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Lake Surface Temperature Dynamics as Precursors to Glacial Lake Outburst Floods: A Case Study of Lake Merzbacher, Central Tianshan

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Abstract

Glacial lake outburst floods (GLOFs) have become increasingly frequent under climate warming. Yet the links between lake surface temperature (LST) dynamics and GLOF triggers remain poorly understood due to the absence of in situ lake temperature observations. This study investigates the potential of MODIS-derived LST to serve as a precursor for GLOFs at Lake Merzbacher, a frequently outbursting ice-dammed lake. We analyzed LST trends from 2000 to 2022 and examined its short-term dynamics preceding 25 documented GLOF events. Our results reveal a significant summer LST warming trend of 0.06 °C·yr^{-1}, exceeding the regional air temperature rise. We identified a critical LST threshold of 12°C, with ~90% of GLOFs occurring above this level. More importantly, we detected distinct thermal precursors: a rapid LST increase (peaking at 0.65 °C·day^{-1}) beginning ~8 days before outburst, and a critical acceleration phase (exceeding a threshold of 1.04 °C·day^{-2}) around 9 days pre-GLOF. Furthermore, the peak discharge of floods showed the strongest correlation with the 15-day cumulative LST before outburst ($r = 0.77$), highlighting the role of integrated thermal energy in controlling flood magnitude. This study establishes LST not merely as a background climate indicator but as a source of diagnostic, short-term warning signals. We propose a multi-parameter framework integrating absolute LST, its rate of change,

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and acceleration to enhance early-warning systems for ice-dammed lakes under climate warming.

Keywords: Lake Merzbacher, GLOF, lake surface temperature, early warning, ice-dammed lake

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1. Introduction

Glacial lake outburst floods (GLOFs) are increasingly recognized as a significant hazard in High Mountain Asia (HMA), where accelerated atmospheric warming has driven widespread glacier mass loss and rapid expansion of glacial lakes over recent decades (Hugonnet et al., 2021; Veh et al., 2023). In the Tianshan Mountains, where warming rates exceed 0.3°C per decade, glacier retreat has led to the formation and enlargement of numerous proglacial and ice-dammed lakes, elevating the risk of ice-dam failure and related floods (Wang et al., 2013; Chen et al., 2016). Ice-dammed lakes are particularly hazardous because they may drain suddenly and repeatedly, causing substantial economic damage and loss of life (Carrivick and Tweed, 2016; Shangguan et al., 2017; Li et al., 2021). Although real-time monitoring systems have improved early warning capabilities (Zheng et al., 2021), predicting the timing of ice-dam failure remains difficult due to their complex and often inaccessible settings (Gu et al., 2023).

GLOF initiation can result from dynamic external disturbances such as rockfalls, ice avalanches, or rapid water input, as well as long-term processes that modify dam stability, including ice melt, permafrost degradation, and evolving subglacial hydrology (Richardson and Reynolds, 2000; Chikita and Yamada, 2005; Rounce et al., 2016). Among these drivers, air temperature has been widely linked to GLOFs through its control on glacier meltwater supply and internal ice-dam weakening (Ng et al., 2007; Ng and Liu, 2009). Yet, despite its acknowledged importance, the temperature sensitivity of ice-dammed lakes—and especially the direct response of lake surface temperature (LST)—remains poorly quantified. Existing models of GLOFs largely focus on simulating hydrographs (Kingslake and Ng, 2013), with fewer efforts addressing the environmental conditions that govern outburst timing.

Lake Merzbacher, located between the Northern and Southern Inylchek glaciers,

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represents one of the world's most frequently draining ice-dammed lakes, with documented GLOFs since 1931 (Mayr et al., 2014). Annual outbursts typically occur between June and October, coinciding with peak meltwater supply during warm summer conditions (Ng and Liu, 2009). Previous studies have developed remote-sensing-based indices to identify pre-outburst signals (Xie et al., 2013) and have quantified the predictability of the timing of dam failure (Kingslake and Ng, 2013). However, a key knowledge gap remains: the role of LST dynamics prior to GLOFs has not yet been systematically evaluated, despite LST being an important indicator of regional climate forcing and subaqueous ice melt (Austin and Colman, 2007; Zhang et al., 2014; Debnath et al., 2018; Attiah et al., 2023).

In this paper, we investigate whether fluctuations in lake surface temperature can provide diagnostic information about the timing and magnitude of GLOFs at Lake Merzbacher. Using MODIS-derived daily LST, we aim to:

(1) Characterize LST evolution in the days to weeks preceding GLOFs;

(2) Quantify LST change rates and accelerations as potential early-warning indicators;

(3) Evaluate the influence of short-term accumulated temperature on peak flood discharge.

These analyses provide new insights into the thermal precursors of ice-dam failure and contribute to the development of temperature-based monitoring tools for GLOF hazard assessment in remote alpine environments.

2. Study area

Lake Merzbacher is situated in the remote Inylchek region in the central Tianshan mountain range in Kyrgyzstan, bordering China, at the confluence of the Northern and Southern Inylchek Glaciers at an altitude of about 3100m, as illustrated in Figure 1. As described below, Northern Inylchek Glacier terminates in a proglacial lake, and down valley lies an ice-dammed lake (impounded by Southern Inylchek Glacier) that has repeatedly outburst to deliver glacier outburst floods (Häusler et al., 2016). Northern Inylchek Glacier and its neighbour Southern Inylchek Glacier comprise the largest compound glacier system in the central Tianshan Mountains. Although located in Kyrgyzstan, both glaciers drain into the Inylchek River. It feeds the Sary-Dshaz River in Kyrgyzstan, whose runoff flows into the Kumarik River of the main tributary of the Aksu River in China to feed that country's largest inland river, the Tarim, which provides a vital water supply to oases around the Taklamakan Desert (Mayr et al., 2014)

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(Fig. 1a). Glacial meltwater contributes at least 35% of the Tarim's total runoff (Aizen and Aizen., 1998). This proportion is predicted to rise over the next few decades (Aizen et al., 2007).

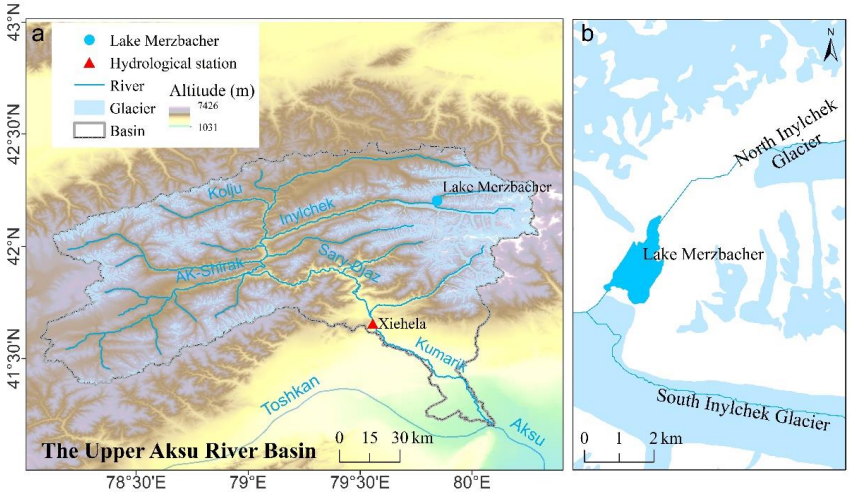

Figure 1. Map of Lake Merzbacher, in the central Tianshan Mountains.

3. Data and Methods

3.1 Glacial Lake Area and GLOF Records

The area of glacial lakes is a key predictor of susceptibility and hazard (Allen et al., 2019). For Lake Merzbacher, historical lake area from 1990 to 2015 and documented outburst dates from 2000 to 2015 were obtained from published sources (Liu, 1993; Glazirin, 2010; Kingslake and Ng, 2013; Shangguan et al., 2017; Li et al., 2020). Lake area and outburst dates from 2016 to 2022 were extracted from high-resolution Planet Scope (DOVA) satellite imagery (Table S1, Supplementary Material). Planet's Dove satellites are CubeSats that weigh 4 kilograms (1000 times lower than other commercial imaging satellites), 10 by 10 by 30 centimetres in length, width and height, orbit at a height of about 400 kilometres and provide imagery with a resolution of 3-5 metres and are envisaged for environmental, humanitarian, and business applications.

For each documented GLOF, the pre-outburst lake area was obtained from the available satellite imagery. A total of 25 GLOF events from 2000 to 2024 were included in this study. Since 2000, no GLOF events triggered by glacier surges were reported in Lake Merzbacher (Liu et al., 2023).

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3.2 Lake Surface Temperature Data

Lake surface temperature (LST) was derived from the MODIS Terra Land Surface Temperature Daily L3 Global 1 km product (MOD11A1). MODIS LST has been shown to accurately reflect in situ lake temperature measurements at Lake Merzbacher, with $R^2 = 0.79$ for 2009–2010 observations (Bormudoi et al., 2012).

To address missing data, gap-filling was performed using the Climate Forecast System Version 2 (CFSv2)–MODIS integration in Google Earth Engine, generating continuous 1 km LST time series (Shiff et al., 2021). The filled dataset (CFSv2_LST) was evaluated against the original MODIS LST using mean absolute error (MAE), bias, and R^2, yielding high consistency ($R^2 = 0.95$, MAE = 1.31°C; Figure S1).

3.3 LST Temporal Analysis

In meteorology, a moving average is commonly used with time series data to smooth out short-term fluctuations and highlight longer-term trends for mean daily air temperatures (Hewitson and Crane, 1996). For the filled daily lake surface temperature (LST) series, the five-day moving average was used to produce smooth LST curves. Xie et al., (2013) divided Lake Merzbacher into four periods according to the outburst index: icefall, quick water storage, early-warning and post-drainage. During these four periods, the lake is filled with water and the water movement is slow; it takes about one month for an outburst to occur and about a week for the lake to empty after the drainage (Xie et al., 2013). Therefore, in this paper, the first and second derivative of the daily LST were calculated for one month before and one week after the glacial lake outburst.

Step 1: Calculate the first derivative of the daily LST to characterize the change rate of LST ($°C \cdot day^{-1}$), and analyse the trend of LST before and after the outburst of the glacial lake.

Step 2: Calculate the second derivative of the daily LST to characterize the change in the rate of temperature change (i.e., acceleration, unit: $°C \cdot day^{-2}$). A positive value indicates an accelerating rate of temperature change, while a negative value indicates a decelerating rate of temperature change.

Step 3: Identify the accelerated temperature rise range and calculate the average value (μ) and standard deviation (σ) of all the second derivative values during the study period. Set the threshold for identifying significantly accelerated temperature rise:

$$\text{Threshold} = \mu + 1.5 * \sigma.$$

The time regions that satisfy the second derivative of the daily LST > the threshold

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are defined as periods with significantly accelerated temperature rise.

Step 4: For each historical glacial lake outburst event, count the frequency of significantly accelerated warming areas (i.e., the second derivative of the daily LST > threshold) within a specific period before its occurrence (the previous 30 days).

Step 5: Calculate the cumulative lake surface temperature in the month before each glacial lake outburst event (i.e., the sum of the average daily LST during that period). Cumulative temperature plays a crucial role in the thermodynamic state of glacial lakes prior to outburst (Liu et al., 2014). By combining with the frequency of significantly accelerated warming events before the outburst and the cumulative temperature of the previous month, as recorded in Step 4, this paper will explore the potential association and influence between these two types of thermal conditions (short-term intense accelerated warming and longer-term heat accumulation) and the occurrence of GLOFs (Fig. 2).

In the case of a glacial lake, the ice point or pressure-melting point is crucial, which determines ice ablation and accumulation (Cogley et al., 2011). Lake surface temperatures above 0°C are considered the effective ablation threshold. The cumulative lake surface temperature, calculated over consecutive days until the outburst event, is defined as follows:

$$T_A^{(N)} = \sum_{k=1}^{N} T_k \,, (k = 1, 2, \ \ldots, N-1)$$

Where N represents the number of continuous ablation temperature days. The cumulative temperatures ($T_A^{(N)}$) represents both the cumulative surface temperature of the lake reaching ablation temperature and the sum of the heat over the period for N days before the glacial lake outburst. T_k is the corrected daily average lake surface temperature. The cumulative temperature change rate is defined as the ratio of the cumulative temperature difference to the time difference.

In this study, to characterize trends in regional terrestrial air temperature, 2 m air temperatures (T) were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) for the land component of the fifth-generation European Reanalysis dataset (ERA5-Land) for the period 2000–2022 (Muñoz-Sabater et al., 2021). Reanalysis data provide a consistent and globally complete description of past climate, allowing evaluation of regional warming trends relevant to LST dynamics and GLOF occurrence.

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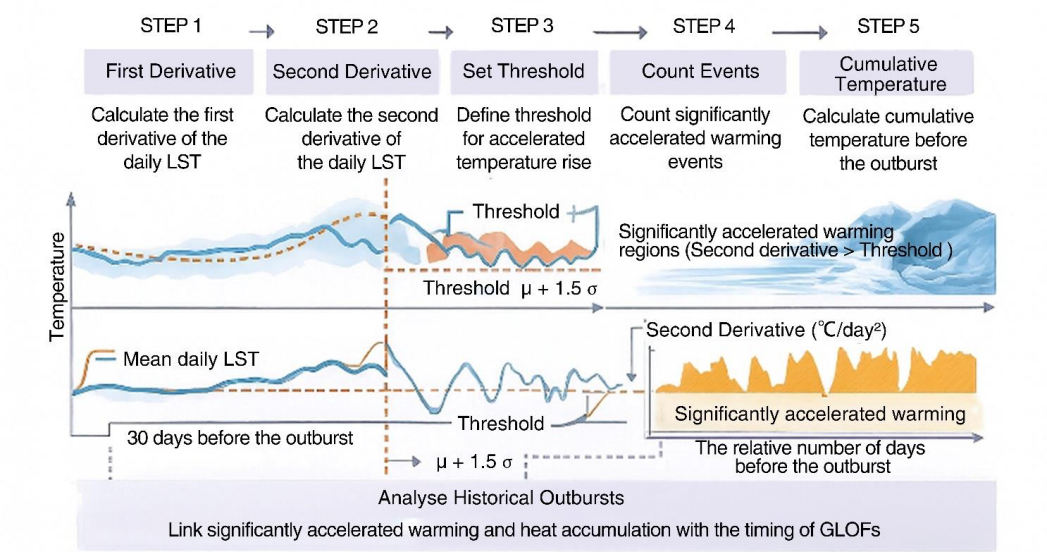

Figure 2. Thermal conditional and glacial lake outburst floods.

4. Results

4.1 Temporal Trends of Lake Surface Temperature and Glacial Lake Outburst Timing

Between 2000 and 2022, lake surface temperatures (LST) in June, July, August, and the summer mean (June–August) exhibited clear upward trends (Fig. 3). Linear regression analysis indicates warming rates of approximately 0.06 °C·yr^{-1} for the summer mean, with July showing the most pronounced increase at 0.10 °C·yr^{-1}—twice the rates observed in June and August. Mann–Kendall tests confirm that these trends are statistically significant ($p < 0.05$) for most LST series. In contrast, air temperature (T) exhibits only modest increases with smaller slopes and weaker significance, suggesting a stronger warming response at the lake surface than in near-surface air.

Satellite image analysis from 1990 to 2024 revealed a declining trend in the glacial lake area (Fig. S2a). The average lake area over this period was 3.22 km², with a maximum of 3.95 km² (9 August 1996) and a minimum of 2.12 km² (4 July 2021). The timing of glacial lake outburst floods (GLOFs) advanced by approximately 0.6 days per year (Fig. S2b), with most post-2000 events occurring from early July to mid-to-early August. This shift is attributed to accelerated summer glacier melt and the reduced water storage period, highlighting the importance of early-warning and flood mitigation strategies.

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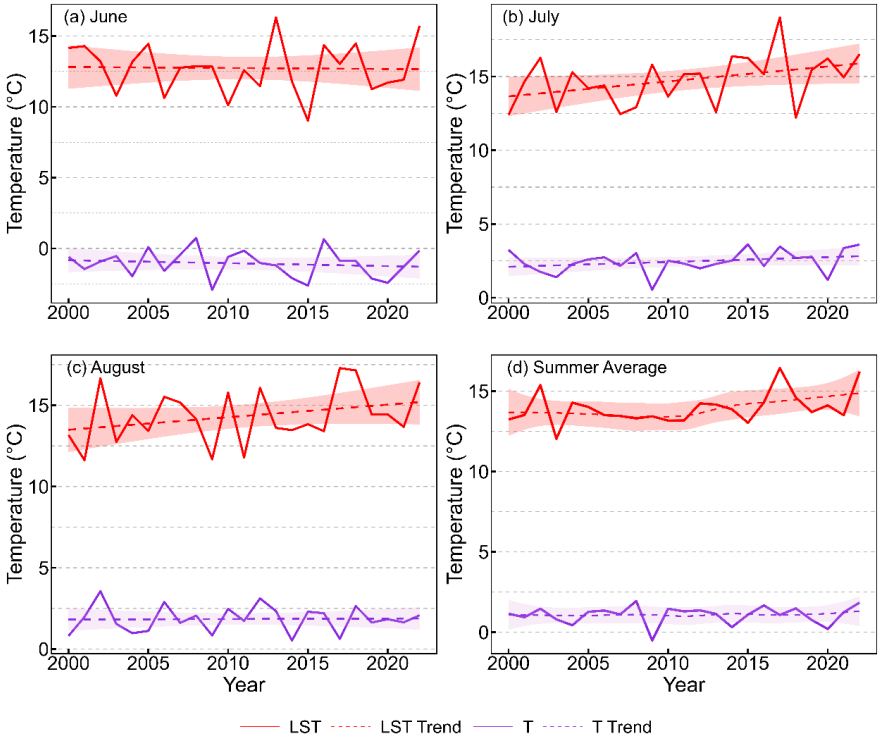

Figure 3. Time series of lake surface temperature (LST, red line) and air temperature (T, purple line) for June, July, August, and the mean summer LST (June–August) between 2000 and 2022. Solid lines show annual observations; dashed lines show linear trends with 95% confidence intervals (shaded).

4.2 Short-Term LST Dynamics Before the Glacial Lake Outburst

Analysis of LST in the 30-day window preceding each GLOF event reveals characteristic warming patterns (Figs. 4–5). GLOFs predominantly occur on days when LST exceeds 12 °C, with ~90% of events falling in the 12–20 °C range, suggesting a critical temperature threshold for ice dam failure. A few extreme events occurred at LST >20 °C (e.g., 25.4 °C on 8 July 2017, 23.5 °C on 10 August 2018), likely associated with heatwaves and intensified ablation (Chikita et al., 2000).

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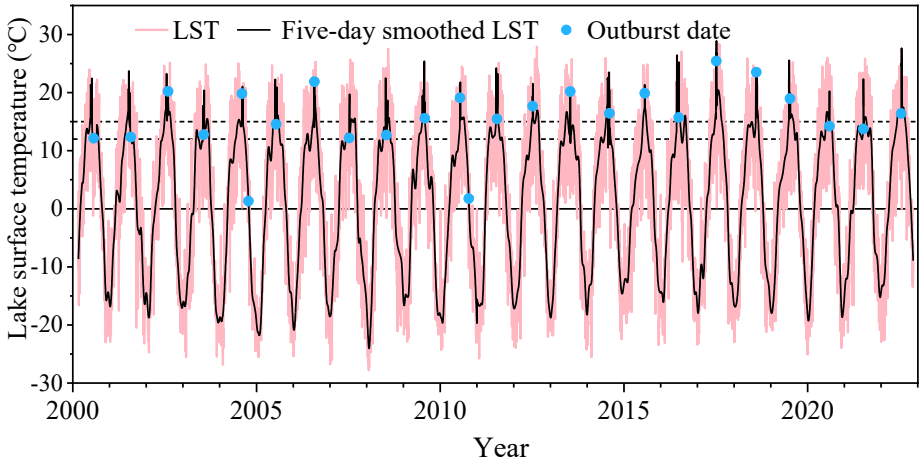

Figure 4. Lake surface temperature fluctuations in Lake Merzbacher from 2000 to 2022. Blue dot represents the outburst date of the glacial lake.

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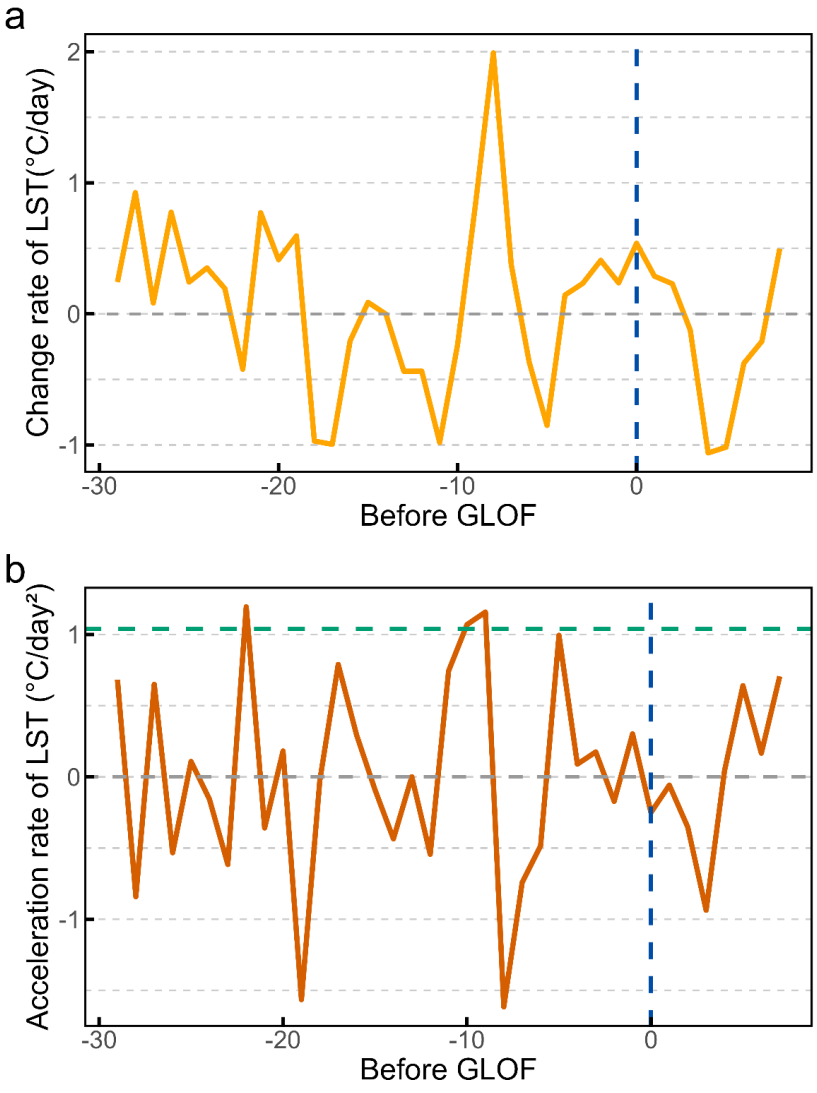

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228 Figure 5. LST characteristics before and after GLOFs. (a) Rate of LST change (dLST/dt)
229 highlighting pre-outburst warming. (b) Acceleration change rate of Pre-outburst LST
230 evolution. Blue dashed line represents the outburst date of the glacial lake. Horizontal
231 green dashed lines indicate critical thresholds: 1.04 °C·day^{-2}.

232 Statistical analysis shows a rapid LST increase within approximately eight days
233 before outbursts (Fig. 5a). A two-sample t-test confirms the presence of a short-term
234 warming signal prior to GLOFs ($p < 0.05$). On the outburst day, the rate of LST change

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peaks at 0.65 °C·day⁻¹.

To quantify thermal acceleration, the second derivative of LST was computed over a 30-day window centered on each outburst. Based on 25 historical events (Table S1), a critical acceleration threshold of 1.04 °C·day⁻² was identified. Two exceedances were observed: 22 days before the outburst (1.20 °C·day⁻²) and 9 days before the outburst (1.16 °C·day⁻²). The earlier signal may indicate the onset of accelerated thermal activity, while the latter corresponds to a pre-outburst thermal reinforcement phase, potentially defining a critical short-term pre-outburst window for early warning. Post-outburst, LST change rates decline rapidly and occasionally turn negative, reflecting system re-equilibration and meltwater inflow (Fig. 5b).

4.3 Short-Term Cumulative Temperature and Peak Discharge

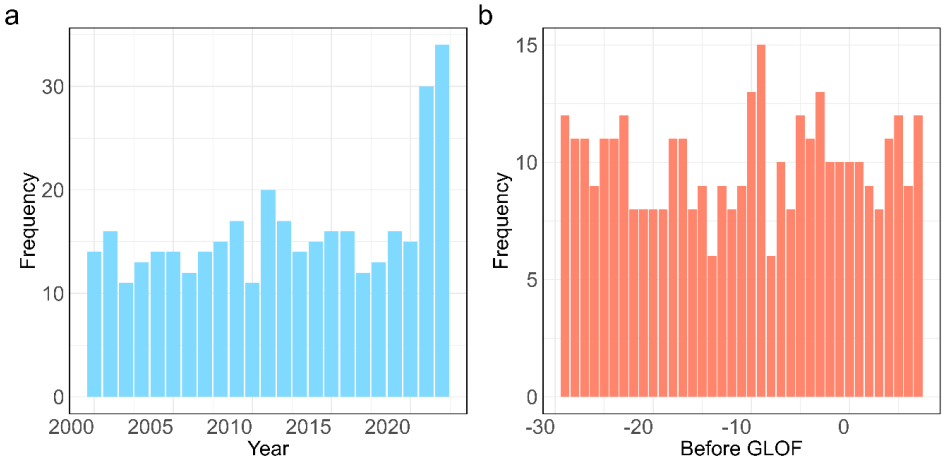

Figure 6. Accelerated warming events: interannual and pre-outburst temporal patterns. annual frequency of accelerated warming events from 2000 to 2022 (a). Temporal distribution of accelerated warming events before the outburst (b).

The frequency of accelerated warming events has increased in recent years, particularly over the past decade, peaking in 2023 (Fig. 6a). From 2000 to the mid-2010s, events were distributed relatively uniformly. Temporal analysis relative to outburst dates reveals clustering approximately 10 days before GLOFs (Fig. 6b), suggesting a thermally driven triggering mechanism. Although acceleration events are observed throughout the 30-day pre-outburst window, the localized peak indicates that abrupt LST acceleration could serve as a short-term early-warning signal.

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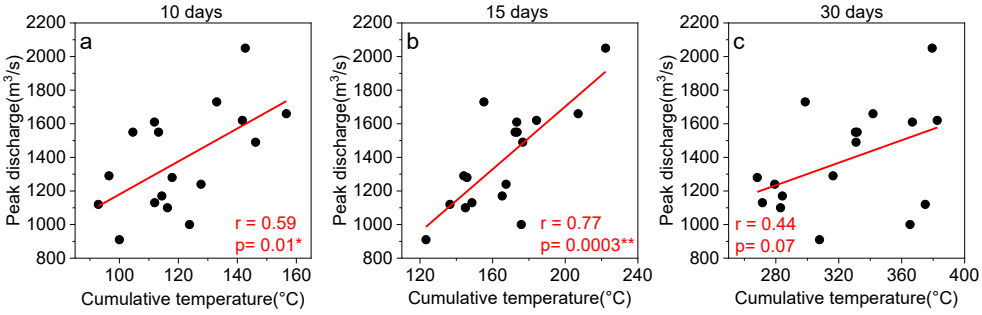

Figure 7. Relationships between short-term cumulative temperature and GLOF peak discharge. Correlation coefficients (r) and significance levels (p) are indicated for 10-, 15-, and 30-day accumulation windows.

To investigate the thermal conditions preceding GLOFs, the correlations between peak discharge and cumulative temperature over 10-day, 15-day, and 30-day windows before each outburst event were analyzed (Fig. 7). A clear positive relationship was identified between cumulative temperature and peak discharge for the shorter accumulation periods. For the 10-day accumulation window, peak discharge increased significantly with higher cumulative temperature ($r = 0.59$, $p = 0.01$), indicating that short-term warming strongly influences flood magnitude. The relationship further strengthened when the accumulation period was extended to 15 days, showing the highest correlation among the three windows ($r = 0.77$, $p = 0.0003$), suggesting that thermal forcing integrated over two weeks is an especially strong predictor of flood magnitude. In contrast, the positive correlation observed for the 30-day accumulation window was weaker and statistically insignificant ($r = 0.44$, $p = 0.07$). This suggests that temperatures averaged over longer periods may dilute the short-term thermal signal most relevant to triggering rapid lake drainage. Overall, these results imply that GLOF peak discharge is most sensitive to short-term (10–15 day) cumulative warming, highlighting the importance of rapid pre-event thermal inputs in controlling flood magnitude.

5. Discussion

5.1 Lake Surface Temperature as a Primary Driver of GLOFs

This study provides a systematic analysis linking Lake Surface Temperature (LST) dynamics to Glacial Lake Outburst Floods (GLOFs) at Lake Merzbacher. Our results demonstrate that the summer LST warming trend (0.06°C·yr^{-1} from 2000 to 2022)

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exceeded the regional air temperature increase. This amplified warming aligns with observations from other global lakes, such as Lake Superior and lakes on the Tibetan Plateau, and is likely driven by positive ice-albedo feedback and the high heat capacity of water, which allows lakes to store more energy than the surrounding atmosphere (Austin and Colman, 2007; Zhang et al., 2014).

Critically, we identified 12°C as a key thermal threshold for GLOFs, with ~90% of events occurring when LST exceeded this value. This strongly implicates thermal forcing as a central mechanism in ice-dam failure. Elevated LST likely promotes dam instability through two primary pathways: (1) by enhancing thermal erosion at the ice-water contact, directly weakening the dam structure (Thorarinsson, 1939), and (2) by accelerating overall glacier melt, which raises lake level and increases hydrostatic pressure, potentially leading to flotation of the ice dam or the rapid expansion of subglacial conduits (Shen et al., 2009; Ng et al., 2007). The occurrence of GLOFs during extreme heatwaves (e.g., LST > 20°C in 2017 and 2018) further underscores the potency of thermal drivers.

5.2 Pre-Outburst Thermal Dynamics and Early-Warning Potential

A significant advancement of this research is the identification of quantifiable thermal precursors.

Short-term warming pulse: the consistent and rapid increase in LST (peaking at 0.65 °C·day^{-1}) beginning approximately eight days before an outburst provides a clear short-term warning signal.

Thermal acceleration threshold: we quantified the acceleration of this warming and established a critical threshold of 1.04 °C·day^{-2}. The exceedance of this threshold around nine days pre-GLOF appears to signal a critical transition in the lake-ice dam system, marking a phase of destabilization and offering a potentially robust indicator for imminent failure.

Cumulative thermal forcing: the strongest correlation between peak discharge and cumulative LST over 10-15 days ($r = 0.77$) indicates that flood magnitude is not solely a function of an instantaneous trigger but is preconditioned by short-term, integrated thermal energy (Liu et al., 2014). The weaker correlation over 30 days suggests that the most relevant thermal forcing for outburst initiation occurs within a two-week window.

Integrating these signals—absolute LST, its rate of change, acceleration, and short-term cumulative temperature—can form the basis of a multi-tiered, quantitative early-warning framework that moves beyond simple lake area or level monitoring.

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5.3 Generality and Limitations of the LST-GLOF Relationship

While this case study focuses on Lake Merzbacher, the thermal mechanisms identified are likely relevant for other ice-dammed lakes and potentially moraine-dammed lakes where thermal erosion plays a role (Debnath et al., 2018). However, the universality of our proposed thresholds (e.g., 12°C, 1.04 °C·day^{-2}) must be tested across different geographic and geomorphic settings. It is crucial to acknowledge that GLOFs have diverse triggers. Our model best applies to gradual, thermally-driven outbursts, as opposed to those caused by dynamic, short-term triggers like ice/rock avalanches (e.g., the 2021 Chamoli disaster), which operate on timescales of minutes to hours (Shugar et al., 2021).

This study has several limitations. The reliance on daily MODIS LST data may miss diurnal temperature variations critical to melt processes. We also simplified local topographic and glacier dynamic complexities (e.g., glacier surge events) to isolate the temperature signal (Häusler et al., 2016), but these factors can modulate the climatic response (Veh et al., 2025). Finally, our statistical relationships need to be grounded in physical processes through the development of coupled models that integrate surface energy balance, subglacial hydrology, and dam mechanics.

Future work should validate these thermal thresholds in other glacial basins using higher-resolution thermal data and incorporate detailed topographic and glaciologic data to refine predictive models and extend this early-warning methodology across High Mountain Asia.

6.Conclusions

This investigation establishes Lake Surface Temperature (LST) as a critical factor controlling the timing and magnitude of GLOFs at Lake Merzbacher. The key findings are:

The lake surface has warmed significantly (0.06°C·yr^{-1} for summer mean LST between 2000 and 2022), at a rate exceeding the local atmospheric warming, highlighting its role as an amplified indicator of climate change.

A critical LST threshold of 12°C was identified, with the vast majority of GLOFs occurring above this level, confirming the importance of thermal conditions for ice-dam stability.

Distinct pre-outburst thermal precursors provide actionable warning signals: a pronounced 8-day warming pulse (up to 0.65 °C·day^{-1}), a critical acceleration phase (>1.04 °C·day^{-2}) around 9 days before the outburst, and a strong influence of 10–15-

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day cumulative LST on peak discharge.

In conclusion, this research demonstrates that LST dynamics are a fundamental, and previously underutilized, element in understanding and predicting ice-dammed lake outbursts. The integration of real-time LST monitoring—focusing on exceedance of absolute thresholds, rates of change, and acceleration patterns—provides a robust scientific basis for enhancing early-warning systems. The methodology developed here offers a promising framework for improving GLOF risk management at Lake Merzbacher and has the potential to be adapted and applied to similar ice-dammed lakes across High Mountain Asia in a warming climate.

Data availability

MODIS/006/MOD11A1 data for this paper are available at https://lpdaac.usgs.gov/data. Meteorological data are available from the China Meteorological Data Service Centre (http://data.cma.cn/en) upon request. The ERA5-Land dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) is available at https://www.ecmwf.int/en/era5-land. The basic geographic information data (River, Glacier, DEM, etc.) used in this paper are from the National Tibetan Plateau Data Centre (https://data.tpdc.ac.cn).

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Author contributions

D. Shangguan initiated the idea. M. Wang, D. Shangguan and D. Li conceived the study. M. Wang and D. Li collected and processed the data. M. Wang performed the analysis, drafted the original manuscript and designed the figures. D. Shangguan, D. Li, Y. Li, R. Wang and J. Wu. A discussed the results. Q. Butt polished the manuscript. All authors reviewed and gave final approval for publication.

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Competing interests

The authors declare no competing interests in this paper.

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