

Quantitative Reconstruction of Salinity and Precipitation Changes in Central Asia over the Past 3 200 Years Using Diatom and Pollen Records of Lacustrine Sediment in Aibi Lake of SW Junggar Basin

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ABSTRACT: The response of lake environments in arid Central Asia to climate change during the Late Holocene over the centennial to millennial timescales remains contentious. The reason that primarily paleoenvironmental proxies diverse and the scarcity of accurate quantitative reconstruction records. In this study, we employed diatoms and pollen records from lacustrine sediment in the Aibi Lake of Southwest Junggar Basin to quantitatively reconstruct salinity and watershed precipitation amounts while exploring the associated forcing mechanisms. The results indicate that Aibi Lake salinity varied between 2 and 47 g/L during the Late Holocene Period, indicating a generally brackish environment, and corresponding to prevailing *Tryblionella granulata* diatom in the lake basin. Westerly-dominated annual precipitation varied between 250 and 320 mm during the Late Holocene Period in the basin, exhibiting a generally semi-arid environment and prevailing desert steppe vegetation. The Aibi Lake has a low salinity of average value of ~15 g/L and exhibits elevated precipitation (average value of ~280 mm) during the periods of the 2 900–1 990, 1 570–1140, and 590–120 cal yr BP. The reconstructed precipitation and salinity exhibit a periodicity of ~200 years, which is consistent with the cycle of phase changes of the North Atlantic oscillation (NAO) and total solar irradiance (TSI). This correlation suggests that variations in NAO and TSI significantly influence the precipitation and salinity changes in Central Asia over centennial to millennial timescales.

KEY WORDS: arid central Asia, diatom, pollen, salinity, precipitation, forcing mechanism.

0 INTRODUCTION

Arid Central Asia is one of the driest regions in the world, its hydroclimatic variations are predominantly controlled by the midlatitude Westerlies, Siberian High, and the northern end of the Indian summer monsoon, all of which together make the hydrological and climatic changes in central Asia extremely complex (Chen et al., 2021; Cai et al., 2017; Zhong et al., 2007). Studies on contemporary climate change in arid Central Asia have demon-

strated that the mid-latitude westerlies facilitate the transport of increased water vapor from distant regions such as the North Atlantic, the Mediterranean, the Black Sea, and the Caspian to the arid zones of central Asia throughout the year (Yan et al., 2019; Lei et al., 2014; Aizen et al., 2001) (Figure 1). Understanding the characteristics and dynamic mechanisms of climate change in the arid central Asia is crucial for predicting climate changes in the context of global warming (Chen et al., 2008). Modern observational data and tree-ring records indicate that in recent decades, precipitation and humidity in arid central Asia have been gradually increasing, while in the monsoon region, they have been decreasing, leading to opposite trends in humidity and precipitation between arid and monsoon regions (Huang et al., 2013; Chen et al., 2011; Zhang et al., 2008; Feng et al., 2007; Ma and Edmunds, 2006). However, the limited period of modern ob-

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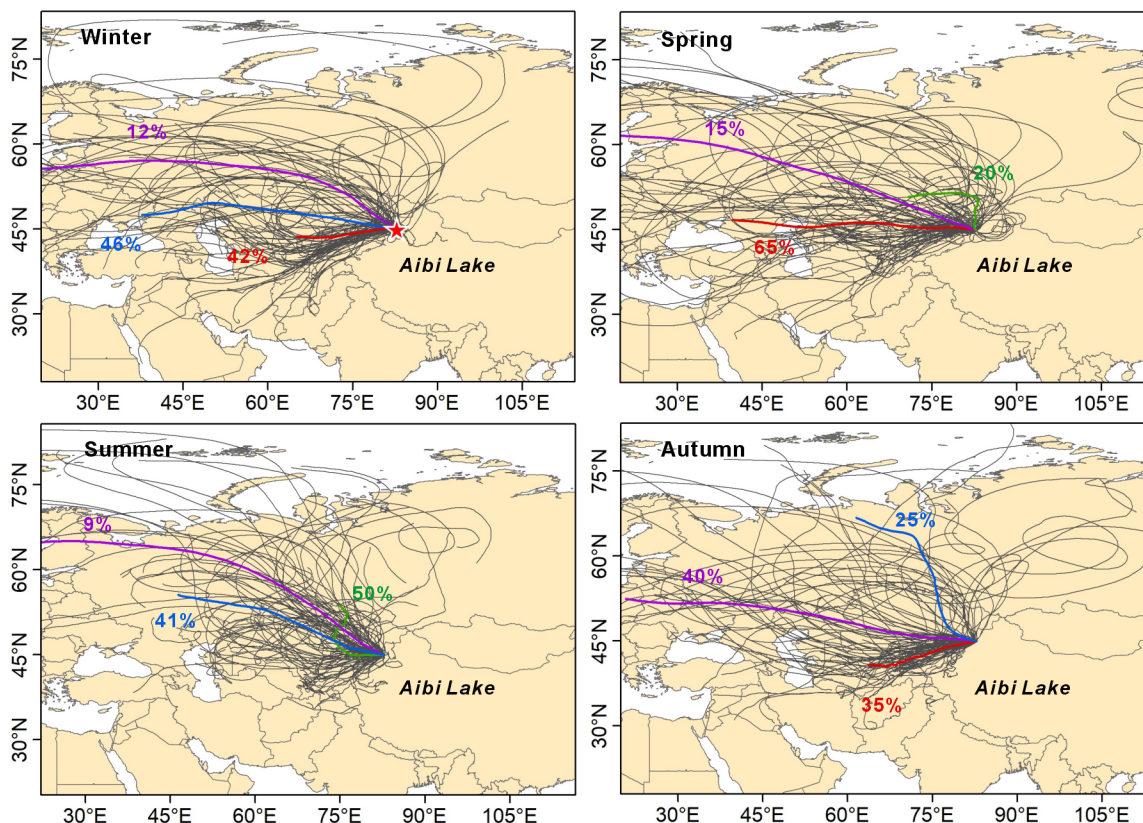


Figure 1. Ensembles of backward air-parcel trajectories (Draxler and Hess, 1997) of the source moisture for Aibi Lake. Water vapor is generally transported from the west to the east and three potential moisture sources can be broadly identified by use of the k-means clustering algorithm: (1) southern trajectories of the westerlies (red lines); (2) northern trajectories of the westerlies (short, green, and long, pink lines), and (3) the local region (blue lines). The percentage indicates the probability for each category of the total trajectories. Back trajectories data indicate starting points of daily backward (144 h) moisture trajectories from January to December 2022, at the height of 2 000 m above ground level. The data for backward trajectories analysis are downloaded from the website (<ftp://arlftp.arlhq.noaa.gov/pub/archives/reanalysis/>).

servations greatly constrains our understanding of precipitation changes and lake environment evolution in arid central Asia. The Late Holocene, spanning past 4 ka to present being the closest geological epoch to the Industrial Revolution, offers well-preserved microfossil materials. This period is particularly valuable for reconstructing changes in precipitation and lake environments within the basin. These reconstructions help us understand the pre-industrial climate and lake environment evolution and offer projections for their future trends.

Lakes are crucial water sources in the arid regions of inland Asia, playing a significant role in the regional water cycle (Li et al., 2024). The salinity changes in closed lakes depend on the balance between watershed precipitation, runoff, and evaporation. Currently, research on the Late Holocene lake environment and climate change in arid central Asia primarily depends on reconstructions derived from diverse proxy indicators. For example, Chen et al. (2010) analyzed 30 lake proxy records and identified a distinct pattern of hydrological and climatic changes in arid central Asia, characterized by increased humidity during the Little Ice Age and heightened aridity during the Medieval Warm Period. Subsequent studies on Sayram Lake (Lan et al., 2020, 2019), Bosten Lake (Fontana et al., 2019; Zhang et al., 2017;

Chen et al., 2006), Aibi Lake (Pan et al., 2024; Ma et al., 2011; Wu et al., 2005), Dalongchi Lake (Feng et al., 2022), Harnur Lake (Lan J H et al., 2018), Ailike Lake (Lan B et al., 2018), Swan Lake (Huang et al., 2015), Balkhash Lake (Feng et al., 2013), Barkol Lake (An et al., 2012), Wulungu Lake (Jiang et al., 2007), and Sugan Lake (Chen et al., 2008) have confirmed that the arid central Asia was more humid during the Little Ice Age compared to the Medieval Warm Period. Although these records have provided a systematic archive of climate change in arid central Asia, previous studies have primarily qualitative descriptive of climate change. The complexity of integrating various palaeoclimate record proxies and the range of potential interpretations across different records make it challenging to accurately assess how lake environments in arid central Asia respond to precipitation changes and the underlying driving mechanisms on centennial to millennial timescales.

Aibi Lake is located north of the Tianshan Mountains near the Alataw Pass. It is a typical closed terminal lake in the Junggar Basin of arid central Asia. The Aibi Lake Basin is rich in biodiversity. The lake sediments contain well-preserved fossil records (ostracods, diatoms, pollen, etc.), making it a valuable resource for reconstructing the Late Holocene climate and lake environment changes in

central Asia (Pan et al., 2024; Jia et al., 2020; Wu et al., 2005). Additionally, the climate system of Aibi Lake is predominantly shaped by the influence of westerlies, making its vegetation and lake environment highly sensitive to climate variations across different timescales. This sensitive position makes Aibi Lake an ideal site for investigating the impact of climatic changes on lake environments in arid central Asia. Extensive research has been conducted on Aibi Lake, including assessments of the basin's modern ecological environment quality using remote sensing images and studies on lake level fluctuations and salt dust migration processes (Zhang et al., 2023; Song et al., 2021; Jing et al., 2020). On the other hand, some studies reveal the characteristics of climate change in the region at different times during the Last Glacial Period, from 34.0 to 28.0 ka, the lake experienced high water levels under humid climatic conditions. Between 28.0 and 12.0 ka, the climate was predominantly dry, resulting in declining lake levels (Zhou et al., 2019). From 11 to 9 ka, dry conditions persisted, whereas the period from 9.0 to 3.6 ka experienced a warm and humid climate. Since 3.6 ka, the region's climate has generally been characterized by warmth and humidity (Jia et al., 2020), with notable variability, including drier conditions during the Medieval Warm Period and increased humidity during the Little Ice Age. The climate began to dry out starting around 1850 gradually (Ma et al., 2011; Wu et al., 2004). Overall, Aibi Lake climate change research mainly focuses on qualitative descriptions of climate using proxy indicators and lacks continuous high-resolution quantitative reconstructions of precipitation and salinity, it remains challenging to understand the driving mechanisms of the lake environment and climate change in this region.

In this study, we quantitatively reconstructed lake salinity using diatom data and precipitation history based on pollen from the sediments of Aibi Lake in the Junggar Basin during the Late Holocene. We also integrated data on lake level, CaCO_3 content, and a reliable AMS ^{14}C -based chronology. These findings shed light on variations in Aibi Lake's salinity and precipitation intensity in the Junggar Basin and revealed the significant influence of the North Atlantic oscillation (NAO) and total solar irradiance (TSI) on these changes.

1 GEOGRAPHICAL SETTING

Aibi Lake (44°54'–45°08'N, 82°35'–83°10'E, 200 m a.s.l.) is replenished seasonally by the Bortala River, Jing River, and Kuitun River, which receives water from glacial melt and precipitation in the Tianshan Mountains, covering an area of more than 522 km² of the lake surface. The region's primary water sources are the Atlantic transported via westerly, and glacial melting from the Tianshan Mountains during spring and summer. In contrast, the Mongolia-Siberian High dominates in winter, bringing minimal precipitation (Ma et al., 2011). Water vapor trajectories analysis indicates that climate variations around Aibi Lake is mainly driven by westerly-induced

precipitation (Figures 1, 2a). According to observing data from weather stations Bole and Jinghe, the maximum average monthly precipitation of the Aibi Lake Basin is 31 mm in May. The highest average monthly temperature of the Aibi Lake Basin is 24 °C in July (Figure 2c).

2 MATERIALS AND METHODS

A 95 cm-long sediment core (AB20E2) was collected from Aibi Lake (44° 55'21.08"N, 82° 50'50.28"E, water depth: 1.3 m) using a piston corer in October 2020 (Figure 2b). After retrieval, the core was opened to document its sedimentary characteristics, and subsampling was conducted at 1-cm intervals in the field (Pan et al., 2024). As illustrated in Figure 2b, a total of 17 surface sediments were collected at different locations of the lake. The water depth of all surface sediment samples was between 0.4 and 1.5 m covering almost the entire lake. In the field, water quality parameters including total dissolved solids (TDS), pH, electrical conductivity (EC), resistivity (RES), and temperature were measured by an SX-650 water quality instrument. The total organic content (TOC), total nitrogen (TN), and total hydrogen (TH) of surface sediments were measured using a CE-440 elemental analyzer in the laboratory.

Six samples were systematically selected at regular intervals from the AB20E2 core for bulk organic radiocarbon ^{14}C dating. Carbonate content was analyzed at 1-cm intervals. Detailed methodologies for ^{14}C dating, diatom identification, and carbonate analysis are provided in the electronic supplementary materials. Additionally, the procedures for quantitative salinity reconstruction, ensemble empirical mode decomposition (EEMD), power spectral analysis, and wavelet analysis applied to Aibi Lake are also described in the electronic supplementary materials.

3 RESULTS

3.1 Chronology

The sediments in core AB20E2 are predominantly composed of lacustrine clay and silt clay. Six organic material samples were calibrated using the CALIB 7.0.2 software to determine their accurate ages (Reimer et al., 2020). A Bayesian age-depth model was applied to establish the chronology for core AB20E2 (Figure 3) (Pan et al., 2024). The calibrated ^{14}C age at the top of the range is 2 311 cal yr BP. To correct the reservoir effect, the radiocarbon ages in this core were adjusted with a uniform 2 311-year reservoir age assumption (Pan et al., 2024).

3.2 Modern Diatom Results

A total of 20 genera and 35 species/subspecies of diatoms were identified across 17 surface sediment samples. Based on habitat preference, diatoms are generally categorized into planktonic and benthic types, with benthic diatoms, particularly *Tryblionella granulata* dominating the assemblages. Figure 4 illustrates the distribution of the diatom abundances in relation to each sample. The diatom assemblages are dominated by *T. granulata* (0–93%), *Cyclotella meneghiniana* (0–79%), *Fragilaria*

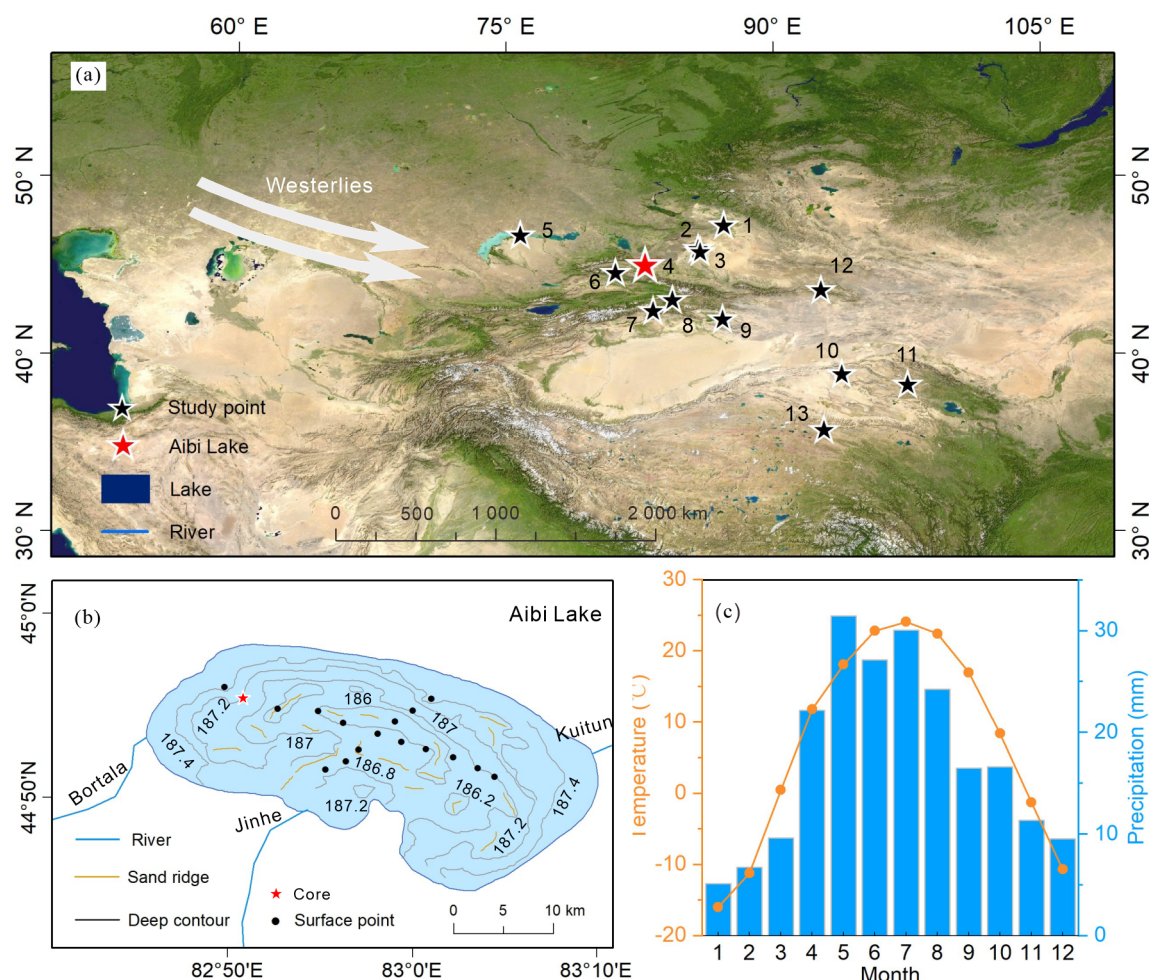


Figure 2. (a) Location of the study area and existing paleoecology records in mid-latitude central Asia. 1. Wulungu Lake (Liu et al., 2017); 2. Ailike Lake (Chen and Liu, 2022); 3. Manas Lake (Lin et al., 1996); 4. Aibi Lake (this study); 5. Balkhash Lake (Feng et al., 2013); 6. Sayram Lake (Lan et al., 2020); 7. Dalongchi Lake (Feng et al., 2022); 8. Swan Lake (Huang et al., 2015); 9. Bosten Lake (Zhang et al., 2017); 10. Sugan Lake (Chen et al., 2008); 11. Harnur Lake (Lan J H et al., 2018); 12. Kusai Lake (Cui et al., 2021). (b) Location of the studied site and the sediment core AB20E2 in Aibi Lake (NW China). The deep contour and sand ridge come from Wu (2010). (c) Average monthly temperature and precipitation in Aibi Lake Basin.

capucina (0–37%), *Nitzschia eglei* (0–19%), *Amphora ovalis* (0–66%) and *Synedra acus* (0–23%). The abundances of some brackish taxa (such as *T. granulata*, *C. oculus-iridis*, and *C. ocellata*) were recorded in all stations. The saltwater diatoms are mainly *N. commutata* and *C. oculus-iridis*. Which *N. commutata* species prefers habit saltwater, which accounts for 0–21.59%, and is only found in the southwestern of the study area near the river (Jinhe and Bohe). *C. oculus-iridis*, which thrives in cold, high-salinity environments, was primarily in the central and eastern areas of Aibi Lake.

3.3 Quantitative Reconstruction of Salinity and Precipitation Change from Diatoms and Pollen in the Aibi Lake, SW Junggar Basin, Arid Central Asia

Diatom communities in the samples are classified based on habitat preference into planktonic and benthic types, with benthic diatoms, with benthic diatoms, especially *Tryblionella granulata*, being the most dominant. Figure 4 displays the distribution of abundance for each

diatom species across the sample. According to Pan et al. (2024), sediment core records from Aibi Lake contain a diverse well-preserved collection of diatom fossils. For example, core AB20E2 includes 48 diatom taxa, 31 of which have an abundance greater than 2% as shown in the diatom diagram (Pan et al., 2024).

Numerical analysis of 17 modern diatom samples and associated environmental parameters indicates that salinity correlates with modern diatom communities (Figure 5, Table 1). Using principal component and constrained ordination methods (PCA and RDA, respectively), the WA and WAPLS models were employed to develop a diatom-inferred salinity transfer function (Figure S1, Figure 5). The model with the best performance was selected for reconstructing lake salinity history by comparing statistical test parameters across models (Table S1). Statistical testing was conducted using the “leave-one-out” cross-validation method and validated through bootstrapping with 1 000 cycles, yielding the highest coefficient of determination ($R^2_{\text{boot}} = 0.88$) and the lowest root

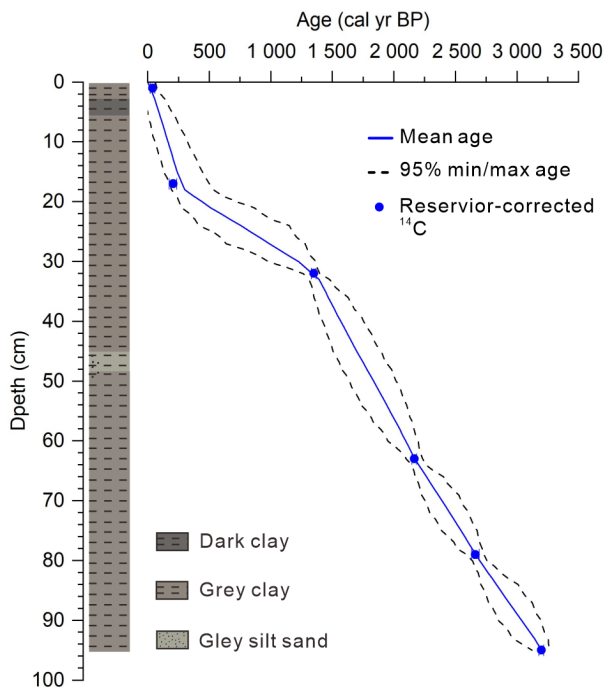


Figure 3. Results of radiocarbon dating of core AB20E2. The age-depth model is established using “Bacon” package in the R program.

mean square error of prediction ($RMSEP_{root} = 3.87$) (Birks, 1995; Ter Braak and Juggins, 1993). The WAPLS one-component model demonstrated optimal performance. Figure 5 illustrates the relationship between predicted and observed salinity against a 1 : 1 line, as well as the predicted residuals versus observed salinity.

A total of 62 pollen types were identified from the core AB20E2 samples (Pan et al., 2024). The pollen composition is predominantly herbaceous, comprising 90% of the total, with significant contributions from *Amaranthaceae*, *Artemisia*, *Poaceae*, *Cyperaceae*, *Thalictrum*, *Ranunculaceae*, and *Apiaceae*. All pollen types with relative abundances greater than 2% in at least one sample were included in the subsequent reconstructions. To establish a pollen-climate correction function, modern pollen samples collected near Aibi Lake were used to create a contemporary pollen dataset (Cao et al., 2022). Six calibration models were developed using spatial extents ranging from 800 to 1 300 km, to identify the best model for the target fossil pollen record. Analysis showed that the coefficient of determination (R^2_{boot}) stabilized at a radius of 1 000 km, yielding the lowest root mean square error of prediction ($RMSEP_{root}$), indicating this spatial extent provided the best model performance (Table 2, Figure S2).

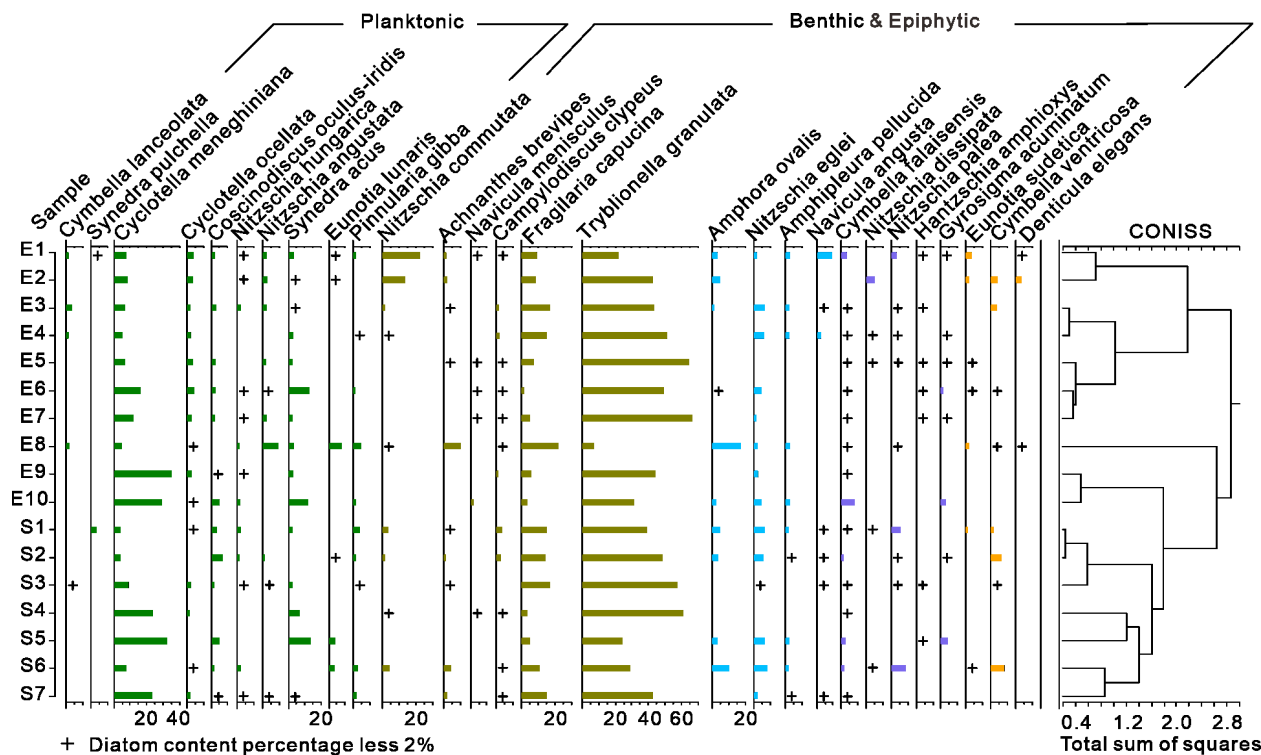


Figure 4. Simplified diatom diagram for the surface sediment Aibi Lake.

Table 1 Statistical characteristics of the modern surface water environment

	EC (mS/cm)	Salinity (g/L)	RES (Ω)	TDS (g/L)	TH (%)	TOC (%)	TN (%)	T ($^{\circ}$ C)	pH
Average	30.8	16.5	34.4	21.5	0.8	0.8	0.14	26.4	7.7
Maximum	45.7	27.6	51	32	1.2	1.1	0.18	27.7	8.5
Minimum	19.6	8.0	22	13.8	0.5	0.4	0.06	24.9	7.4

The calibration dataset consisted of 742 samples. Results from the WAPLS calibration showed that the two-component model had the lowest cross-validated RMSE- P_{root} (157.26) over 1 000 bootstrap cycles, with a high R^2_{boot} (0.56) (Table. 2). Accordingly, the WAPLS two-component model was selected for precipitation reconstruction (Figure 6). Statistical tests on the climate reconstructions using fossil pollen data from core AB20E2 and the 742 modern calibration samples (Cao et al., 2022) (Figure S2) demonstrated that mean annual precipitation

was the primary factor influencing fossil pollen assemblage changes.

3.4 Periodic Changes in the Salinity and Precipitation in the Arid Central Asia

In this study, we applied the EEMD model to analyze salinity and precipitation, CaCO_3 (%), and $< 4 \mu\text{m}$ (%). Given the duration and timescale of the records, we filtered out noise and removed long-term trends. Our findings show that the combination of the first two intrinsic

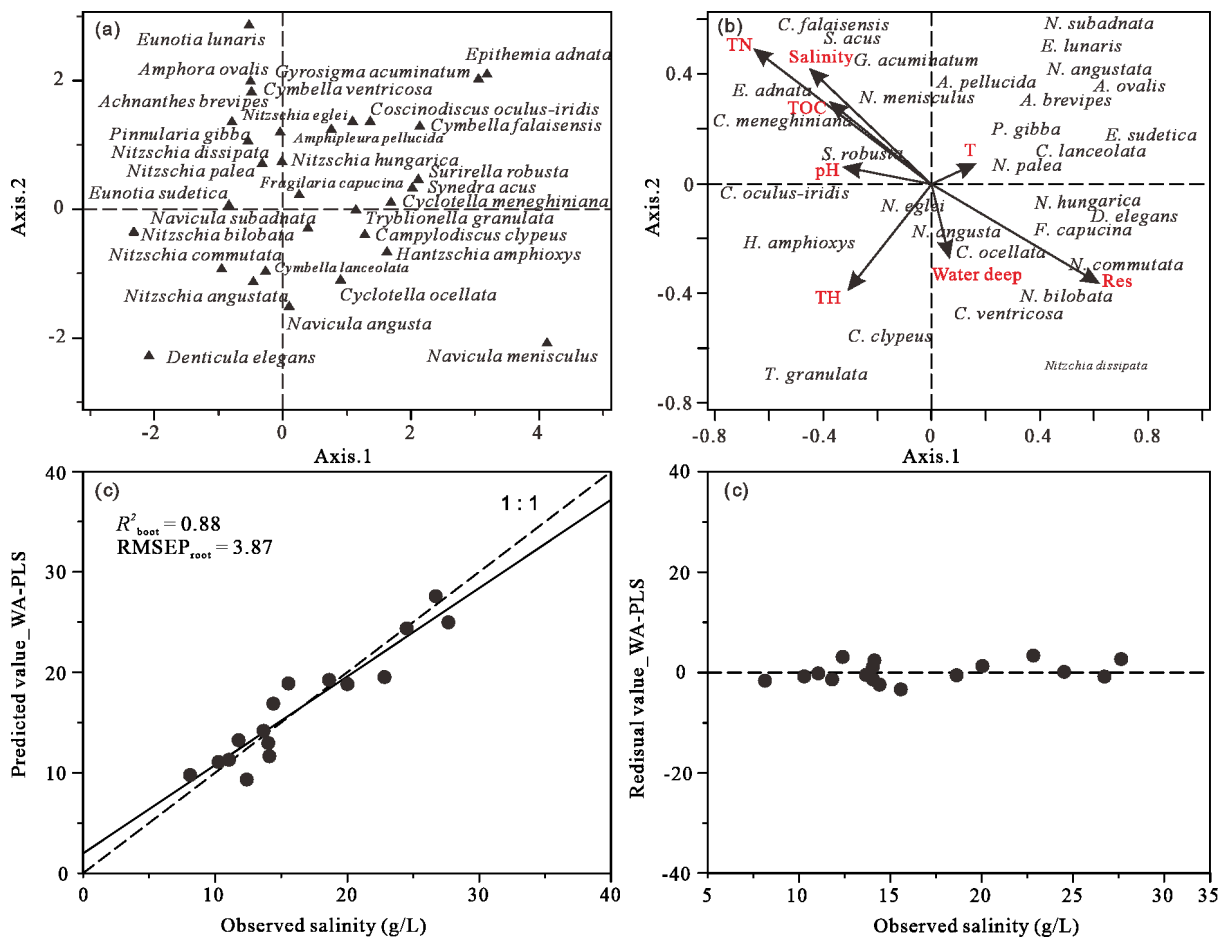


Figure 5. (a) Principle component analysis (PCA) of the species data, where the most common species are displayed. (b) Redundancy analysis (RDA) showing based on the forward-selection method. Environmental variables and the most common species are presented in ordination. (c) Development of the diatom-inferred salinity transfer function model (dotted line is the fitting line of the scatter plot).

Table 2 Summary of bootstrap-derived performance statistics for the WAPLS calibration function for 6 modern calibration sets of varying spatial extent with the radius range of 800–1 300 km around the fossil pollen site at Aibi Lake. Model errors are expressed as the root mean square error of prediction (RMSEP). The coefficients of determination between predicted and observed Pann values (R^2), the average and maximum bias of the Pann estimate, ΔRMSEP , and the P-value of the randomization t-test are also shown.

Radius (km)	Number	Select component	RMSEP (mm)	R^2	Average bias (mm)	Maximum bias (mm)	ΔRMSEP (%)	p
800	564	1	184.11	0.39	-1.23	328.05	-21.47	0.001
900	672	1	181.03	0.43	-1.10	269.36	-24.51	0.001
1 000	742	2	157.26	0.56	-0.30	182.71	-3.67	0.001
1 100	922	2	171.08	0.42	0.63	255.82	-3.11	0.001
1 200	960	2	170.47	0.43	-0.29	249.83	-2.36	0.001
1 300	985	2	169.84	0.43	-0.29	250.64	-2.32	0.001

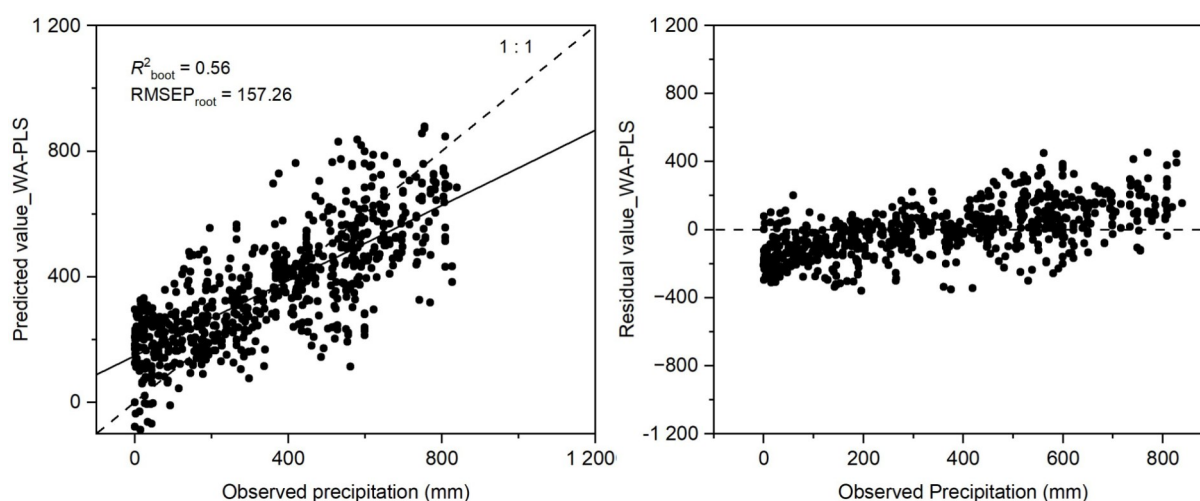


Figure 6. Pollen-predicted precipitation values vs. observed precipitation values; residuals vs. observed precipitation values.

mode functions (IMFs) in the EEMD model accurately captures the key information from these records, revealing distinct oscillations (Figure S4, S5). After comparison and analysis, we found that the sum of IMF1 and IMF2 (IMF1 + IMF2) effectively reconstructed these records, with salinity, CaCO_3 (%), precipitation, and $< 4 \mu\text{m}$ (%) exhibiting similar oscillatory patterns.

We performed spectral and wavelet analysis on the detrended of salinity (sum of IMFs 1 and 2, Figure S4a), CaCO_3 (%) (sum of IMFs 1 and 2, Figure S4b), precipitation (sum of IMFs 1 and 2, Figure S5a), and $< 4 \mu\text{m}$ (%) (sum of IMFs 1 and 2, Figure S5b) to identify key periodic components. The salinity analysis revealed significant periods with central frequencies of 0.005 cycles/year, corresponding to approximately 200 years, and these results passed the 95% Monte Carlo significance test. Wavelet analysis (Torrence and Compo, 1998) further confirmed that the ~200-year oscillations show stable, significant patterns over the past 3 200 years (Figures 7a, 7b). Additionally, the spectral and wavelet analysis of effective humidity identified a prominent period with a central frequency of approximately 0.005 cycles/year, corresponding to cycles of ~200 years (Figures 7e, 7f). Similarly, spectral and wavelet analyses of precipitation (Figures 7c, 7d) and $< 4 \mu\text{m}$ (%) (Figures 7g, 7h) revealed similar periodicities of ~200 years, reinforcing the robustness and reliability of our findings.

4 DISCUSSION

4.1 Quantitatively Reconstructed Salinity and Precipitation Variations of the Aibi Lake, Arid Central Asia during the Late Holocene

In arid inland regions, such as closed basin lakes, salinity dynamics are controlled by the balance between precipitation, runoff, and evaporation (Smol and Cumming, 2000). This balance directly influences fluctuations in lake water levels (Fritz, 1990), which, in turn, correlate negative correlation with changes in salinity (Yang et al., 2003). The quantitative salinity reconstruction based on diatoms shows that Aibi Lake's salinity has fluctuated be-

tween 2 and 47 g/L over the past 3 200 years, reflecting a generally stable, slightly brackish water environment (Figure 8a).

From 3 200 and 2 900 cal yr BP, the lake's salinity remained consistently high, averaging 10 g/L; Between 2 900 and 1 990 cal yr BP, lake salinity significantly decreased, ranging from 2 to 25 g/L. During this period, planktonic species like *Cyclotella meneghiniana* and *Synedra acus* exhibited notable increases, while the benthic diatom *Achnanthes brevipes* decreased (Pan et al., 2024). From 1 990 to 1 570 cal yr BP, salinity ranged from 12 to 27 g/L, accompanied by a decline in planktonic *Fragilaria capucina* and an increase in benthic species such as *Achnanthes brevipes*, suggesting a minor reduction in lake level. From 1 570 to 1 140 cal yr BP, salinity values ranged from 19 to 27 g/L, while planktonic species like *Fragilaria capucina*, and benthic species including *Amphora ovalis* and *Achnanthes brevipes* increased (Pan et al., 2024). Between 1140 and 590 cal yr BP, lake salinity slightly increases, ranging from 28 to 47 g/L. During the period from 590 to 120 cal yr BP, lake salinity ranged from 11 to 43 g/L. From 120 cal yr BP to the present, the salinity of the lake remained low, ranging from 7 to 10 g/L. Diatom assemblages mainly consisted of large benthic, saltwater, and brackish species such as *Nitzschia commutata*, *Tryblionella granulata*, and *Nitzschia dissipata*, indicating a favorable environment for aquatic plant growth (Pan et al., 2024).

The quantitative reconstruction results for precipitation derived from pollen analysis show that the precipitation values within the Aibi Lake Basin fluctuate between 250 and 320 mm, suggesting a semi-arid climate within the region (Figure 8g), which corresponds to a generally semi-arid environment in southwest Junggar Basin, central Asia and prevailing desert steppe vegetation in the basin.

In particular, between 3 200 and 2 900 cal yr BP, precipitation within the basin varied between 260 and 280 mm, suggesting arid climatic conditions. During the period from 2 900 to 1 990 cal yr BP, the precipitation was relatively high, ranging from 250 to 320 mm, with an aver-

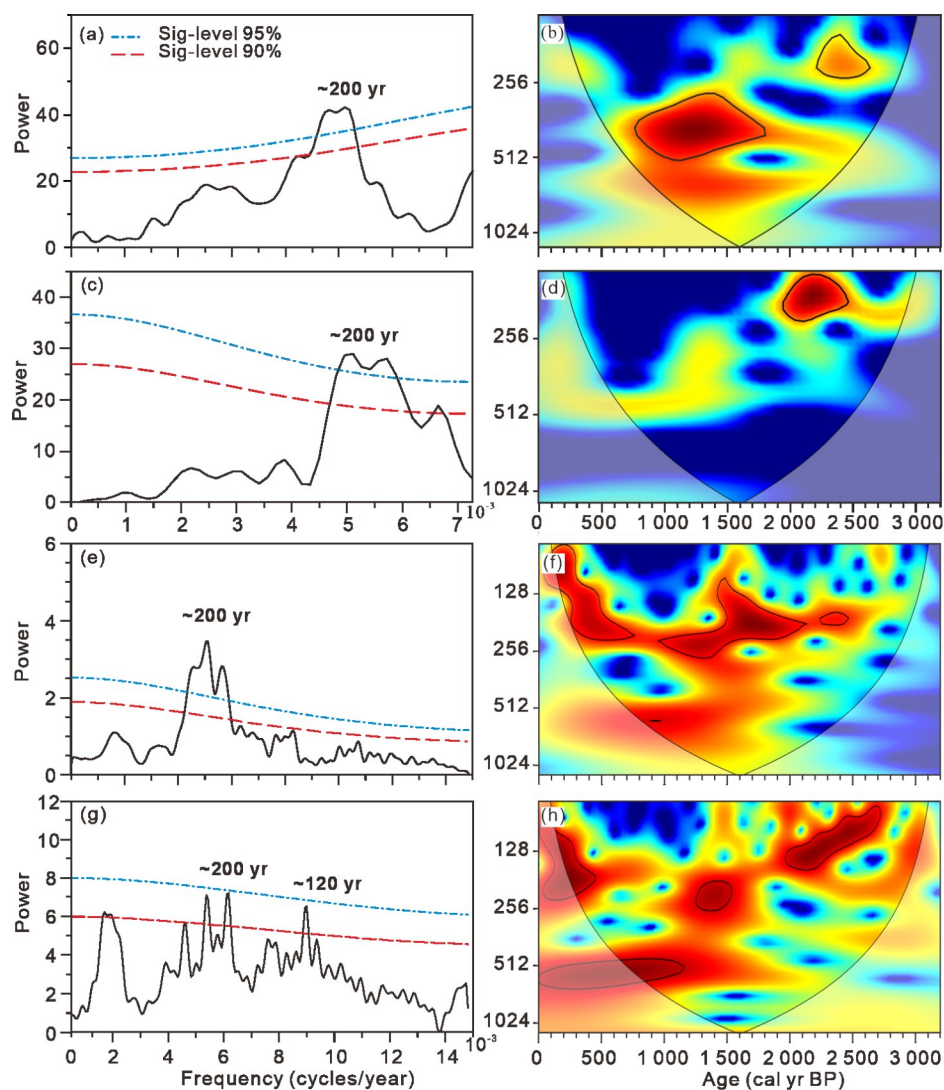


Figure 7. Spectral and wavelet analysis results of the salinity and precipitation, CaCO_3 (%), lake level ($4 \mu\text{m}$) record for Aibi Lake. (a), (b) Spectral wavelet analysis of the sum of salinity EEMD (imf 1 + imf 2); (c), (d) spectral and wavelet analysis of the sum of precipitation (mm) EEMD (imf 1 + imf 2); (e), (f) spectral and wavelet analysis of the sum of CaCO_3 (%) EEMD (imf 1 + imf 2); (g), (h) spectral and wavelet analysis of the sum of $4 \mu\text{m}$ (%) EEMD (imf 1 + imf 2).

age value of 280 mm. The increased vegetation coverage within the basin further indicates precipitation increased. Additionally, between 1 990 and 1 570 cal yr BP, there was a slight decrease in precipitation. Followed by a relatively large fluctuation of precipitation ranging from 260 to 280 mm during the period from 1 570 to 1 140 cal yr BP. The presence of moisture-loving taxa such as *Ranunculaceae* and *Thalictrum* increased (Pan et al., 2024). Between 590 and 120 cal yr BP, the precipitation showed a slightly increased compared to the previous period, ranging from 260 to 290 mm. Additionally, the occurrence of moisture-loving plants such as *Typha* and *Potamogetonaceae* within the basin indicates relatively humid climate conditions during this time. During the period from 120 cal yr BP to the present, the precipitation within the basin exhibited significant fluctuations, ranging from 260 to 300 mm. Dominant pollen taxa included *Artemisia* and *Amaranthaceae*.

4.2 The Response Patterns of Lake Salinity and Precipitation to Westerly Climate in Aibi Lake over Centennial to Millennial Timescales

The spatial patterns of hydroclimate changes in central Asia during the late Holocene are complex, influenced by the interaction of various climate systems, including the midlatitude westerlies, the Siberian anticyclone, and the Asian summer monsoon (Chen F H et al., 2019, 2010; Chen J H et al., 2019). In Aibi Lake, reconstructed salinity levels were primarily affected by basin precipitation, showing a negative correlation. Notably, three distinct low-salinity periods occurred at 2 900 – 1 990, 1 570–1 140, and 590–120 cal yr BP in the Aibi Lake, while the precipitation in the basin showed significantly high values.

We conducted a comparative analysis of the salinity, precipitation, and effective humidity records from Aibi Lake with data from other sites across central Asia, all in-

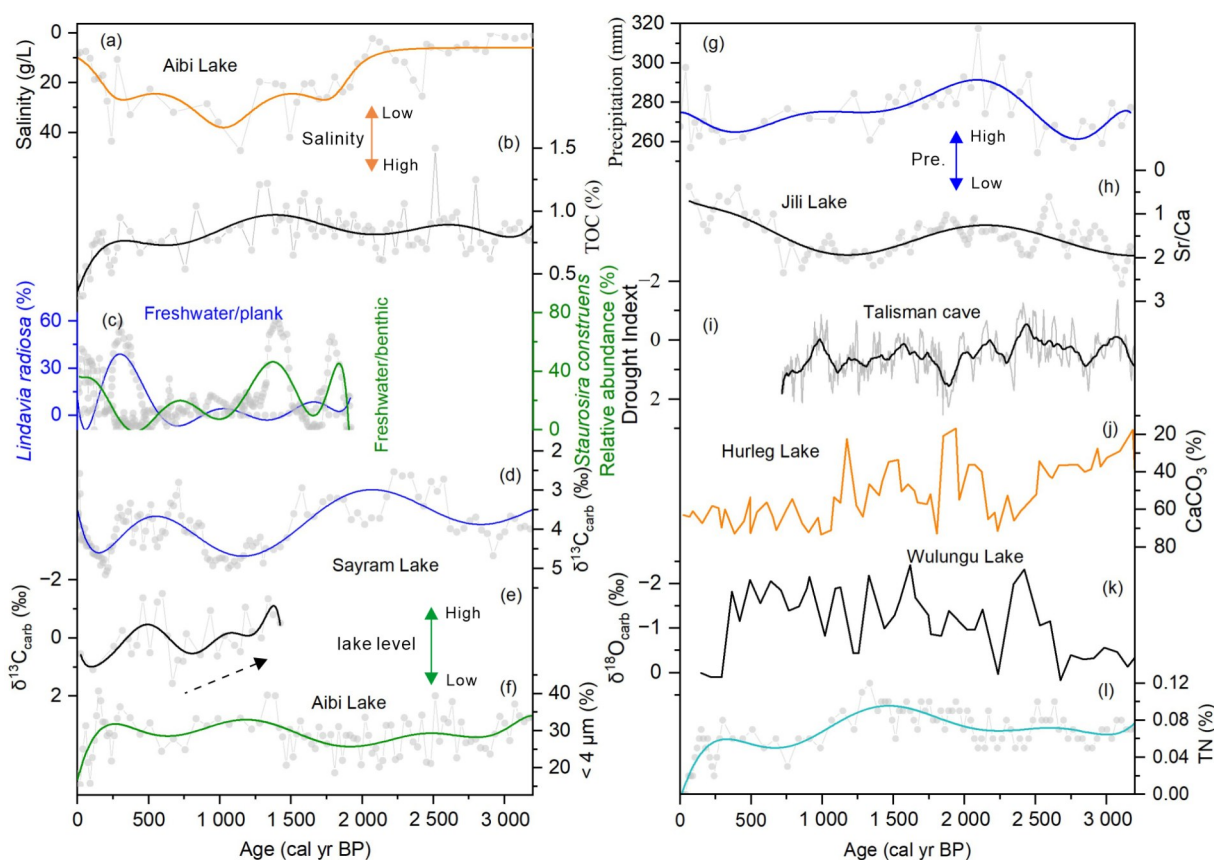


Figure 8. Comparison of hydroclimatic variations at Aibi Lake (a) Salinity; (b) TOC (%); (c) diatom indicators of paleoenvironmental changes (*Lindavia radiosa* and *Staurostra construens*, %) from Bosten Lake (Fontana et al., 2019); (d) $\delta^{13}\text{C}_{\text{carb}}$ (‰) in Sayram (Lan et al., 2020); (e) $\delta^{13}\text{C}_{\text{org}}$ (‰) in Aibi Lake (Ma et al., 2011); (f) $< 4 \mu\text{m}$ (%) in Aibi Lake (Pan et al., 2024); (g) precipitation (mm) is reconstructed by pollen; (h) Sr/Ca from Jili Lake (Chen R J, 2019); (i) Drought index record represented by the PCA results of $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ and Sr/Ca record (Tan et al., 2024); (j) CaCO_3 (%) from Hurlig Lake (Zhao et al., 2010); (k) $\delta^{18}\text{O}_{\text{carb}}$ (‰) of Ostracod shell in Wulungu Lake (Jiang et al., 2007); (l) TN (%) from core AB20E2 (Pan et al., 2024).

fluenced by the midlatitude westerly circulation (Figures 1 and 8). Our findings reveal a consistent correlation between the precipitation and lake level ($< 4 \mu\text{m}$) of Aibi Lake (Figures 8f, 8h) and the regional humidity variations inferred from the carbonates $\delta^{18}\text{O}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{carb}}$ of Sayram Lake (Figure 8d; Lan et al., 2020). These records also align with pollen concentrations in Sayram Lake (Jiang et al., 2013), as well as with organic matter $\delta^{13}\text{C}_{\text{org}}$, the carbonate $\delta^{18}\text{O}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{carb}}$ reconstructed precipitation presented by Ma et al. (2011) (Figure 8e). Additionally, Sr/Ca ratios in Talisman Cave, Kyrgyzstan (Tan et al., 2024), and effective moisture levels inferred from Ostracoda isotopes ($\delta^{18}\text{O}_{\text{PDB}}$ and $\delta^{13}\text{C}_{\text{PDB}}$) in Bosten Lake (Mischke and Wünnemann, 2006) indicate periods of increased precipitation at 2 900–1 990, 1 570–1 140, and 590–120 cal yr BP, which coincide with intensified pastoral activity. Fluctuations in Aibi Lake levels also match regional precipitation patterns inferred from the carbonate $\delta^{18}\text{O}_{\text{carb}}$ in Wulungu Lake (Jiang et al., 2007). Additionally, the grain size of Hanur Lake in the central Tianshan Mountains (Lan J H et al., 2018) further indicates increased precipitation and high lake levels during the Dark Ages Cold Period (DACP) and LIA, while precipitation decreased and lake levels were low during the

MWP. Similar patterns are observed in ostracod records from Dalongchi in the central Tianshan Mountains (Mao et al., 2023) and diatom records from Bosten Lake in the southeastern Tianshan Mountain (Figure 8c; Fontana et al., 2019). These records also suggest that reduced precipitation led to lake level decreases and meso-eutrophic environment during the MWP and Current Warm Period (CWP), with sharp lake level increases and oligotrophic environment during the LIA when precipitation levels escalated. Consequently, we contend that a consistent hydroclimate pattern on a centennial timescale has been evident in the mid-latitude arid central Asia, primarily influenced by the prevailing westerly circulation.

4.3 Possible Forcing Mechanisms on Hydroclimatic Variations in Aibi Lake, Arid Central Asia

Modern climate change in central Asia is mainly driven by the interactions between the mid-latitude westerlies, the Siberian Anticyclone, and the Asian Summer Monsoon (Chen S Q et al., 2025; Chen F H et al., 2011; Aizen et al., 2001). The mid-latitude westerlies transport water vapor from distant regions, such as the North Atlantic, Mediterranean, Black Sea, and Caspian, to the arid zones of central Asia year-round (Yan et al., 2019; Lei et

al., 2014; Aizen et al., 2001). In contrast, the Siberian High, primarily brings cool, dry air, exerting minimal influence on precipitation in the region (Aizen et al., 2001).

The North Atlantic oscillation (NAO) is one of the key teleconnection patterns in the northern hemisphere's mid and high latitudes (Hurrell, 1995), influencing central Asia's hydroclimatic conditions by affecting the strength and position of westerly winds (Thompson and Wallace, 2001; Wanner et al., 2001). Precipitation data from 145 stations across central Asia show an inverse relationship with the NAO, with increased precipitation during the negative phase, when the mid-latitude westerlies shift southward (Aizen et al., 2001). Additionally, $\delta^{18}\text{O}$ records from ice cores in the Altai and Tianshan mountains highlight the significant role of mid-latitude westerlies in shaping regional precipitation patterns (Aizen et al., 2006). This is further corroborated by modern air mass trajectory data from Aibi Lake, analyzed using the NOAA Hysplit model (Figure 1).

To explore potential forcing mechanisms, we conducted our reconstructed records of precipitation and lake salinity changes in Aibi Lake with NAO indices from Greenland Lake (Olsen et al., 2012). The results indicate that the precipitation and lake salinity in Aibi Lake exhibited several prominent and abrupt fluctuations over the past 3 200 years, aligning closely with shifts in NAO phases (Figure 9). Particularly, the period between 2 900–1 990, 1 570–1 140, and 590–120 cal yr BP, during which precipitation in the Aibi Lake Basin in the arid central Asia increased, lake salinity remained relatively low, and the NAO index registered negative values. This suggests that NAO may influence the fluctuations of lake salinity or precipitation in the Aibi Lake Basin over centennial to millennial timescales. The findings highlight the NAO as a key driver of the midlatitude westerlies, which affect their intensity and positioning, thereby impacting hydroclimatic changes in arid central Asia (Lan et al., 2020; Wanner et al., 2001). Furthermore, Chen F H et al. (2019) also elucidated that the climatic instability during the LIA may also be attributed to the variability of the NAO induced by changes in the westerlies.

We conducted further comparisons between the precipitation and salinity records from Aibi Lake and reconstructions of total solar irradiance (TSI) over the past millennium (Steinhilber et al., 2012), along with atmospheric detrended $\Delta^{14}\text{C}$ (Reimer et al., 2020). Our analysis reveals that higher precipitation and lower lake salinity in the Aibi Lake Basin during 2 900–1 990, 1 570–1 140, and 590–120 coincide with periods of low solar irradiance. In addition, we also observed a positive correlation between solar irradiance and lake salinity, along with a negative correlation with precipitation, consistent with previous studies in arid central Asia (Liu et al., 2019; Zhao et al., 2009). During periods of minimum solar irradiance, the southward migration of mid-latitude westerlies, coupled with increased precipitation in arid central Asia, coincides with elevated water levels in lakes such as Sayram Lake in Northwest China (Lan et al., 2019).

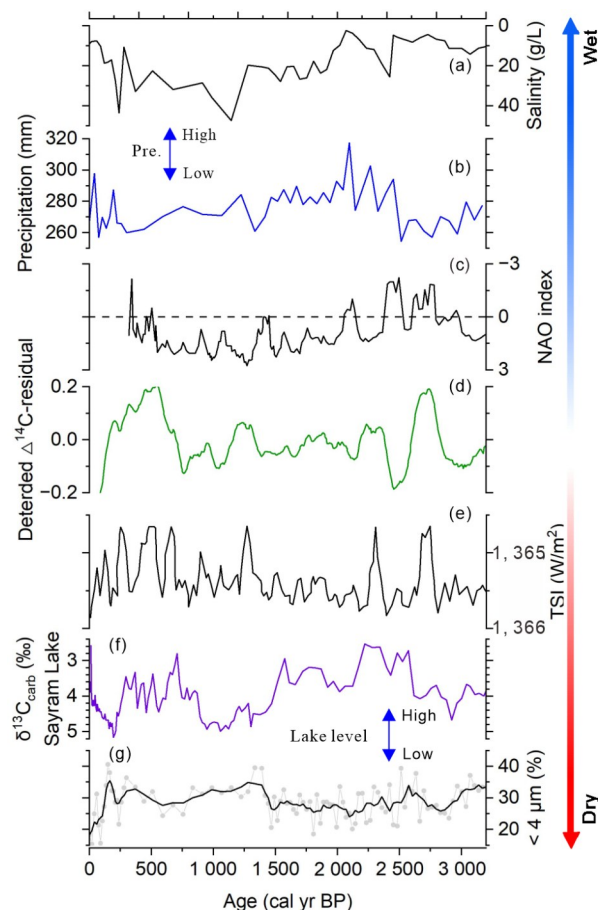


Figure 9. Forcing mechanisms. (a) The result of salinity (g/L); (b) precipitation (mm) at Aibi Lake (this study). (c), NAO index reconstructed from Greenland lake sediments (Olsen et al., 2012). (d) indicators of solar irradiance from atmospheric detrended $\Delta^{14}\text{C}$ -residual (Reimer et al., 2020; Stuiver et al., 1998). (e) Solar activity (Steinhilber et al., 2009). (f) $\delta^{13}\text{C}_{\text{carb}}$ record from Sayram Lake (Lan et al., 2020). (g) $< 4 \mu\text{m}$ (%) from AB20E2 core (Pan et al., 2024).

The salinity records of Lake Gahai in the northeastern Tibetan Plateau suggest that wet conditions corresponded with periods of minimum TSI (He et al., 2013). Meanwhile, the Dalongchi Lakes in the southern Tianshan Mountains also displayed pronounced characteristics of elevated water levels, as evidenced by ostracod compositions (Mao et al., 2023). These findings, along with our Aibi Lake records, suggest that solar irradiance exerts significant external forces on hydroclimate changes in arid central Asia over millennial timescales.

To investigate the relationship between internal and external factors and the regional hydroclimate in the Aibi Lake Basin, we performed spectral and wavelet transform analyses on salinity and precipitation data. The results revealed notable peaks in the power spectrum occurring at approximately ~200 years in the reconstructed salinity records. The precipitation, effective humidity, and lake level records exhibit a ~200-year cycle at the 95% confidence level over the past 3 200 years, indicating a consistent pattern of climate change (Pan et al., 2024) (Figure 7). This ~200-year cycle corresponds closely to

the negative/positive phases of approximately 200 years of the NAO evident in the extant North Atlantic paleoclimate record (Olsen et al., 2012), supporting a negative NAO phase can enhance the intensity of the westerlies, thereby transporting more water vapor to arid central Asia (Cui et al. 2021), leading to an increase in precipitation inside arid central Asia. Furthermore, in arid central Asia, some lake salinity is often influenced by intense evaporation driven by local high temperatures (Wu et al., 2020; Wang et al., 2014). As depicted in Figure 9, Aibi Lake salinity is strongly correlated with total solar irradiance (TSI), which indicates that variations in solar activity may influence lake salinity by increasing temperatures and evaporation rates. This viewpoint has been confirmed by many studies (Feng et al., 2022; Cui et al., 2021; Lan et al., 2020). Steinhilber et al. (2012), drawing upon ice core and tree ring data, elucidated de Vries cycle (~200 years) variations in the influence of solar activity on climate dynamics across decadal to centennial scales.

Following the analysis above, we suggest that salinity and precipitation changes in the Aibi Lake Basin are primarily influenced by the NAO phase change. During the negative NAO phase, increased precipitation in the Aibi Lake Basin corresponds with decreased solar irradiance. Furthermore, ~200-year cycle variability also supports NAO and TSI driving changes in precipitation and salinity in the Aibi Lake Basin.

5 CONCLUSION

Diatoms and pollen were used to quantitatively reconstruct the salinity and precipitation within the Aibi Lake Basin, central Asia spanning the Late Holocene, and the forcing mechanisms of lake environment response to precipitation changes from centennial to millennial timescales are clarified. The results show that the Aibi Lake salinity varied between 2–47 g/L during the Late Holocene, reflecting a generally brackish environment in Aibi Lake. Precipitation varied between 250 and 320 mm in the basin, showing a generally semi-arid climate with prevailing desert steppe vegetation. Aibi Lake experienced three distinct periods of low salinity and high precipitation: 2 900–1 990, 1 570–1 140, and 590–120 cal yr BP. Additionally, salinity and precipitation reconstructions revealed a notable ~200 cyclic pattern, which aligns with the phase shifts of NAO and TSI. These findings suggest that salinity and precipitation dynamics in the Aibi Lake Basin were primarily influenced by fluctuations in the mid-latitude NAO phase, driven by solar irradiance changes.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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