *589*(7842), 402–407. https://doi.org/10.1038/s41586-020-03119-1

Xing, Z., Li, Y., Dai, Y., Wei, J., Ma, M., Zhang, X., et al. (2026). Quantifying the spatial extent and attenuation of lake thermal regulation at diurnal scales under extreme heat. *Weather and Climate Extremes*, *51*, 100847. https://doi.org/10.1016/j.wace.2025.100847

Xu, F., Zhang, G., Woolway, R. I., Yang, K., Wada, Y., Wang, J., & Crétaux, J.-F. (2024). Widespread societal and ecological impacts from projected Tibetan Plateau lake expansion. *Nature Geoscience*.

Yan, Y., Hou, H., Murayama, Y., Wang, R., & Hu, T. (2024). How do landscape patterns affect cooling intensity and scale? Evidence from 13 primary urban wetlands in China. *Ecological Indicators*, *166*, 112574. https://doi.org/10.1016/j.ecolind.2024.112574

Yang, Y., Deng, J., Woolway, R. I., Jeppesen, E., Shi, K., Qin, B., et al. (2025). Lakes are experiencing more severe heatwaves than the atmosphere. *Communications Earth & Environment*, *6*(1), 959. https://doi.org/10.1038/s43247-025-02907-9

Zhang, G., Yao, T., Chen, W., Zheng, G., Shum, C. K., Yang, K., et al. (2019). Regional differences of lake evolution across China during 1960s–2015 and its natural and anthropogenic causes. *Remote Sensing of Environment*, *221*, 386–404. https://doi.org/10.1016/j.rse.2018.11.038

Zhang, X., Liu, L., Chen, X., Gao, Y., Xie, S., & Mi, J. (2021). GLC_FCS30: Global land-cover product with fine classification system at 30 m using time-series Landsat imagery. *Earth System Science Data*, *13*(6), 2753–2776. https://doi.org/10.5194/essd-13-2753-2021

Zhu, L., Jin, J., Liu, X., Tian, L., & Zhang, Q. (2018). Simulations of the impact of Lakes on local and regional climate over the Tibetan Plateau. *Atmosphere-Ocean*, *56*(4), 230–239. https://doi.org/10.1080/07055900.2017.1401524