

Glacier meltwater modulation of lake warming trends in China

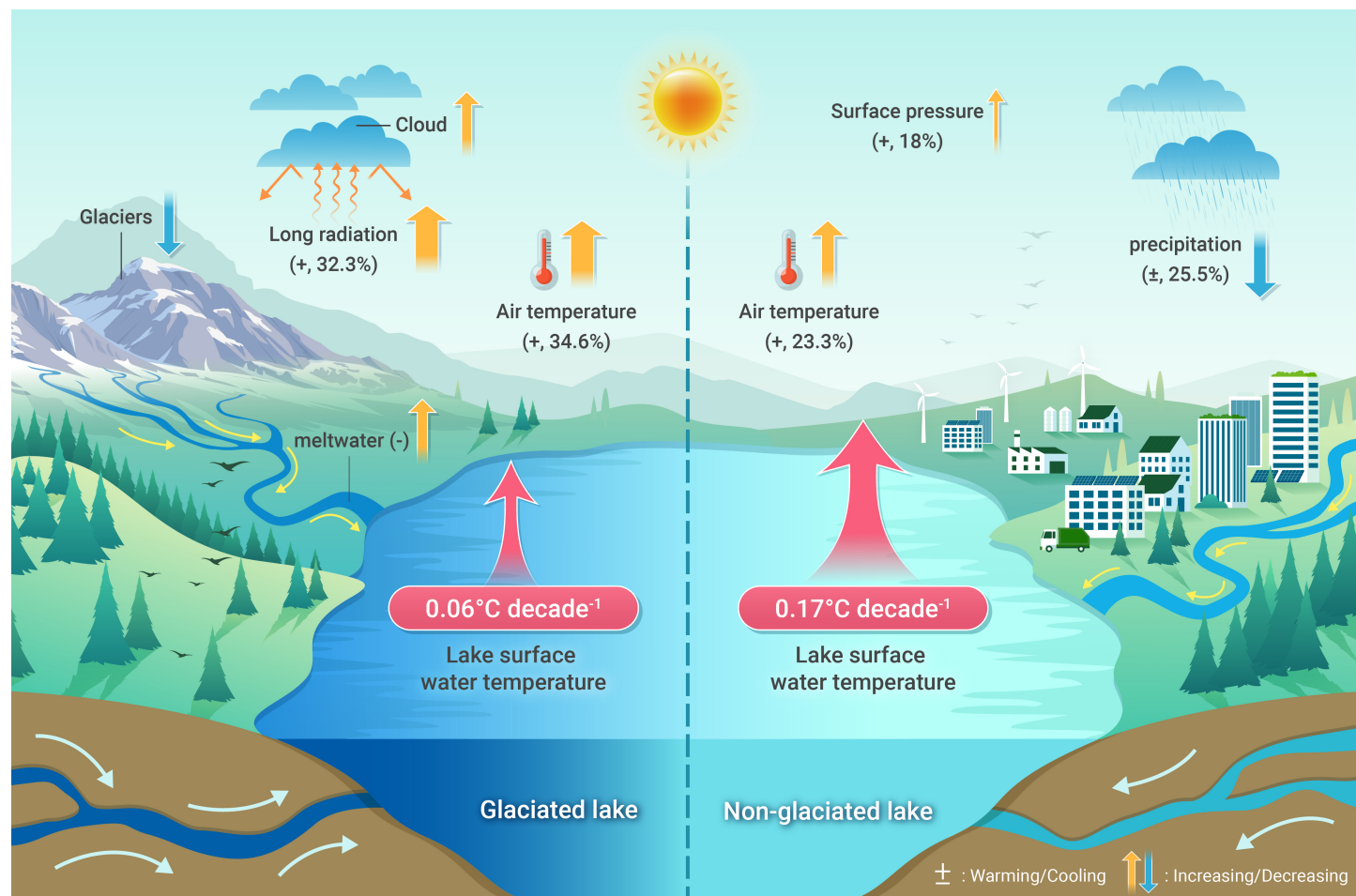
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- We studied 2,260 lakes in China to assess how glacier meltwater modulates lake warming.
- Glacier meltwater suppressed over 86% of surface warming in glaciated lakes.
- Lakes in glaciated regions warmed less, especially during spring and summer melt seasons.
- Longwave radiation and air temperature drive glacier melt, controlling warming in glacial lakes.

Glacier meltwater modulation of lake warming trends in China

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Global warming has led to a rapid rise in lake surface water temperature (LSWT) over the past few decades. However, in some regions, enhanced glacier meltwater due to climate change may mitigate these trends. In this study, we investigated 2,260 lakes across China to understand the impact of glacier meltwater on LSWT from 1985 to 2022. We found that glaciated regions have a significantly lower average warming rate ($0.06 \pm 0.004^\circ\text{C decade}^{-1}$) compared to lakes in non-glaciated regions ($0.17 \pm 0.004^\circ\text{C decade}^{-1}$) ($p < 0.05$). This difference is more pronounced during the glacier melting season (spring and summer). Importance assessment suggested that increased longwave radiation and air temperature accelerate glacier melting, controlling warming rate in glaciated lakes (66.9%). Moreover, we find that glacier meltwater significantly impacts LSWT trends ($-0.1^\circ\text{C decade}^{-1}$) suppressing over 86% of the warming rates in lakes located in glaciated regions. These findings provide important references to accurately evaluate the warming trend of LSWT in China, as well as more broadly, providing valuable insights for climate change impact studies and water resource management.

INTRODUCTION

Global warming has become a defining issue of the 21st century, influencing various natural processes and ecosystems.¹ Among the most affected ecosystems by climate change are lakes.²⁻⁴ Lake surface water temperature (LSWT), often described as a master factor in aquatic ecosystems,⁵ is particularly sensitive to climatic variations.⁶⁻⁸ Recent studies have shown that LSWTs have increased significantly in recent decades,^{8,10} with seasonally ice-covered lakes typically experiencing the highest warming rates.¹⁵⁻¹⁷ In some regions, LSWT trends have outpaced air temperature changes,^{4,16} or increased at higher rates than expected from changes in air temperature alone.¹⁸ Higher warming rates are often attributed to changes in, among others, solar radiation,¹⁹ wind speed,²⁰ or changes in watershed characteristics.^{21,22} Without mitigating greenhouse gas emissions, LSWTs are projected to increase further this century, at a rate of $0.53^\circ\text{C per decade}$.¹⁷

Changes in LSWT influence key physical processes in lakes, including evaporation, thermal stratification and vertical mixing, as well as biogeochemical processes including nutrient cycling, greenhouse gas production, and primary productivity.^{2,21} These changes can disrupt lake ecosystems^{7,20,23} and impact human societies reliant on these water bodies.^{8,9} Thus, understanding the drivers of LSWT change is of critical importance. While the global rise in LSWT is well-documented, less attention has been given to lakes in glaciated regions, where glacier meltwater can affect the lake thermal environment. Some research suggests that meltwater may moderate LSWT increases,^{24,25} but large-scale studies are limited.

Glacial meltwater not only alters the chemical composition and nutrient content of lakes but also their thermal dynamics.^{26,27} China, home to the largest glacier area in the mid- and low latitudes, has 48,571 glaciers covering $51,480\text{ km}^2$.^{28,29} Unlike other regions where climate warming has caused lake shrinkage or disappearance, high-altitude plateau lakes are expanding or even forming new lakes due to substantial glacial meltwater inputs.^{30,31} Since 1990, glacier melt has driven substantial lake expansion across the Asian highlands, particularly on the Qinghai-Tibetan Plateau (TP).³¹ The TP, known as the "Third Pole" and "Asia's Water Tower", has an average elevation exceeding 4,000 m and contains over 1,100 alpine lakes (each $\geq 1\text{ km}^2$), with a

total area surpassing $46,527\text{ km}^2$.³² Characterized by its unique and complex atmospheric, cryosphere, hydrological, geological, and environmental systems, the TP has become a critical indicator of climate warming and serves as an early warning signal for global climate change.^{33,34} Records showed that the TP has experienced the most severe warming, with rates doubling the global average.³⁵ This accelerated warming has led to rapid glacier mass loss and consequent dramatic expansion of TP lakes.^{36,37} Between 1986 and 2022, the total lake area increased by approximately $10,000\text{ km}^2$.³⁸ Projections indicate that lake surfaces will expand by over 50% this century, with water levels rising by about 10 meters, even under the low greenhouse gas emission scenario SSP1-2.6.³⁹ Many lakes in these high mountain and plateau areas receive substantial glacial meltwater, potentially suppressing LSWT warming. Despite the recognized influence of glacier meltwater, its impact on LSWT warming is not well understood. Previous studies have observed lower LSWT warming rates in the Qinghai-Tibet Plateau,^{40,41} but the processes remain underexplored. To address this, our study investigates 2,260 lakes in China to elucidate the process and quantify the degree to which LSWT is modulated by glacier meltwater. This research enhances understanding of glacier meltwater impacts and helps accurately assess LSWT trends in China.

MATERIAL AND METHODS

Lake surface water temperatures

Lake surface water temperature data were obtained from the *Daily Scale Dataset of Surface Water Temperature of Chinese Lakes and Lakes with Extreme High Temperature Removal (1985-2022)*. This dataset is based on the air2water model, which used observed data from six lakes for model validation (Lake Erhai, Lake Hulunhu, Lake Namco, Lake Luguhu, Lake Qian-daohu, and Lake Taihu, covering both glaciated and non-glaciated lakes) and is of high modeling accuracy ($R^2 \geq 0.93$, $MAE < 2.00^\circ\text{C}$).¹¹ Additionally, these 2,260 lakes exhibit a spatially uniform distribution, with surface areas ranging from 1 to $4,266\text{ km}^2$, volumes spanning 0.5 to $99,007\text{ mcm}$ ($1\text{ mcm} = 0.001\text{ km}^3$), mean depths varying between 0.5 and 205 m, and elevations extending from -3 to $5,446\text{ m}$. This dataset provides strong representativeness for lakes across China (Figure S1). To verify the authenticity of the research results, we compared the dataset with another produced by combining satellite observation and the Flake model.¹⁷ The dataset has been validated against measured water temperature data from 29 lakes distributed across the globe, which include both glaciated and non-glaciated lakes, demonstrating a high level of accuracy ($R^2=1$, $MAE=1.15^\circ\text{C}$). These two datasets have been extensively utilized in other research studies.^{12,13} Firstly, 529 lakes in the Chinese region were matched with the same lake number, including 330 glaciated lakes and 199 non-glaciated lakes. Subsequently, LSWT data of 20% of the lakes were randomly selected to calculate the R^2 , MAE, and RMSE values between the two datasets. The results showed that the two datasets are comparable (glaciated lakes: $R^2=0.6$, $MAE=1.01^\circ\text{C}$, and $RMSE=1.02^\circ\text{C}$; non-glaciated lakes: $R^2=0.8$, $MAE=0.63^\circ\text{C}$, and $RMSE=0.65^\circ\text{C}$) (Figure S2), indicating that the LSWT dataset used in this study is reliable.

In addition, in glacier areas, lake drainage areas serve as smaller supply units than lake basin areas. When there are glaciers in the drainage area, it is certain that the lake can directly receive glacier meltwater. In this regard, lake drainage dataset was used to further validate our research findings. Firstly,

2,352 lake drainage areas in China were matched using the same lake number as the LSWT data (the reason why the number of matched lake drainage areas is larger than the number of lakes with LSWT is that lake drainage areas are divided based on lake outlets, and some lakes have multiple drainage areas because they have multiple outlets). Then, we merged the drainage areas of lakes with multiple lake outlets to produce 2,260 drainage areas. Furthermore, by overlaying glacier data with lake drainage data, 321 lake drainage areas with glaciers and 1,939 lake drainage areas without glaciers were identified to investigate the differences in their warming rates (Figure S3). The results showed that the LSWT warming rate of glaciated lakes is $0.05\text{ }^{\circ}\text{C decade}^{-1}$ using the lake drainage area dataset (Figure S4), which is comparable with the warming rate ($0.06\text{ }^{\circ}\text{C decade}^{-1}$) obtained based on the lake basin area dataset, indicating that using the lake basin area dataset to investigate glacial meltwater in this study is reasonable.

Statistical methods

To further demonstrate the scientific validity of dividing lakes into glaciated and non-glaciated categories, we used the K-means clustering algorithm to classify them into two groups based on the average LSWTs / trend in LSWTs and latitude and longitude of these lakes. K-means algorithm is an unsupervised machine learning algorithm commonly used for data classification. It first randomly selects K initial center points, then assigns each data point to the nearest center point, and recalculates the center points of each cluster. This process is repeated until the cluster center no longer undergoes significant changes.

We use Theil Sen slope estimation method to calculate the annual and seasonal warming trends of LSWTs, with four seasons defined as spring (March-May), summer (June-August), autumn (September-November), and winter (December-February). The statistical significance of temperature differences between glaciated and non-glaciated regions was assessed using t-tests and analysis of covariance (ANCOVA). Theil Sen is a non-parametric method used to fit linear regression models, with the main advantage of strong robustness to outliers. It estimates the slope of the regression line by calculating the slopes of all point pairs in the data, and then takes the median of these slopes as the final estimated value.

We used partial correlation analysis to analyze the effects of air temperature and longwave radiation on changes in LSWT. Partial correlation analysis is a statistical method commonly used in the study of multiple strongly correlated variables. It measures the linear relationship between two variables by controlling for the influence of one or more other variables, helping us to more accurately understand the true relationship between the two variables.

Classification of lake types and identification of watershed areas with the greatest glacier meltwater cooling effect

To distinguish between lakes with and without glaciers in their watershed, we first overlaid data from 12 sub watersheds in China and glacier data and added the attributes of glaciers to the data of 12 sub watersheds. We divided the watersheds with glaciers and those without glaciers at different watershed levels. Then, the surface water temperature data of lakes were overlaid using watersheds with and without glaciers respectively, and lakes with and without glaciers were delineated at different watershed levels. In addition, based on the average lake volume, water depth and surface area, lakes are further divided into two categories: large and small lakes i.e., for those lakes exceeding the average value and lakes below the average value (see Figures S5-S6).

During the flow process of glacier meltwater (surface runoff or groundwater), its cooling effect will be attenuated through heat exchange. Therefore, we determined the watershed range with the maximum cooling effect of glacier meltwater by reducing the watershed range (Figure S7). To identify the watershed range with the most significant cooling effect of glacier meltwater, we calculated the average warming rate of lakes with glaciers and lakes without glaciers based on the size of the watershed range, and calculated the difference between them (the average warming rate of lakes with glaciers is always lower than that of lakes without glaciers). The results showed that in the 6th level watershed, their difference reaches the maximum value (0.11°C

decade^{-1}), which indicates that the cooling effect of glacier meltwater is the most significant in the 6th level watershed.

The glacier data are obtained from the Second Glacier Cataloging Dataset of China. This dataset records the main glaciers in the western China, including vector data and attribute data for each glacier. The dataset was compiled based on Landsat TM/ETM+ and ASTER satellite imagery acquired after 2004, with reference to the First Chinese Glacier Inventory and other relevant literature. Through a rigorous technical process including image correction, automated interpretation, field verification, manual revision, cross-checking, and expert review, it achieves comprehensive coverage of 85.5% of China's total glacierized area. The product has a spatial resolution of 30 meters, with absolute and relative errors in glacier area estimation measured at $\pm 1,411\text{ km}^2$ and 3.2%, respectively. The dataset's authors used the internationally recognized band ratio threshold segmentation method to extract glacier boundaries, developed a glacier segmentation algorithm to extract glacier segmentation ranges, and used it for the segmentation of a single glacier. Meanwhile, they used internationally recognized algorithms to calculate glacier attributes. The lake basin data are obtained from the HydroBASINS dataset, which includes a global sub basin boundary dataset and provides 12 layered nested sub basins. We used Chinese administrative boundary data to crop 12 sub watershed data in sequence, resulting in 12 sub watershed data in China.

Importance assessment

In this study, we evaluated the importance of annual changes in surface water temperature of two types of lakes based on a random forest algorithm. We selected eight meteorological factor data from the ERA5 Land dataset, namely air temperature, surface pressure, longwave radiation, shortwave radiation, total evaporation, total precipitation, u-wind, and v-wind, and calculated the annual average values of each meteorological factor in the areas with and without glaciers in the watershed from 1985 to 2022. Finally, we calculated the contribution of each factor to the variation of LSWTs. The values of meteorological factors for each lake are calculated by averaging over the entire study period within the watershed.

The random forest algorithm is an ensemble learning method. It constructs multiple decision trees, each trained on a randomly selected subset of features, and the final prediction result can be obtained through voting or calculating the average. This method effectively reduces the risk of overfitting while improving the accuracy and stability of the model.

ERA5 Land is a global surface reanalysis dataset released by the European Centre for Medium Range Weather Forecasts (ECMWF). It has high spatial resolution ($0.1^{\circ}\times 0.1^{\circ}$) and temporal resolution (hours), covering various meteorological reanalysis data from 1950 to present, including air temperature, precipitation, wind speed, humidity, radiation and other element data. The data covers the global land surface and is suitable for long-term climate change research. ERA5 Land data is based on advanced numerical models and global observation data, with good accuracy, continuity, and completeness. It has also been validated by many studies and is widely used in climate impact research.¹⁴

Influence of glacial meltwater on LSWTs

We used the Theil Sen method to linearly fit the average water temperatures and average air temperatures of lakes without glaciers in the watershed, and obtained a fitting formula ($R^2=0.85$), which is defined as the sensitivity formula of water temperatures to air temperatures. The sensitivity formula is then used to correct the surface water temperatures of lakes with glaciers in the watershed, thereby removing the impact of glacier meltwater on the surface water temperature of lakes with glaciers. After removing the impact of glacier meltwater on lake surface water temperature, we used the Theil Sen method to construct linear fitting functions for the average LSWTs and RIOT-LSWTs from 1985 to 2022, respectively. The difference between the values of the two linear functions in 2022 was recorded as the difference in 2022 (marked as BC in the figure S8b), and the initial temperature was set as the linear function value of the 1985 LSWT (marked as A in the figure S8b). The degree of inhibition of glacial meltwater on LSWTs is defined as the

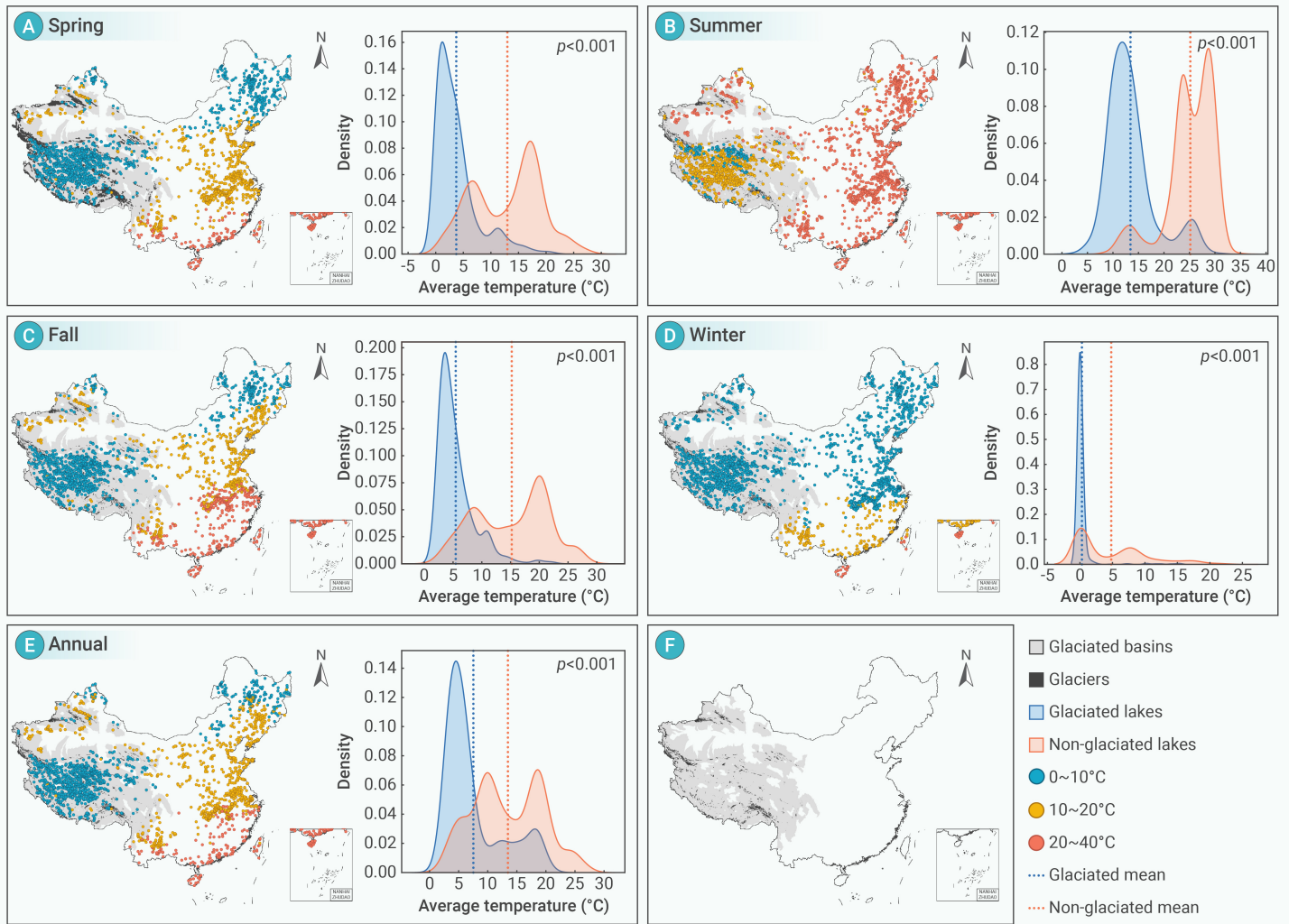


Figure 1. Spatial and density distribution of the average LSWT (i.e., across the study period): (A) spring; (B) summer; (C) fall; (D) winter; (E) annual; and (F) spatial distribution of glaciers.

difference in 2022 divided by the total variable, i.e. BC / AC .

Limitations and uncertainties

The LSWT dataset used in this study was reconstructed using the air2water model, which is widely used due to its simplicity and accuracy. However, when simulating the LSWT during freezing period, the simulated values of LSWT shall not lower than the ice threshold value (0.0°C). The same applies to the Flake model. Due to the spatial heterogeneity of lakes, this model performs poorly in certain lakes, such as deep lakes and lakes with complex characteristics. Glacier meltwater flows into lakes through various pathways, affecting the water temperature of lakes and subsequently impacting LSWT. However, the cooling effect of glacier meltwater is delayed and weakened from flowing into the lake to manifested in the surface temperature, which may underestimate the degree of cooling of lake water temperature by glacier meltwater. The diffusion process of glacier meltwater after flowing into lakes is also unknown. All these need to be considered in future lake water temperature simulation models. Although it is generally believed that when there are glaciers in a lake basin or lake catchment area, the lake can directly or indirectly receive glacier meltwater supply, due to the lack of continuous and high-precision glacier monitoring data and inflow monitoring data, we cannot accurately calculate the amount of glacier meltwater in time and space, nor can we accurately distinguish whether the lake has glacier meltwater supply. All of these will lead to uncertainty in our understanding of the impact of glacier meltwater on LSWT. To further investigate the impact of glacier meltwater on lake water temperature, we need to estab-

lish more monitoring points for the spatial heterogeneity of lakes and glaciers, then we can quantify the entire key processes of glacier meltwater on lake water temperature.

RESULTS

Lake surface water temperatures in glaciated and non-glaciated regions

Across the studied lakes, the average LSWT is 11.2°C . The key drivers of LSWT across the studied lakes are air temperature and longwave radiation (Figure S9). Moreover, we used K-means clustering to divide these lakes into two groups based on their average LSWT and the latitude and longitude of these lakes. Our results suggest that the clustering boundary closely coincides with the boundary of glaciers in the country, and that 98.4% of the glaciated lakes ($n = 885$) belongs to the same group (Figure S10a-b).

Our results suggest that an important factor influencing mean LSWT is whether a lake is situated in a glaciated region, and, in turn, its surface water is influenced by glacial meltwater. To further investigate the influence of glacial meltwater on LSWT, we first separated the studied lakes into those situated in glaciated and non-glaciated regions (see Methods). Between these two regions we calculate and compare the average of LSWT. Our analysis suggests that average LSWTs (i.e., across the study period) in glaciated regions ($7.5 \pm 0.33^{\circ}\text{C}$) (Mean $\pm$ 95% confidence interval) are substantially lower than those in non-glaciated regions ($13.5 \pm 0.31^{\circ}\text{C}$). Seasonally, average LSWTs of glaciated lakes (spring: $3.7 \pm 0.25^{\circ}\text{C}$, summer: $13.4 \pm 0.31^{\circ}\text{C}$, autumn: $5.5 \pm 0.21^{\circ}\text{C}$, and winter: $0.3 \pm 0.11^{\circ}\text{C}$) are significantly lower than that of non-glaciated lakes (spring: $13.1 \pm 0.32^{\circ}\text{C}$, summer: $25.2 \pm 0.25^{\circ}\text{C}$, autumn: $15.2 \pm 0.33^{\circ}\text{C}$, and winter: $4.8 \pm 0.29^{\circ}\text{C}$) (Figure 1).

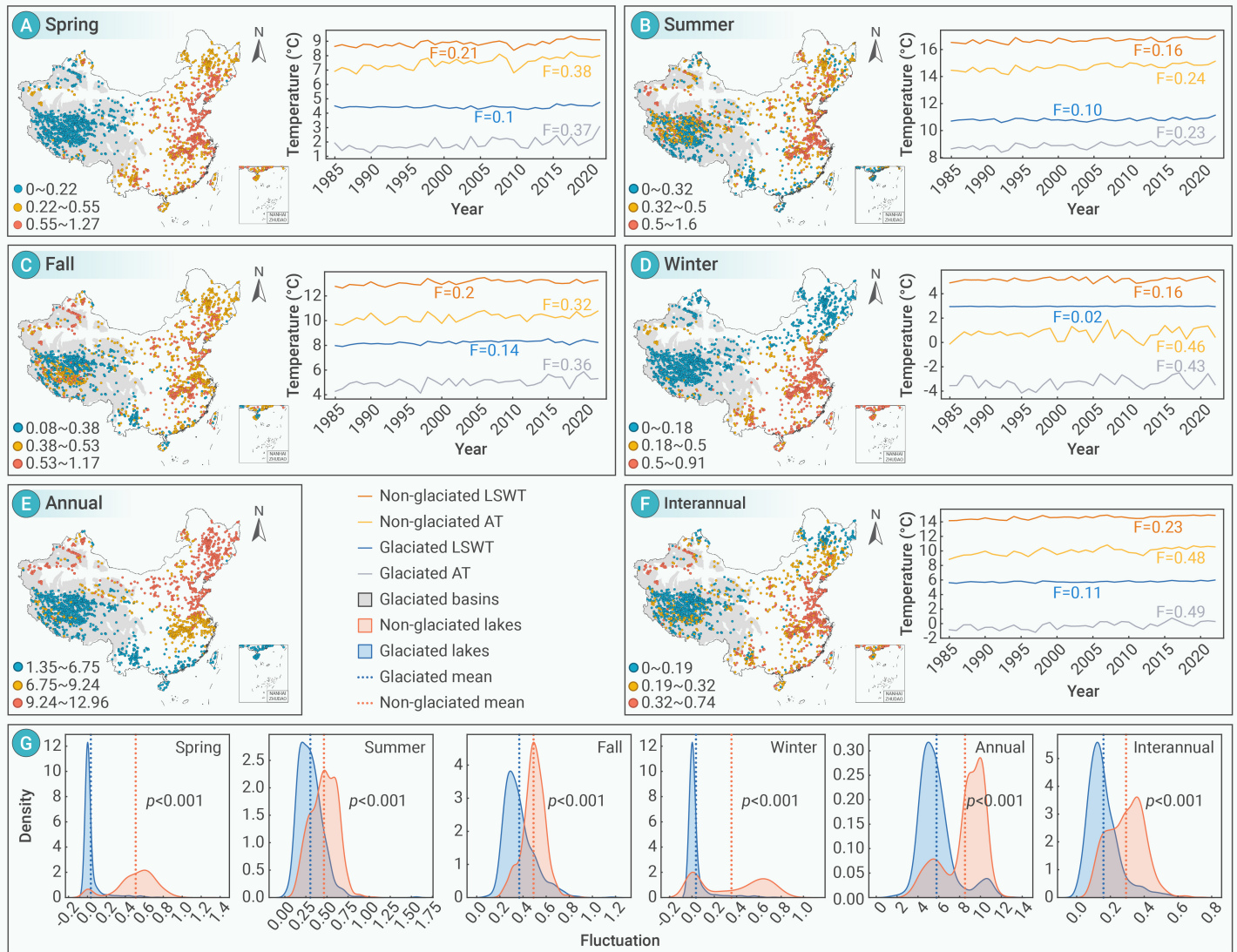


Figure 2. Fluctuations in lake surface water temperature and air temperature: (A) spring; (B) summer; (C) autumn; (D) winter; (E) annual; (F) interannual; and (G) density distribution of interannual, annual, and seasonal LSWT fluctuations.

We used the standard deviation of air temperature and LSWT to represent the degree of fluctuation, and the results showed that while air temperature fluctuations are generally consistent, in glaciated and non-glaciated areas, surface temperature fluctuations of the former are lower than those of non-glaciated lakes (Figure 2). Specifically, the surface water temperature of non-glaciated lakes exhibited average fluctuations higher than those of glaciated lakes by 0.47, 0.16, 0.12, 0.32, 2.73, and 0.13 in spring, summer, fall, winter, annual, and interannual scales, respectively. Additionally, our findings suggest that the correlation between LSWT and air temperature is lower in lakes situated in glaciated ($R=0.82$, $p<0.001$) compared to non-glaciated ($R=0.94$, $p<0.001$) regions (Figure S11).

Influence of glacial meltwater on lake surface temperature trends

The same K-means clustering method was applied to the warming rates of LSWT. The partitioning results exhibited a high coincidence rate of 86% with the initial classification (Figure S10c-d), further substantiates the scientific validity of our classification. Across the studied lakes, we estimate an average LSWT trend of 0.13 ± 0.004 °C decade⁻¹ (Mean $\pm$ 95% confidence interval), but with notable differences across altitudes ($R=-0.75$, $p<0.001$; Figure S12) as well as between glaciated and non-glaciated regions. Most notably, lakes situated in glaciated regions exhibit an average trend of 0.06 ± 0.004 °C decade⁻¹, a rate that is approximately three times slower than that calculated for lakes in non-glaciated regions (0.17 ± 0.004 °C decade⁻¹) (Figure 3C). Our

analysis suggests that almost three quarters ($n = 1,083$) of the studied lakes with relatively weak warming trends (< 0.1 °C decade⁻¹) are situated in glaciated regions (Figure 3A). Moreover, we estimate that 92% of lakes with glaciers in their watershed have warming rates below the rate of change calculated for lakes in non-glaciated areas. Generally, LSWT warming rates in glaciated regions are below 0.1 °C decade⁻¹, whereas those without glaciers are above 0.1 °C decade⁻¹. This observation of lower LSWT trends in glaciated regions also emerges among lakes with similar area, average depth, and volume (Figure 3B).

Across the studied lakes, as well as more broadly, air temperature is considered the main driver of change in LSWT. Generally, it is expected that LSWT will warm by 70-85% of the increase in air temperature.¹⁸ Across the 2,260 studied lakes, we estimate that air temperature has increased at a rate of 0.34 °C decade⁻¹ during the study period. The rate of change in air temperature is comparable between glaciated (0.4 °C decade⁻¹) and non-glaciated (0.32 °C decade⁻¹) regions. By comparing these air temperature trends with those of LSWT, we estimate that LSWTs in glaciated and non-glaciated regions have increased respectively by 15% and 53% of the increase in air temperature (Figure S13). This indicates a considerable influence of other external drivers and suggests a potential glacial meltwater modulation of LSWT trends. For all the studied lakes, the differences in warming rates between glaciated and non-glaciated regions are most pronounced during spring (0.11 °C decade⁻¹) and summer (0.06 °C decade⁻¹), and considerably less

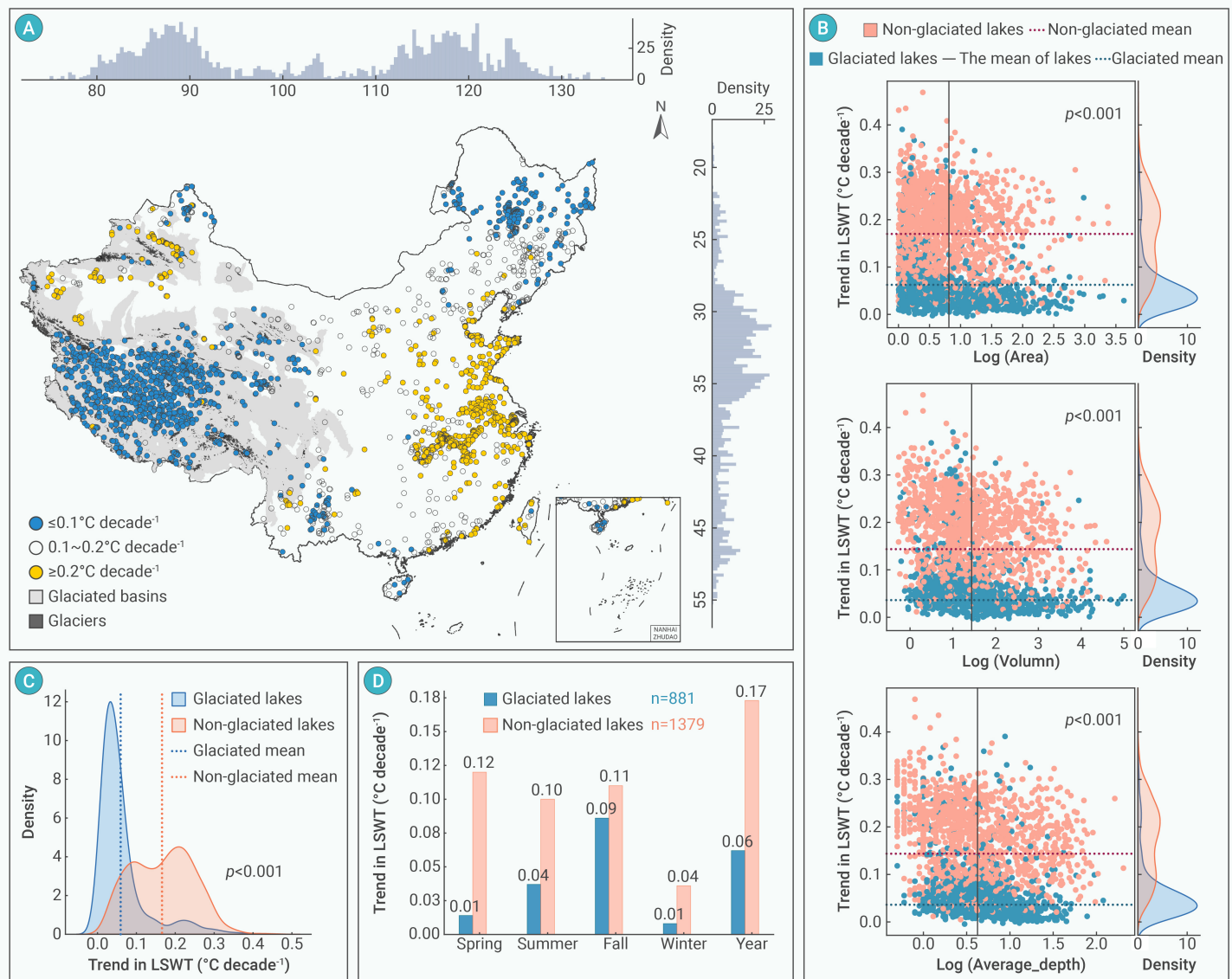


Figure 3. Warming rates of LSWT in China: (A) the spatial relationship between the warming rates of LSWT and glaciers; (B) the relationship between the warming rates of LSWT and lake properties; (C) density distribution of LSWT warming rates of glaciated lakes and non-glaciated lakes; and (D) the differences in annual and seasonal warming rates of LSWT for glaciated and non-glaciated lakes.

during autumn ($0.02^{\circ}\text{C decade}^{-1}$) and winter ($0.03^{\circ}\text{C decade}^{-1}$) (Figure 3D).

To further investigate the spatial patterns in LSWT trends, and better evaluate the impact of glacial meltwater on the warming rates, we separate the studied lakes according to the climate zones in which they are located. These climate zones are defined according to the Köppen climate zoning method (same air temperature and precipitation patterns within the same climate zone). The studied lakes can be categorized into 5 climate zones, namely a tropical zone (without glaciers), warm zone, continental zone, polar zone, and arid zone (Figure 4A). We found that irrespective of the climate zone, LSWT trends vary considerably among lakes and the warming rates are considerably larger for lakes without glaciers in their watersheds. Specifically, the warm zone has the largest difference ($0.13^{\circ}\text{C decade}^{-1}$), while the polar zone has the smallest difference ($0.02^{\circ}\text{C decade}^{-1}$), and the differences between the continental and arid zones are consistent ($0.09^{\circ}\text{C decade}^{-1}$) (Figures 4B & 5-6). The observed differences demonstrated statistical significance in the covariance analysis ($p < 0.001$).

In each climate zone, except for polar regions, lakes with glaciers exhibit significantly lower warming rates compared to lakes without glaciers, with this difference being most pronounced during spring and summer. To facilitate a clearer comparison between seasons influenced by glacial meltwater (spring and summer) and those less influenced (autumn and winter), we

aggregated the differences in warming rates. We termed the difference in warming rates during the glacial meltwater seasons as the "glacier meltwater season difference", and similarly, for non-glacial meltwater seasons, as the "non-glacial meltwater season difference" (Figures 4C & 5A-D). Notably, the arid zone shows the largest disparity in warming rates, with the glacier meltwater seasons difference ($0.31^{\circ}\text{C decade}^{-1}$) being 5.2 times greater than the non-glacial meltwater season difference ($0.06^{\circ}\text{C decade}^{-1}$). In the continental zone, the glacier meltwater season difference ($0.33^{\circ}\text{C decade}^{-1}$) is 4.1 times greater than the non-glacial meltwater season difference ($0.08^{\circ}\text{C decade}^{-1}$). In the warm zone, the glacier meltwater season difference ($0.45^{\circ}\text{C decade}^{-1}$) is 2.5 times greater than the non-glacial meltwater season difference ($0.18^{\circ}\text{C decade}^{-1}$). In contrast, polar regions exhibit a relatively minor difference between glacial and non-glacial meltwater seasons.

Within the same climate zone, lakes with similar attributes (volume, area, and average depth), experience lower warming rates when glaciers are present (Figures 5-6). In the arid zone, polar zone, continental zone, and warm zone, 87%, 80%, 96%, and 96% of lakes with glaciers show lower warming rates of LSWTs compared with lakes without glaciers in the watershed. We found that, except for polar regions, large lakes show a more significant difference in the warming rates of LSWTs between glaciated and non-glaciated lakes (see Figures S5-S6). This may be because large lakes often

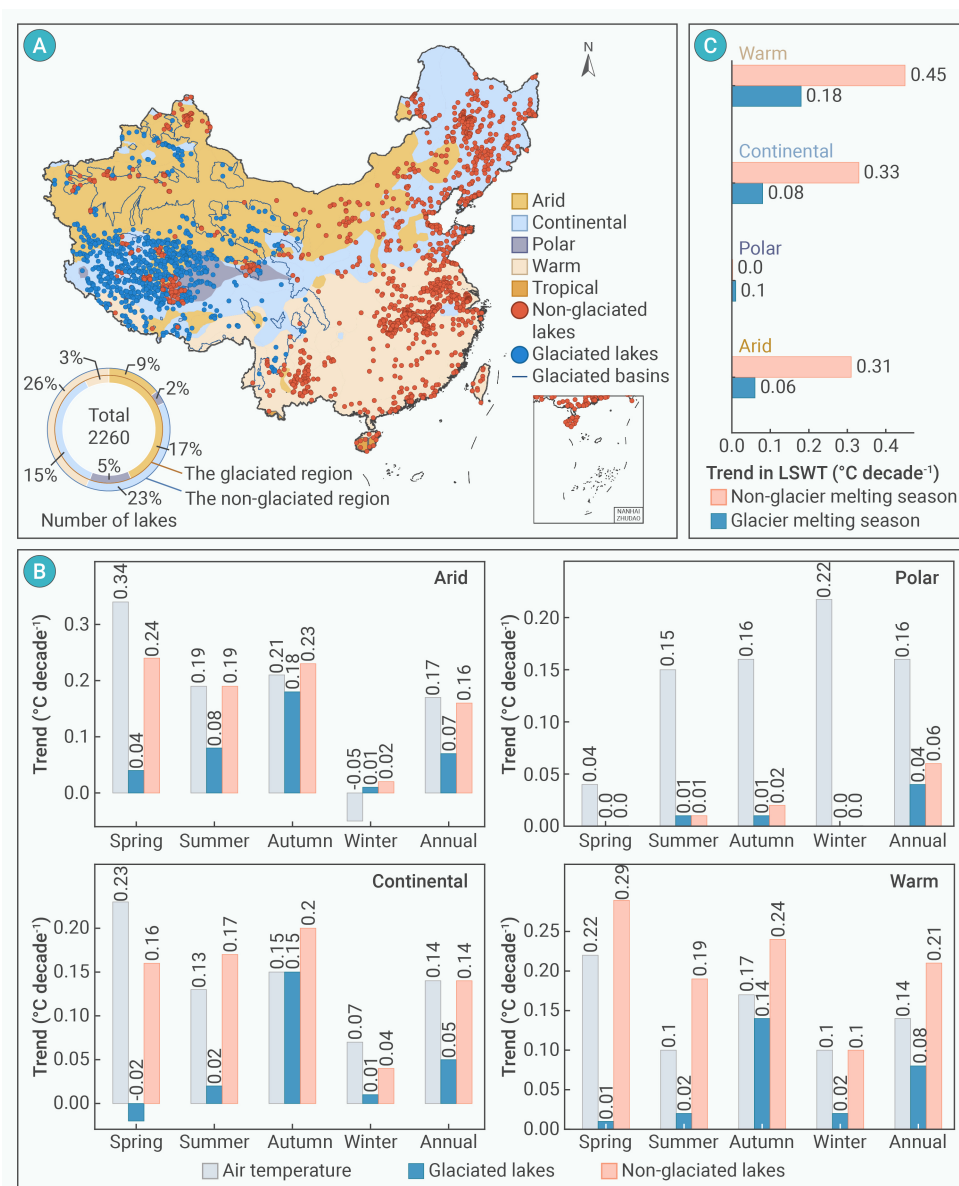


Figure 4. Differences in the warming rate of lake surface water temperature in different Köppen Climate Zone: (A) the spatial distribution and proportion of lakes with or without glaciers in the watershed in different climate zones; (B) annual and seasonal differences in LSWT and warming rate of LSWT in different climate zones; and (C) the difference in the warming rates of LSWT between the glacial meltwater season and the non-glacial meltwater season.

temperature changes (Figure S8a). This allowed us to estimate the warming rate of lakes with glaciers in the absence of glacial meltwater influence (Figure S8b). Our analysis suggests that, after excluding the impact of glacier meltwater, the surface water temperature warming rate for lakes with glaciers increased from $0.06\text{ }^{\circ}\text{C decade}^{-1}$ to $0.16\text{ }^{\circ}\text{C decade}^{-1}$. This analysis suggests that glacier meltwater has suppressed approximately 86% of the warming rates of LSWTs in lakes with glaciers in their watershed.

DISCUSSION AND CONCLUSION

Glacier meltwater acts as a natural coolant for inland waters.^{48,49} In lakes with glaciers in the watershed, glacial meltwater can enter through various channels (surface runoff and underground runoff), thereby influencing LSWT. Our study suggests an important but largely underexplored processes; glacier meltwater significantly influences lake responses to climate change, especially during the glacier meltwater season (spring and summer). As air temperatures increase, more glacier meltwater flows into lakes, intensifying this cooling effect on LSWT warming. Additionally, polar lakes, located in high-altitude areas, are subject to cold descending winds from glaciers, which bring cold air to lower altitudes and reduce local temperatures. This phenomenon diminishes or negates the inhibitory effect of glaciers on LSWT warming in polar lakes. As the

have direct access to glacier meltwater replenishment and the replenishment is typically large.^{42,43}

Evaluating the cooling impact of glacier meltwater on LSWT trends

We used a random forest algorithm to evaluate the importance of various meteorological factors contributing to the calculated changes in LSWT. Our results suggest that in glaciated regions, the contribution of air temperature (34.6%) and longwave radiation (32.3%) to lake warming is 66.9% (Figure 7A). Typically, air temperature and longwave radiation are strongly correlated. To separate the contributions of longwave radiation and air temperature to changes in LSWT, we used partial correlation analysis, and the results showed that longwave radiation is the most dominant factor affecting the changes of LSWT in glaciated lakes ($R=0.55$, $p<0.001$) (Figures 7C-D). However, in non-glaciated regions, total precipitation (25.5%), air temperature (23.3%), and surface air pressure (18.5%) are the most important drivers of lake warming, contributing 67.3% (Figure 7B). The increase in low-level cloud cover and greenhouse gases such as carbon dioxide at night has also been proved to result in increased downward longwave radiation, which raises air temperatures on the Qinghai Tibet Plateau.^{44,45} This increase in longwave radiation accelerates the warming of the Qinghai Tibet Plateau, contributing to accelerated glacier melting.^{46,47}

To quantify the cooling impact of glacier meltwater on LSWT in glaciated lakes, we calculated the sensitivity of LSWTs in non-glaciated lakes to air

climate continues to warm, the effect of these cold descending winds is expected to intensify.⁵⁰

Our findings suggest that glacier meltwater has suppressed the warming rate of 904 lakes in China, compared to those expected when influenced by air temperature trends. We estimate that the average warming rate of Chinese lakes is $0.13\text{ }^{\circ}\text{C decade}^{-1}$, but without considering the cooling effect of glacier meltwater, this rate would increase to $0.16\text{ }^{\circ}\text{C decade}^{-1}$. Our analysis suggests that longwave radiation are the dominant factors affecting surface water temperature changes in lakes with glaciers in their watershed. Increased longwave radiation accelerates glacier melting, producing substantial amounts of meltwater that flow into lakes.⁵¹ This influx of cold meltwater can suppress the warming of LSWT under climate change. In some lakes, the addition of meltwater not only raises the lake level and increases its volume but also weakens thermal stratification that typically forms seasonally.⁵² This weakening of stratification leads to a deeper surface mixed layer, where a larger volume of water interacts with the atmosphere through air-water heat exchange. As a result, the lake's surface water responds more slowly to atmospheric changes, leading to lower trends in LSWT increases. A deeper mixed layer means that the lake's overall temperature changes more gradually, as the greater volume of water requires more energy to alter its temperature.²³

Despite these insights, accurately quantifying LSWT in Chinese lakes

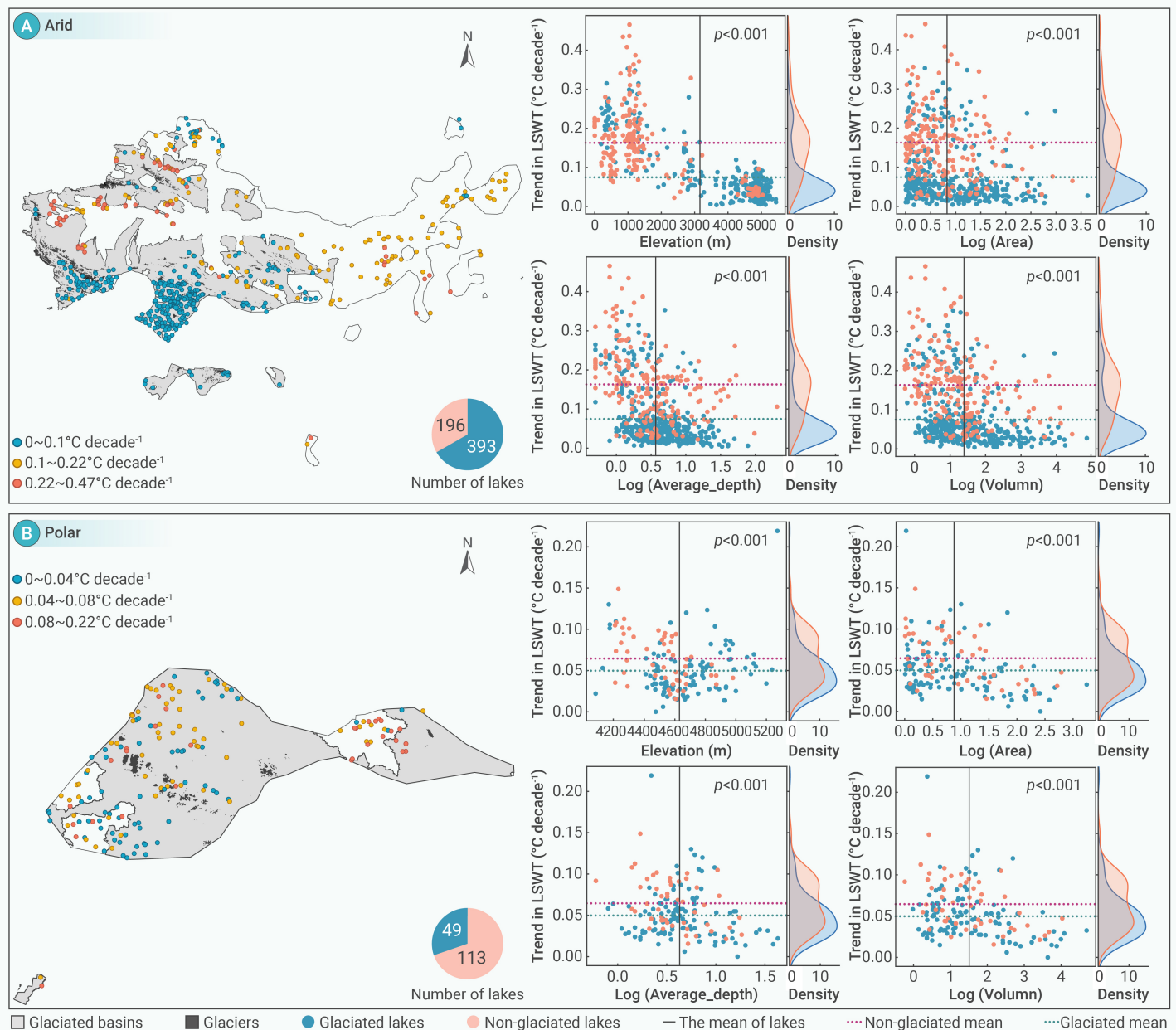


Figure 5. The relationship between lake attributes and warming rates in different climate zones: (A) the left side is the spatial distribution of warming rates in arid lakes, while the right side is the relationship between the four attributes of lakes and their warming rates; (B) the left side is the spatial distribution of warming rates in polar lakes, while the right side is the relationship between the four attributes of lakes and their warming rates. On the right side of the scatter plot is the density distribution curve.

remains uncertain due to significant spatial heterogeneity influenced by natural conditions and human activities. In urban areas, summertime precipitation creates surface runoff from impermeable surfaces, raising LSWTs. During summertime precipitation events, rainwater rapidly flows off these surfaces, carrying with it heat accumulated on the hot urban surfaces. This runoff, often warmer than the natural water bodies, flows into lakes, thereby raising LSWTs.⁵³⁻⁵⁶ Additionally, the runoff can carry pollutants and other materials that can further alter the thermal properties of the lake water. The combined effects of urban heat islands, increased surface runoff, and the introduction of pollutants contribute to elevated LSWTs in urban-adjacent lakes. These human-induced changes complicate the task of accurately measuring and predicting LSWT, as they introduce localized warming effects that can vary significantly from one area to another. Additionally, the harsh conditions in glaciated regions make large-scale field measurements of glacier meltwater temperatures impractical with current technology, preventing accurate calculations of the volume and temperature of cooling glacier meltwater entering lakes. This variability, driven by both environmental

factors and human impacts, contributes to the overall uncertainty in understanding and predicting LSWT in these regions.

Despite existing uncertainties, our research holds significant implications. Under global warming, non-glaciated lakes experience rapid surface water temperature increases, leading to lake shrinkage, prolonged stratification, deep-water deoxygenation, and consequent aquatic organism mortality/reorganization, algal blooms, and water quality degradation—ultimately harming human communities dependent on these water bodies.^{4,10,12-34} In contrast, glaciated lakes, benefiting from meltwater inputs, show mitigated effects (Figure S14).

We note that as glaciers disappear altogether with global warming, lakes in glaciated regions could, in the future, experience accelerated warming i.e., as they would no longer experience the cooling effect of meltwater. Our findings not only enhance our understanding of how lakes respond to climate change but also provide a scientific basis for developing lake protection and management strategies to address the ecological and environmental challenges.

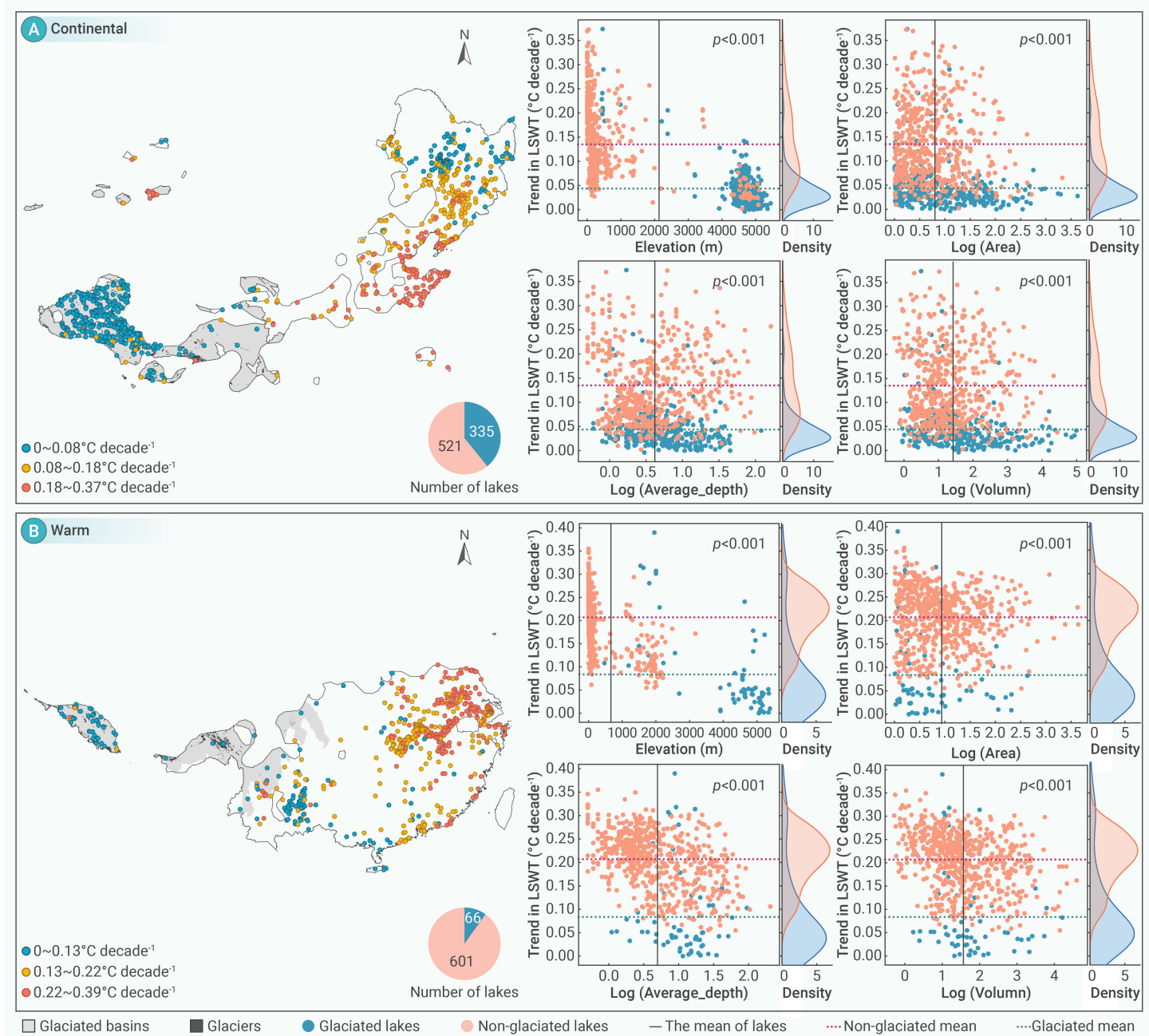


Figure 6. The relationship between lake attributes and warming rates in different climate zones: (A) the left side shows the spatial distribution of warming rates in continental lakes, while the right side shows the relationship between the four attributes of lakes and their warming rates; and (B) the left side is the spatial distribution of warming rates in warm zone lakes, while the right side is the relationship between the four attributes of lakes and their warming rates. On the right side of the scatter plot is the density distribution curve.

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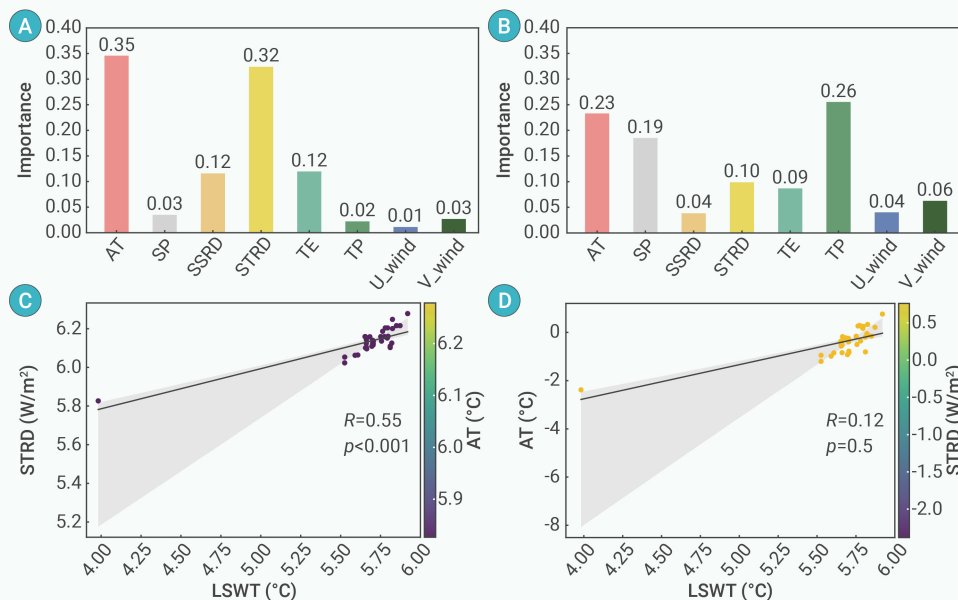


Figure 7. Importance assessment: random forest analysis results: (A) glaciated lakes; and (B) non-glaciated lakes. AT: air temperature, SP: surface pressure, SSRD: surface solar radiation downwards, STRD: surface thermal radiation downwards, TE: total evaporation, TP: total precipitation, U_wind: horizontal wind speed, and V_wind: vertical wind speed. Partial correlation analysis results in glacier areas: (C) the relationship between longwave radiation (STRD) and LSWT when controlling AT; and (D) the relationship between AT and LSWT when controlling STRD.

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AUTHOR CONTRIBUTIONS

LC: Methodology, Investigation, Writing - review & editing; YL: Supervision, Funding acquisition, Conceptualization, Methodology, Project administration, Investigation, Writ-

ing - review & editing; KY: Supervision, Funding acquisition, Conceptualization; SZ: Investigation, Writing - review & editing; RIW: Investigation, Writing - review & editing; AL: Investigation; YG: Investigation; GL: Investigation; HC: Investigation; HZ: Investigation; All authors contributed to the manuscript and approved the final version. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

The ERA5-Land data are available at: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land?tab=overview>; the data of LSWT are available at: <https://data.tpdc.ac.cn/en/data/73ebd0f-a019-43c9-9705-c60462999ac6>; the data of lake basins are available at: <https://www.hydrosheds.org/products/hydrobasins>; the Second Glacier Cataloging Dataset of China are available at: <https://data.tpdc.ac.cn/zh-hans/data/f92a4346-a33f-497d-9470-2b357ccb4246>; the data of Köppen climate zoning method are available at: <https://www.geodata.cn/data/datadetails.html?dataguid=60984931148062&docid=3953>; the data of lake drainage are available at: <https://essd.copernicus.org/articles/15/3483/2023>; the data of LSWT for verification are available at: <https://zenodo.org/records/8322038>.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.xinn-geo.2025.100147>

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