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Meltwater-Induced Lake Freshening and Muted Warming in Northern China Under Contemporary Global Warming

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Key Points:

- Meltwater pulses over the last millennium inferred from lake water temperature and hydrology records in northern China
- Abrupt freshening and muted warming of lake water over current warm period linked to meltwater pulses under anthropogenic warming
- Meltwater effect on lake conditions in climatic warming periods would mute the amplitude of warming in climatic transition period

Supporting Information:

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

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Abstract Despite clearly documented in instrumental temperature records, the warming amplitude over the current warm period (CWP) inferred from lacustrine archive is very limited. The potential role of meltwater pulses in lake hydrology and their influence on lake water temperature under anthropogenic warming remain poorly investigated. Here we present and summarize lake water temperature and hydrology records in northern China to address potential meltwater effects over the last millennium. Our results show abrupt freshening and muted warming of lake water over the CWP, which appears to have also occurred along with climatic warming previously. Hence, substantial meltwater pulses to lakes, a transient response to climatic warming, could partly account for the muted warming over the CWP as indicated by lake water temperature records.

Plain Language Summary Compared to the instrumental temperature data, synthesized North Hemisphere temperature records and temperature records inferred from lacustrine archives show muted warming amplitudes since ∼1860 AD. The potential effects of meltwater pulses on lake conditions under anthropogenic warming remain poorly investigated. Our lake water temperature and hydrology records in northern China, together with previously reported records from this region, collectively show abrupt freshening and muted warming of lake water over the current warm period. This indicates that meltwater pulses appear to disrupt the warming signal in lake water temperature records, as occurred in previous climatic warming periods. Our results suggest that meltwater pulses, associated with climatic warming, could mute the amplitude of warming in the climatic transition period and has important implications for hydroclimatic reconstructions and projections in northern China and perhaps over the globe.

1. Introduction

Proxy-based temperature reconstructions play a vital role in understanding the climatic background prior to instrumental observations, comprehending climate system sensitivity, and enhancing the accuracy of climatic projections. Reconstructed Northern Hemisphere temperature changes (Esper et al., 2024; Moberg et al., 2005; PAGES 2k Consortium, 2013) over the last millennium reveal relatively warm conditions during the Medieval Warm Period (MWP) and cold conditions during the Little Ice Age (LIA). However, syntheses of North Hemisphere temperature records (Esper et al., 2024; Moberg et al., 2005; PAGES 2k Consortium, 2013; Schneider et al., 2023) show muted warming amplitudes compared with instrumental air temperature (Brohan et al., 2006; Schneider et al., 2023) changes since ∼1860 AD, complicating the contextualization of recent global warming within the context of past natural variability. Several lake water temperature records from northern China and the Tibetan Plateau (He et al., 2013; X. Li et al., 2015; Z. Liu et al., 2017; Zhao et al., 2018) exhibit muted or even no warming trends over the current warm period (CWP), while tree-ring-based temperature record from northern China (Y. Liu et al., 2011) shows a continuously rising trend consistent with instrumental North Hemisphere temperature changes (Brohan et al., 2006). Meanwhile, a recent simulation (L. Huang et al., 2023) reveals decreased surface water temperatures in several Tibetan Plateau lakes over past four decades. Factors

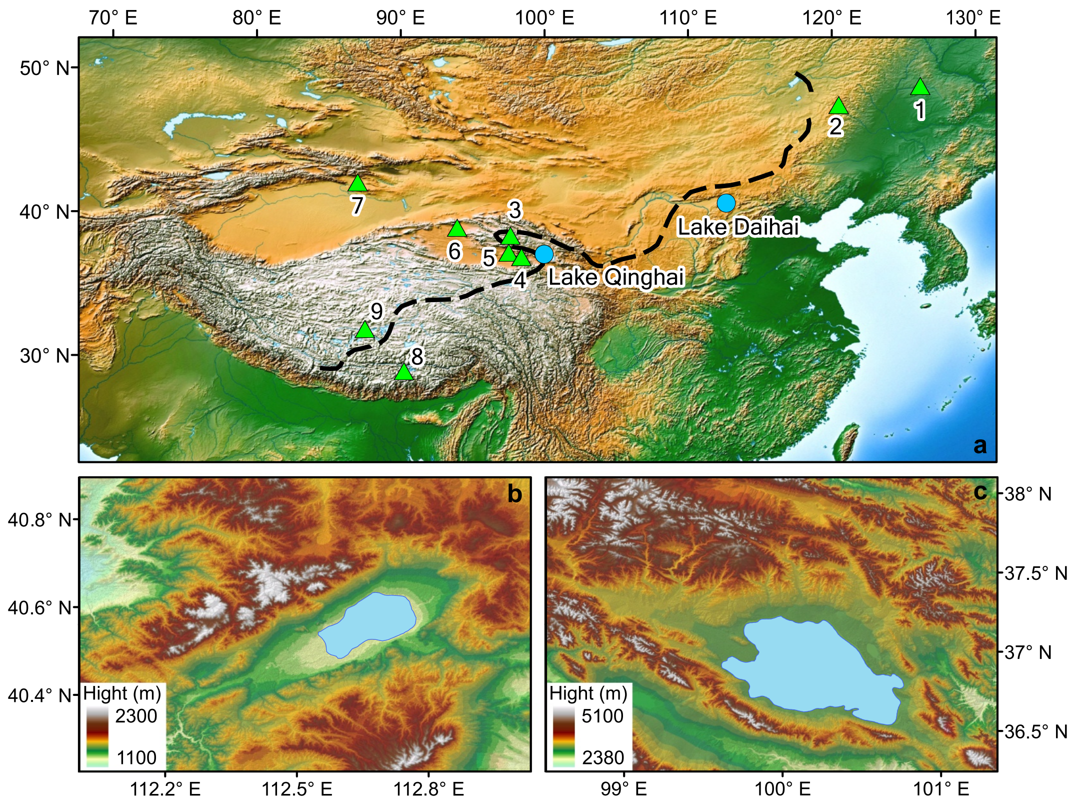

Figure 1. Site location maps. (a) Map showing the locations of Lake Daihai and Qinghai in this study (blue dots), and localities of other records in northern China and the Tibetan Plateau (green triangles). 1: Lake Wudalianchi, 2: Lake Luming, 3: Lake Hala, 4: Lake Xiligou, 5: Lake Gahai, 6: Lake Sugan, 7: Lake Boston, 8: Qiangyong Co, and 9: Dagze Co. The black dashed line indicates the 300 mm annual precipitation line in China, roughly the boundary between Asian monsoon and westerlies circulation systems. Topographic maps of (b) Lake Daihai and (c) Qinghai region.

other than environmental temperature appear to have influenced lake water temperature changes in northern China over this time interval, thus resulting in discrepancies between reconstructed and instrumental warming trends.

Substantial meltwater contribution to lake water budget within the deglaciation and early Holocene, the unstable climatic transition period, appears to be a large-scale phenomenon in mid-latitude Asia (Aichner et al., 2022; J. Jiang et al., 2022; C. G. Li et al., 2021; G. Li et al., 2024; Y. Li et al., 2021; Zhou et al., 2016). A recent study also suggests that abrupt meltwater pulses along with climatic warming appear to restrain lake water temperature increase and thus delayed lake warming over the early Holocene (C. G. Li et al., 2023). Under contemporary global warming, intensified glacier/snow melt and permafrost thawing continuously affect freshwater availability and regional hydrological conditions in the arid and semi-arid regions of mid-latitude Asia (Immerzeel et al., 2010; Kraaijenbrink et al., 2021; Walvoord & Kurylyk, 2016; F. Xu et al., 2024). The climatic conditions in northern China over the last millennium have been characterized by contrasting hydrological changes and opposite temperature-moisture associations, that is, warm and wet versus warm and dry conditions, in regions dominated by monsoon and westerly circulations respectively (Chen et al., 2019). Previous studies indicate that substantial meltwater input to lakes in both regions over the last millennium appears to affect lake-level changes (C. G. Li et al., 2021; Y. Li et al., 2021; Y. Yao et al., 2021). Nevertheless, the potential effects of meltwater pulses on lake hydrology and water temperature changes in northern China during climatic warming intervals over the last millennium, particularly over the CWP and MWP, remain poorly investigated.

Here we present alkenone records from Lake Daihai, grain size and element compositions records from Lake Qinghai and synthesize available lake temperature and hydrological records, to infer possible meltwater pulses over the last millennium (Figure 1, Figures S1–S3, Tables S1 and S2 in Supporting Information S1). The two lakes are located at the margin of monsoonal regions of northern China. Our results, together with other climatic records from northern China, allow us to reveal effects of meltwater pulses on lake hydrology and temperature changes, which could provide new insights into climatic reconstructions and projections.

2. Materials and Methods

Lake sediment cores were retrieved from Lake Daihai and Qinghai. Lake Daihai (40°29′–40°37′N, 112°33′–112°46′E, 1,221 m asl) is a hydrologically closed brackish lake located in southern Inner Mongolia, China, with an area of 133 km^2 and an average water depth of ∼7 m (Xiao et al., 2006; L. Xu et al., 2017; Zeng et al., 2013). The lake basin is surrounded by the Manhan Mountains (∼1,600–2,300 m asl) to the north and the Matou Mountains (∼1,400–2,000 m asl) to the south (Xiao et al., 2006; L. Xu et al., 2017; Zeng et al., 2013). The lake is fed by five major rivers originating from the south and the east, and some short intermittent streams from the north of catchment (L. Xu et al., 2017). Two ∼100 cm-long parallel sediment cores, DH15-1 and DH15-2, were collected from the northern sector of the lake using a gravity corer in 2015. The age model suggests a basal age of ∼880 AD for the cores from Lake Daihai (Figure S1a and Text S1 in Supporting Information S1). Lake Qinghai (36°32′–37°15′N, 99°36′–100°47′E, 3,194 m asl) is a closed-basin, brackish to saline lake on the northeastern Tibetan Plateau, Qinghai, China. The lake has developed within a basin surrounded by mountain ranges, with an area of 4,400 km^2 and an average water depth of ∼21 m (X. Li & Liu, 2017; H. Wang et al., 2014). Active glaciers are situated in the northwest portion of catchment (Zhou et al., 2016). Observations indicate that net precipitation, surface runoff, and groundwater discharge are the primary sources of water supply to Lake Qinghai (Z. Jin et al., 2010; X. Li & Liu, 2017). A 204 cm-long core (QHH12A) was retrieved from the northeast sector of the lake at a water depth of ∼5 m in 2012 (Z. Liu et al., 2017; Meng et al., 2020). The age model suggests a basal age of ∼500 AD for the core from Lake Qinghai (Text S1 in Supporting Information S1, Meng et al., 2020).

We have generated alkenone records from Lake Daihai and grain-size and element composition records from Lake Qinghai. A detailed description of methodology is given in Texts S2 and S3 in Supporting Information S1. We have collected published temperature and hydrological records inferred from lacustrine archives in northern China and the Tibetan Plateau, and the detailed description of data collection is given in Text S4 and Table S2 in Supporting Information S1.

3. Results and Discussion

3.1. Proxy Interpretation

Alkenone unsaturation index ($U^{K'}_{37}$) and proportion of $C_{37:4}$ (%$C_{37:4}$) have been successfully applied to reconstruct lake water temperature and salinity, respectively, in mid-latitude Asia (He et al., 2013; J. Jiang et al., 2024; Q. Jiang et al., 2022; Z. Liu et al., 2017, Text S5 in Supporting Information S1). A recent phylogeny study suggests that changes in species or subclades of alkenone-producing Isochrysidales may impact the relative abundance of alkenone compounds, which could potentially complicate the interpretation of alkenone-derived indicators in some lakes (Y. Yao et al., 2022). The alkenone C_{37} isomer has not been detected in investigated sediment cores (Table S1 in Supporting Information S1), indicating that alkenones in Lake Daihai and Qinghai (Z. Liu et al., 2017) are only produced by Group 2 Isochrysidales over the last millennium. Additionally, analysis of surface sediment samples collected from Lake Daihai and Qinghai has revealed that alkenones in both lakes, with the absence of Group 2w2, are exclusively produced by Group 2i and 2w1 Isochrysidales (Y. Yao et al., 2022). Hence, the %$C_{37:4}$-based salinity records in investigated lakes are not affected by proposed high proportion of $C_{37:4}$ produced by Group 2w2 species (Y. Yao et al., 2022). A recent study hypothesizes that Group 2i species, characterized by the presence of $C_{39:4}$Me alkenone, might produce alkenones with high $U^{K'}_{37}$ values in cold conditions and thus confound the $U^{K'}_{37}$-based temperature records (Zhao et al., 2024). %$C_{39:4}$ values from Lake Daihai are >25% since ∼1925 AD (Figure S2c in Supporting Information S1), while our $U^{K'}_{37}$ record shows lower rather than higher values (Figure S2a in Supporting Information S1). Our alkenone result from Lake Daihai does not support the hypothesized impacts of Group 2i species on $U^{K'}_{37}$-based temperature records (Zhao et al., 2024). Meanwhile, the variations in $U^{K'}_{37}$ and %$C_{37:4}$ records from Lake Daihai (Figures 4b and 4c) and Qinghai (Figures 4e and 4f, Z. Liu et al., 2017) indicate relatively warm/wet conditions during the MWP and cold/dry conditions during the LIA, consistent with climatic changes inferred from different proxies in monsoonal regions (Figures S4a–S4c in Supporting Information S1, Chen et al., 2019; Lan et al., 2020). This again confirms the effectiveness of $U^{K'}_{37}$ and %$C_{37:4}$ indices as reliable climatic indicators over the last millennium in investigated lakes. Collectively, alkenone-based temperature and salinity records from Lake Daihai and Qinghai are unlikely to be affected by potential phylogenetic effects over the last millennium. Alkenone records from investigated lakes tend to reflect warm season climatic changes, thus largely capturing water temperature and salinity signals in Chinese lakes during periods more susceptible to changes in atmospheric temperature and meltwater discharge (Wan et al., 2018). Hence, we use alkenone $U_{37}^{K\prime}$ and $\%C_{37:4}$ as indicators of lake water temperature and salinity, respectively.

A detailed description of $\%C_{37:4}$ and C_{37}/C_{38} records from Lake Qinghai and element composition records interpretation is given in Text S5 in Supporting Information S1.

3.2. Lake Water Temperature and Hydrological Changes

$U_{37}^{K\prime}$ record from Lake Daihai indicates increased temperature since ~1770 AD, while abrupt lake freshening and muted warming appear after ~1925 AD (Figures 2b and 3a). Mean grain size and Rb/Sr records from Lake Qinghai exhibit exceptionally high and low values, respectively, since ~1925 AD (Figure 3b, Figure S3 in Supporting Information S1), indicating increased input of coarse-grained terrigenous material to lake basin. Previously reported alkenone records from the same sediment core (Z. Liu et al., 2017) also exhibit concurrent lake freshening and muted warming since ~1925 AD (Figures 2c and 3c). The muted lake warming in Daihai and Qinghai over the CWP coincides with abrupt lake freshening and intensified physical weathering (Figures 2b, 2c, and 3a–3c). Meanwhile, warm and high lake-level conditions during the MWP have been documented in alkenone records from Lake Daihai (Figures 4b and 4c) and Qinghai (Figures 4c and 4d, Z. Liu et al., 2017), followed by cool and low lake-level conditions during the LIA, consistent with regional and North Hemisphere temperature records (Figure 4a, Y. Liu et al., 2011; Moberg et al., 2005) and hydrological changes in monsoonal regions (Figures S4a–S4c in Supporting Information S1, Chen et al., 2019). The temperature-moisture association observed in both lakes over the last millennium appears to have been disrupted since ~1925 AD (Figures 4b–4f). Further, when placed together with other existing lake hydrological and water temperature records from northern China that exhibit marked shifts over the CWP (Table S2 in Supporting Information S1), the abrupt lake freshening and muted warming observed in investigated lakes remain clearly discernible (Figures 2 and 3).

Muted lake warming over the CWP in Lake Qinghai and Daihai is supported by several lake water temperature records from northern China (Figure 2). $U_{37}^{K\prime}$-based lake water temperature records from Gahai (Figure 2d, He et al., 2013; Zhao et al., 2018) and Sugan (Figure 2e, He et al., 2013) on the northeastern Tibetan Plateau, and Dagze Co on the central Tibetan Plateau (Figure 2f, X. Li et al., 2015), consistently display increased temperature at the onset of CWP, but followed by muted lake warming within the last century and thus diverging from the rising trend in instrumental air temperature records (Figure 2a).

Meanwhile, lake hydrological changes over the CWP, as observed in Lake Qinghai and Daihai, have been widely documented in various records from monsoonal regions of northern China (Figures 3a–3g, Figure S5d in Supporting Information S1). For example, bulk carbonate carbon and oxygen records from Lake Xiligou (Figure 3d, Qin et al., 2023) and Hala (Figure 3e, Cao et al., 2007) on the northeastern Tibetan Plateau show particularly depleted isotopic values during the time interval ~1900–1950 AD, indicating substantially more negative isotopic values of lake water associated with abrupt meltwater pulses to lakes (J. Jiang et al., 2022; Qin et al., 2023). RIK_{37} records from Lake Luming (Figure 3f, Y. Yao et al., 2023) and Wudalianchi (Figure 3g, Y. Yao et al., 2021) in northeastern China show exceptionally low lake salinity at ~1840–1920 AD and since ~1970 AD, respectively, inconsistent with relatively inappreciable precipitation changes in northern China (Yang et al., 2014; Y. Yao et al., 2021), and appear to indicate increased contribution of meltwater pulses to lake water budget. Anomalously old pollen ^{14}C ages in a sediment core from Qiangyong Co on the southern Tibetan Plateau (Figure S5d in Supporting Information S1, J. F. Zhang et al., 2017) are suggested to be associated with old terrestrial carbon carried by meltwater during the warming and glacier retreat periods.

Similarly, lake freshening and muted warming trends may have also occurred at the time interval ~900–1000 AD, the transition to the MWP, in this monsoonal region. At Lake Qinghai, relative low lake water temperature and fresher conditions can be observed (Figures 4e and 4f, Z. Liu et al., 2017), which is again broadly concurrent with remarkably fluctuations in mean grain size and Rb/Sr records (Figure 4g). For Lake Daihai, low alkenone concentrations at this interval (Table S1 in Supporting Information S1) prevents estimating lake water temperatures, however, the extremely low concentration itself may indicate substantially fresher conditions than, for

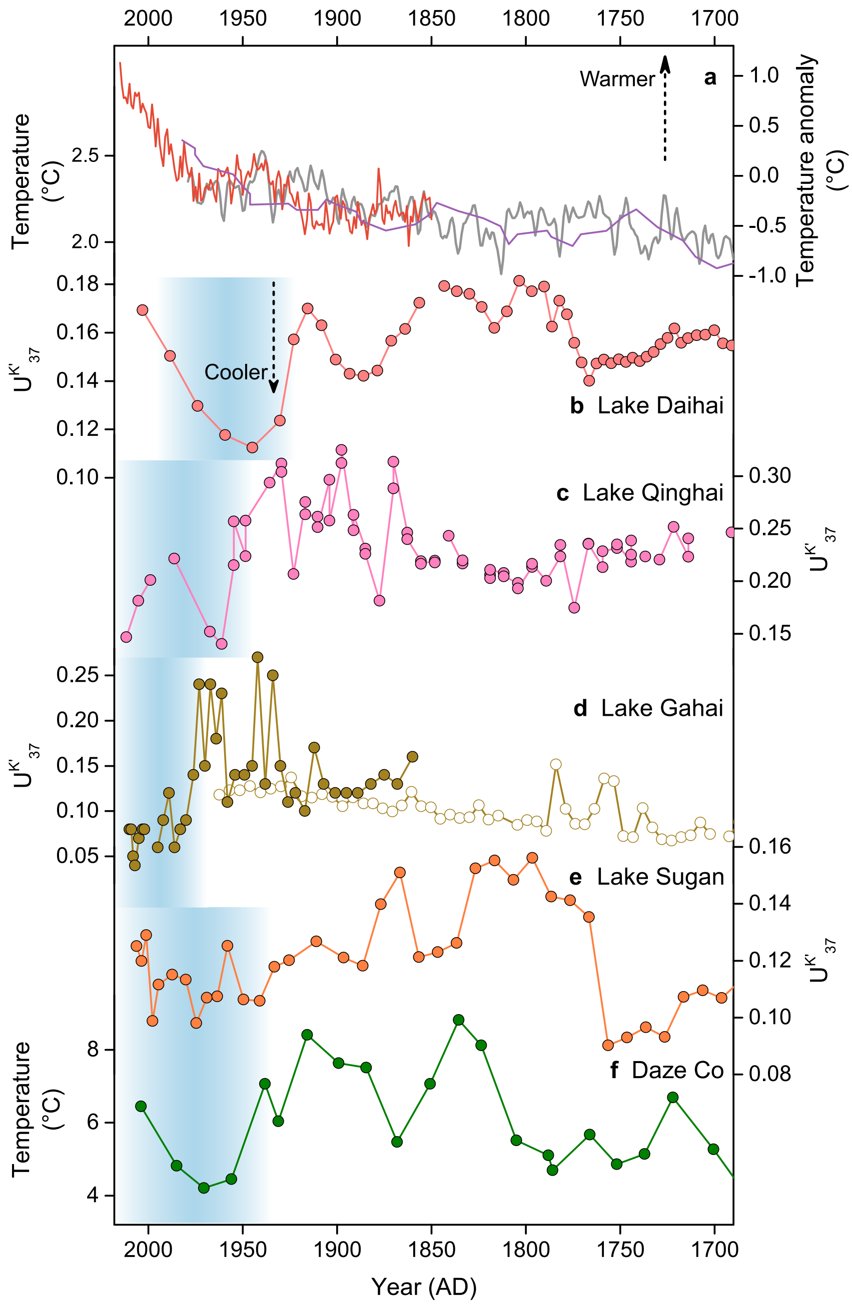

Figure 2. Temperature records since ∼1700 AD. (a) Reconstructed (gray line, Moberg et al., 2005) and instrumental (red line, Brohan et al., 2006) Northern Hemisphere temperatures, and tree-ring-based temperature changes in northern China (purple line, Y. Liu et al., 2011). Alkenone $U^{K'}_{37}$ records from (b) Lake Daihai (this study), (c) Qinghai (Z. Liu et al., 2017), (d) Gahai (He et al., 2013; Zhao et al., 2018), (e) Sugan (He et al., 2013) in northern China, and (f) $U^{K'}_{37}$-based temperature record from Dagze Co on the central Tibetan Plateau (X. Li et al., 2015); Blue bars highlight the time intervals with muted lake warming.

instance, the MWP. Further, higher values of the alkenone C_{37}/C_{38} ratio (Figure 4d), associated with fresher conditions (He et al., 2020), did occur at this interval, and after ∼1925 AD within the CWP. We hence suggest that substantial meltwater pulses at the onset of the MWP in this monsoonal region resembles that observed for the CWP. Corroborative evidence from additional records is warranted to understand the meltwater effects in northern China at the onset of the MWP, another climatic transition period over the last millennium.

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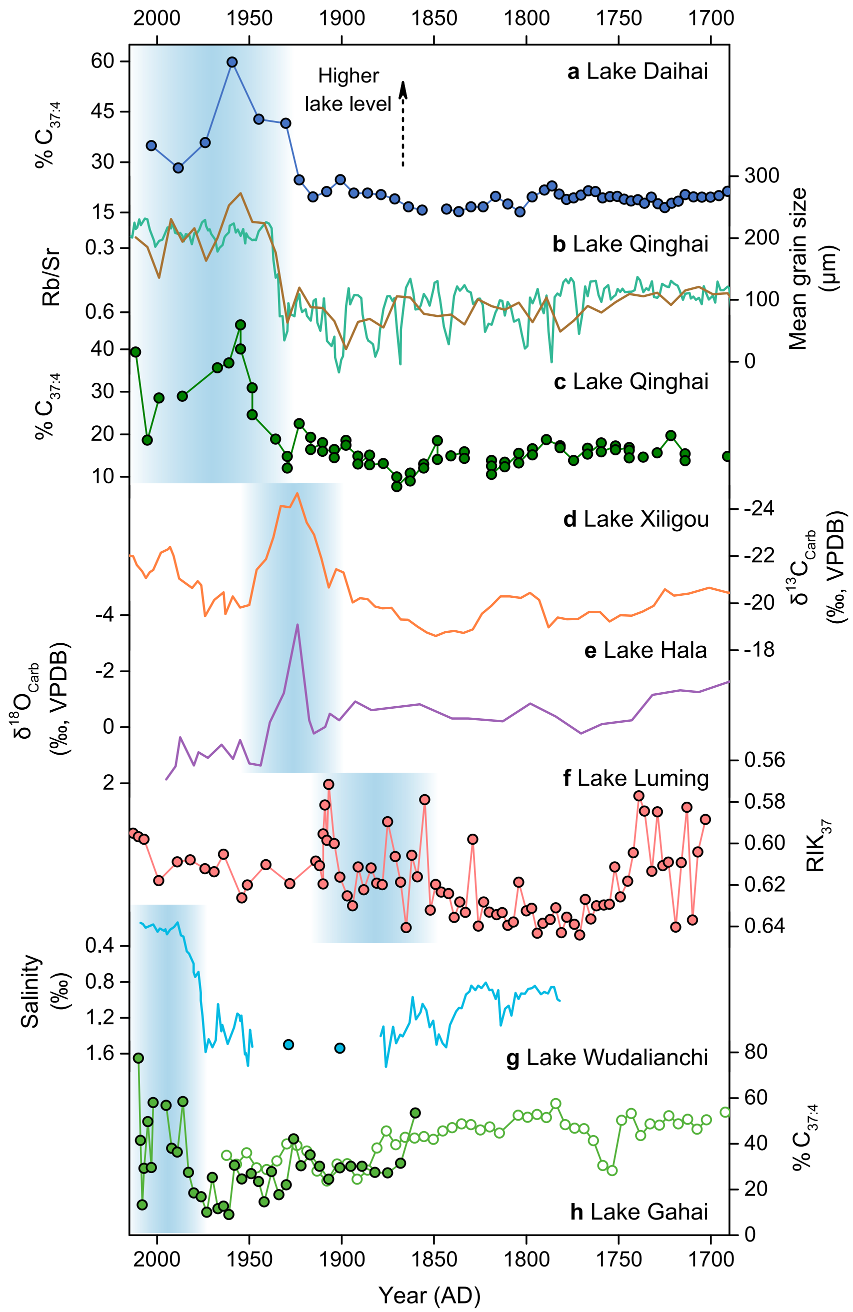

Figure 3. Hydrological records from northern China and the Tibetan Plateau since ~1700 AD. (a) Alkenone $\%C_{37:4}$ records from Lake Daihai (this study), (b) Mean grain size and Rb/Sr record from Lake Qinghai (brown and green line, respectively, this study), (c) $\%C_{37:4}$ records from Lake Qinghai (Z. Liu et al., 2017), (d) $\delta^{18}C_{org}$ record from Lake Xiligou on the northeastern Tibetan Plateau (Qin et al., 2023), (e) $\delta^{18}O_{carb}$ record from Lake Hala on the northeastern Tibetan Plateau (Cao et al., 2007), (f) Alkenone RIK_{37} record from Lake Luming in northeastern China (Y. Yao et al., 2023), (g) RIK_{37}-inferred salinity record from Lake Wudalianchi in northeastern China (Y. Yao et al., 2021), and (h) $\%C_{37:4}$ records from Lake Gahai on the northeastern Tibetan Plateau (He et al., 2013; Zhao et al., 2018). Blue bars highlight the time intervals with substantial meltwater pulses to lakes.

3.3. Meltwater-Induced Muted Lake Warming

Muted lake warming in northern China could be associated with abrupt meltwater pulses to lake water budget under contemporary global warming. The mountainous regions surrounding lake basins experienced increased snow and glacier accumulation during the cold LIA (T. Yao et al., 1996), which was likely accompanied by the

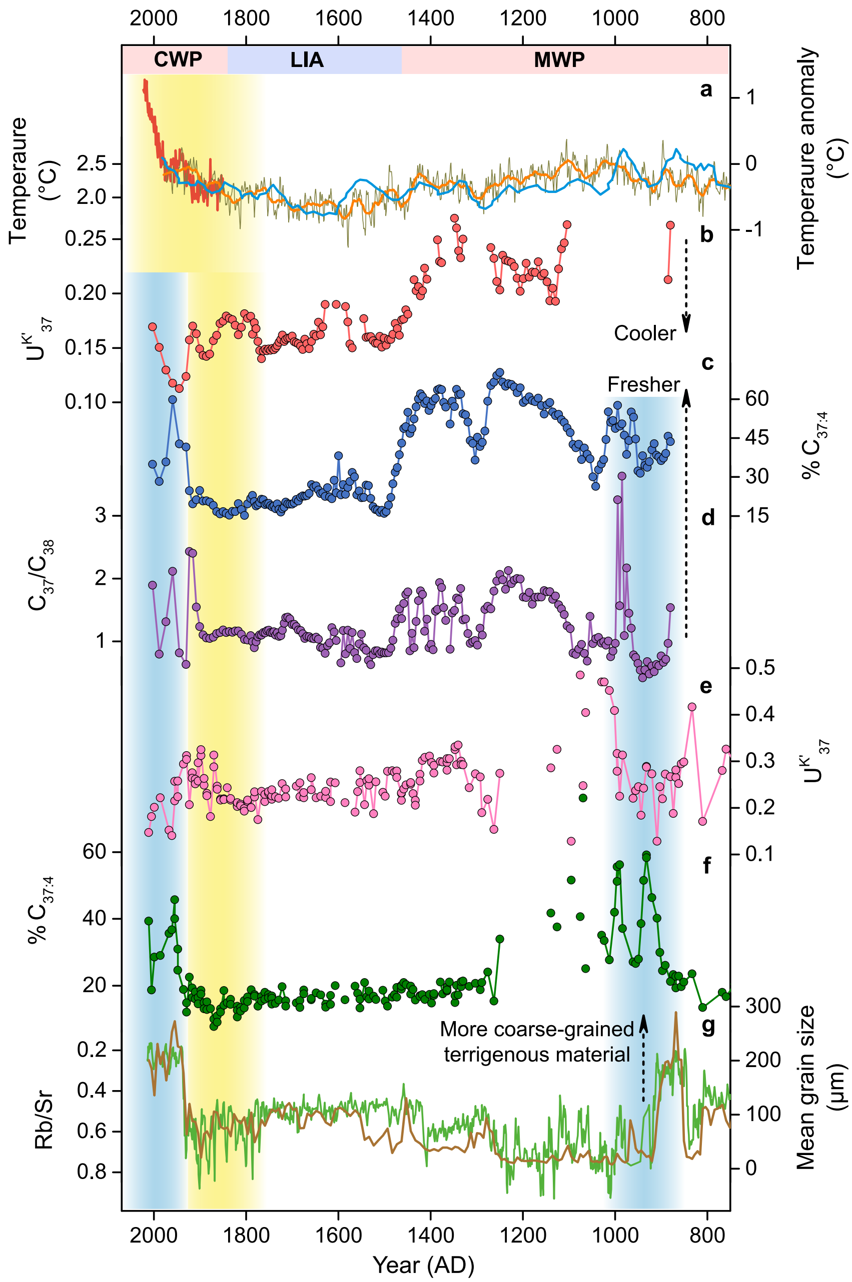

Figure 4. Temperature and hydrological records over the last millennium. (a) Reconstructed (gray line, Moberg et al., 2005) and instrumental (red line, Brohan et al., 2006) Northern Hemisphere temperatures, and tree-ring-based temperature changes in northern China (purple line, Y. Liu et al., 2011). Alkenone (b) $U^{K'}_{37}$ (temperature record), (c) %$C_{37:4}$, (d) C_{37}/C_{38} records (hydrological records) from Lake Daihai (this study), (e) $U^{K'}_{37}$, (f) %$C_{37:4}$ records from Lake Qinghai (Z. Liu et al., 2017), and (g) Mean grain size and Rb/Sr record from Lake Qinghai (brown and green line, respectively, this study); Yellow bars indicate warm climatic background over the current warm period, blue bars highlight the time intervals with substantial meltwater pulses and muted lake warming.

expansion and thickening of regional permafrost (H. Jin et al., 2020). Climatic warming over the CWP could have triggered intensified melting of glaciers and snow, as well as permafrost thawing (Mernild et al., 2013; Walvoord & Kurylyk, 2016; T. Yao et al., 2007). This process could have led to abrupt increases in cool and fresh meltwater discharge once temperature thresholds were exceeded, potentially impacting the thermal and hydrological dynamics of the lake systems in the region. Enhanced surface runoff associated with increased meltwater discharge could have facilitated the transport of coarser particles into the lake basins, and thus increased sediment grain size and decreased Rb/Sr values during abrupt lake freshening interval over the CWP (Figures 3b and 3c). Meanwhile, the cooling effects of meltwater pulses could have restrained the increase in lake water temperature, to some extent, and thus muted lake warming trends compared with terrestrial and instrumental temperature records (Figure 2). While the alkenone records tend to reflect climatic conditions of specific seasons, the muted lake warming under contemporary global warming, coupled with decreased water temperature in several Chinese lakes over the past decades inferred from satellite data and model simulations (L. Huang et al., 2023; Wan et al., 2018; G. Zhang et al., 2014), cannot be solely attributed to seasonal temperature changes. Due to limited water temperature records for Chinese lakes over the past few centuries, the magnitude and spatial distribution of meltwater effect on lake water temperature remain unclear. Meanwhile, lake conditions are influenced by various environmental factors, necessitating the assessment of potential meltwater effects based on various indicators in other Chinese lakes. More paired water temperature and hydrological records would enhance our understanding of meltwater pulses.

Lake level increases in both monsoonal and westerlies-dominated northern China over the CWP (Figure 3), together with muted or even no warming trends in lake water temperature records (Figure 2), indicate that the effects of meltwater pulses on lake hydrology and water temperature during this climatic warming interval seem to be a large-scale phenomenon in northern China. In westerlies regions, alkenone records from Lake Gahai (He et al., 2013) show relatively low lake level during the MWP compared to the LIA (Figure S4d in Supporting Information S1), consistent with other hydrological records from westerlies-dominated region (Figures S4e–S4g in Supporting Information S1, He et al., 2013; X. Z. Huang et al., 2009; Song et al., 2015). However, $\%C_{37:4}$ records from Lake Gahai show abrupt lake freshening instead of increased salinity since ~1970 AD (Figure 3h, He et al., 2013; Zhao et al., 2018), contrasting with the regional temperature-moisture association over the last millennium, where dry (wet) conditions corresponded to warm (cold) intervals (Chen et al., 2019). Lake level increases observed in westerlies-dominated region over the CWP (He et al., 2013; Zhao et al., 2018) appear to be associated with abrupt temperature-driven meltwater pulses, thereby surpassing the impact of precipitation on lake-level changes. In monsoonal regions, higher lake level generally corresponded to warmer rather than colder conditions over the last millennium (Figure 4, Figures S5a–S5c in Supporting Information S1, Chen et al., 2019). The regional temperature-moisture association appears to be disrupted over the CWP (Figure 4). We acknowledge that monsoonal regions experience slight increases in precipitation during the CWP (Yang et al., 2014; Y. Yao et al., 2021). However, muted lake warming under climatic warming conditions (Figure 2) strongly suggests substantial meltwater pulses to lakes, which could abruptly alter lake hydrological dynamics, serving as a key driver for the observed lake freshening over the CWP (Figure 3). Hence, abrupt lake freshening accompanied with muted warming in monsoonal regions over the CWP could not be explained by temperature-induced precipitation changes, again suggesting meltwater pulses to lakes.

Lake hydrological and water temperature records from northern China suggest substantial meltwater pulses and thus abrupt lake freshening and muted lake warming over the CWP, the climatic transition period. However, the timing, duration, and degree of its potential effect on lake hydrology and water temperature seem to vary among lakes (Figures 2 and 3), which depends on local hydrological settings and other environmental factors, although we acknowledge that chronological uncertainty may have also contributed to the difference in timing. Meanwhile, the profound effects of meltwater pulses on lake hydrology and water temperature changes mostly occur at the climatic transition over the Holocene (Aichner et al., 2022; J. Jiang et al., 2022; C. G. Li et al., 2021; G. Li et al., 2024; Y. Li et al., 2021; Z. Wang et al., 2024), if the onset of the MWP can serve as an example (Figure 4). Lake Qinghai reached a quasi-stable condition (Z. Liu et al., 2017) and followed regional hydrological (Chen et al., 2019) and temperature (Y. Liu et al., 2011) changes since ~1000 AD (Figures 4e–4g), possibly associated with decreased contribution of meltwater to lake water budget under relatively stable warm conditions. Considering the stabilization of lake conditions following substantial meltwater pulses over the early Holocene (J. Jiang et al., 2022; C. G. Li et al., 2021; G. Li et al., 2024; Y. Li et al., 2021) and the MWP, we suggest that transient meltwater discharge does not appears to affect long-term lake evolution. Current lake water temperatures documented in core top samples (Figures 2b–2f), which do not yet display high temperature signals, indicate that lakes in northern China seem to be in a meltwater-influenced climatic transitional phase and have not reached a quasi-stable condition.

Numerous studies have reported intensified melting of the terrestrial cryosphere and increased meltwater flux in mid-latitude Asia in the context of global warming. For example, glacier fluctuation records from the Tibetan Plateau (Yang et al., 2008) and the mid-to-high latitudes of the Northern Hemisphere (Figure S5e in Supporting

Information S1, Solomina et al., 2016) indicate marked intensifications in glacier melt since ~1900 AD. Substantial meltwater contribution to river runoff in northern China during the CWP has been widely recognized (Z. Li et al., 2016). Hence, the effects of meltwater pulses should be considered when examining recent wetting trends in arid and semi-arid regions of northern China and conducting hydrological projections (Chen et al., 2023). Furthermore, the continuous expansion of high mountain lakes in arid and semi-arid regions of mid-latitude Asia and the Tibetan Plateau in recent decades, driven by warming-induced meltwater discharge (X. Wang et al., 2016; F. Xu et al., 2024; Zheng et al., 2019), presents a complex and uncertain future scenario due to the proposed long-term reduction in meltwater influx in this region (Pritchard, 2019).

4. Conclusions

In summary, we have presented and synthesized temperature and hydrological records from northern China. Our results indicate abrupt freshening and muted warming of lake water during the CWP, associated with substantial meltwater pulses under anthropogenic warming. Divergent from instrumental air temperature records, the meltwater effects could partly disrupt the warming signal in lake water temperature records. Findings in this study highlight the transient meltwater effect on lake conditions in climatic warming periods, which would mute the amplitude of warming in climatic transition period and has important implications for hydroclimatic reconstructions and projections in northern China and perhaps over the globe.

Data Availability Statement

We declare that all new data in support of this study have been deposited in Figshare (Z. Liu, 2025).

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