Response mechanism of sediment organic matter of plateau lakes in cold and arid regions to climate change: a case study of Hulun Lake, China

Wenwen Wang · Li Zhao · Wei Li · Junyi Chen · Shuhang Wang

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Abstract
Lake organic matter is one of the important forms of terrestrial carbon, and its sedimentary evolution is affected by many factors such as climate and sources. However, few studies have been conducted on the feedback mechanism of the sedimentary evolution of organic matter to climate change in cold and arid lakes. Historical variations and compositions of sources of the sediment organic matter (SOM) of Hulun Lake, a typical lake in the cold and arid region of China, were studied by multiple methods. The interactions and feedback mechanisms between the sedimentary evolution of SOM and climate change, and compositions of SOM source change, were also discussed. Overall, the characteristic indexes of the SOM, including total organic carbon (TOC), carbon stable isotope ($\delta^{13}C$), carbon to nitrogen ratio (C/N), and fluorescence intensity (FI) of the protein-like component in water extractable organic matter (WEOM), showed obvious and uniform characteristics of periodical changes. The indexes were relatively stable before 1920, and fluctuated from 1920 to 1979. Since the 1980s, values of TOC, $\delta^{13}C$, and FI of the protein-like component in WEOM has increased, while C/N decreased. The absolute dominant contribution of terrestrial source to the SOM had changed, and the relative average contribution rate of autochthonous source increased from 17.6% before 1920 to 36.9% after 2000. The increase of temperature, strong evaporation concentration effect, and change of compositions of SOM sources are the important driving factors of the sedimentary evolution of organic matter in Hulun Lake.

Keywords Plateau lake · Hulun Lake · Sediment organic matter · Sedimentary evolution · Climate change · Response mechanism

Introduction
Organic matter exists widely in various aquatic environments and is one of the important forms of terrestrial carbon (Imbeau et al. 2021; Zhang et al. 2021). Lake sediments are important storage sites of organic matter (Lin et al. 2021; Sobek et al. 2014). After entering the water body, organic matters from various sources settle to the bottom of the lake and become part of the sediments through a series of complex physical, chemical, and biological effects. The information, including climatic conditions, primary productivity, nutrient status of the water body, and pollution sources and so on, carried by the organic matter is well recorded in the sediments with the deposition of organic matter (Lin et al. 2021; Zhao et al. 2021). The information recorded by the sediments is high-resolution and continuous. Many research results indicate that the vertical historical evolution of sediment organic matter (SOM) indicators, such as total organic carbon (TOC), carbon to nitrogen ratio (C/N), and carbon stable isotope ($\delta^{13}C$), can reflect the historical changes of the climate, aquatic environment, and human activities in the lake basin. Research in Lugu Lake showed that the C/N and $\delta^{13}C$ values had a gradual and slight decrease trend and suggested an increasing contribution of phytoplankton to SOM (Lin et al. 2021). Sun et al. presented the $\delta^{13}C$ and $\delta^{15}N$...
records from Muge Co Lake in the southeastern Qinghai-Tibetan Plateau, and found that the trend of the greenhouse gas efflux index (GGEI) based on the δ13C and δ15N records could reflect well the records of climate change, with higher GGEI values indicating a warmer and wetter climate, and vice versa (Sun et al. 2016). The migration, transformation, and deposition of organic matter among different mediums in lake aquatic environment are very complex and are affected by many factors, including human activities and their intensity, the lake aquatic environment, hydrological conditions, the climate environment and change of the basin, and pollution sources (Jiang et al. 2020; Razum et al. 2021). The change of climate factors (i.e., temperature, precipitation, and evaporation) in lake basin will change the primary productivity, source, and amount of organic matter input in the lake aquatic environment, consequently affecting the burial characteristics of organic carbon (Chen et al. 2012; Lipczynska-Kochany 2018; Liu et al. 2021). The aquatic environments of lakes in cold and arid regions are sensitive to human disturbance and climate change (Jensen et al. 2020; Lozano-Garcia et al. 2013; Qiang et al. 2005, Yi and Zhang 2015). The lakes in cold and arid regions are hence ideal areas for studying the occurrence characteristics, migration, transformation, sedimentary evolution, and influencing factors of lake organic matter. In recent years, the aquatic ecological environment of lakes in cold and arid regions has changed to a certain extent due to global climate change. Driven by climate change, summer blooms occur frequently in Hulun Lake, Qinghai Lake, Xingkai Lake, and other lakes in cold Northern China, and some lakes (such as Hulun Lake) have been erupting by algal blooms regularly in summer. Climate change leads to the change of the terrestrial and aquatic ecological environments of lakes, and further affects the compositions of sources, occurrence characteristics, and sedimentary evolution of organic matter (Zhang et al. 2018b; Zhao et al. 2021). Therefore, studying the sedimentary evolution and source variation characteristics of organic matter in cold and arid lakes is of great significance for understanding the migration and transformation of lake carbon and the historical changes of the basin climate and the aquatic environment.

Hulun Lake is the largest lake in Northern China and a typical lake in cold and arid regions, playing an irreproachable role in maintaining the ecological balance of Hulun Buir Grassland and even ecological security in Northern China (Bao et al. 2021; Li et al. 2019, Liu and Yue 2017). The climate in the Hulun Lake basin has been gradually warming and drying in recent years (Bao et al. 2021; Chen et al. 2012). The source and occurrence characteristics of SOM are bound to change with the climate. However, the response mechanism of the occurrence characteristics and sedimentary evolution of SOM to climate change is still not very clear. In view of this, this study performed the following:

1. determined the depth-chronology model of the sediment cores of Hulun Lake by adopting the lead (210Pb) and cesium (137Cs) isotopic dating technology;
2. analyzed the sedimentary and evolution characteristics of the characteristic indexes of SOM, including the TOC, C/N, δ13C, and protein-like component in water extractable organic matter (WEOE) in the sediment cores;
3. analyzed the historical variation of the compositions of SOM sources; and
4. determined the influence and feedback mechanism of the sedimentary evolution of the organic matter in Hulun Lake due to changes in climate and compositions of sources. This study will help in the comprehensive understanding of the sedimentary evolution characteristics of organic matter in Hulun Lake and their indicative effect on the environmental changes of the basin and the ecological environment protection of Hulun Lake.

Materials and methods

Study area

The Hulun Lake (48.55°–49.33°N, 116.97°–117.81°E) basin, which has an area of 2.92×105 km², is located in China and Mongolia. The length, width, circumference, and average water depth of Hulun Lake are 93 km, 32 km, 447 km, and 5.7 m, respectively (Li et al. 2019). The highest, lowest, and average temperatures of the Hulun Lake basin are 20.8, –23.3, and –0.2 °C, respectively, with an ice-forming period of 6 months (Ao et al. 2020). Evaporation is large and precipitation is small in the basin, and precipitation is mainly concentrated in June to September, accounting for 80–86% of the annual average precipitation. Grassland is the main land use type, and the natural grassland area is 20,132.69 km², accounting for 81% of the total basin area (Wang et al. 2021a).

Sample collection and treatment

Two sediment cores (HLH 16 and HLH 26) with a length of 65 cm were collected in July 2019 using a Beeker cylindrical sampler (NL, Φ = 12 cm, Eijkelkamp, 04.23; SA, the Netherlands). The sampling sites are shown in Fig. 1. The core samples were stratified at the site at an equal spacing of 1 cm. The stratified sediment samples were stored in clean ziplocked bags in an incubator at 4 °C and immediately transported back to the laboratory.

Experimental methods

The ratio of TOC to TON

The inorganic carbon in the sediment samples were removed by pretreatment with 3 mol/L HCl (AR, SCR, SINOPHARM,
China, and inorganic nitrogen was removed by pretreatment with 2 mol/L KCl (AR, SCR, SINOPHARM, China) and 0.5 mol/L HCl (AR, SCR, SINOPHARM, China) (Zhang et al. 2018b). The pretreated samples were then freeze-dried and sieved using a 100-mesh (0.15 mm) nylon sieve. The TOC and total organic nitrogen (TON) were analyzed using the Elementar (Elementar vario MACRO cube, Elementar Analysensysteme GmbH, Germany). C/N refers to the TOC to TON ratio.

**Extraction and spectrum scanning of WEOM**

A sediment sample (1 g) and 50 mL of ultrapure water was added in a 100-mL centrifuge tube. The tube was oscillated in a water bath at 25 °C for 1 h and then centrifuged. The supernatant was filtered with a 0.45-μm membrane to obtain the WEOM extract. The full wavelength (200–700 nm) and three-dimensional fluorescence excitation emission matrix (EEM) fluorescence spectrum of the WEOM were respectively scanned using an ultraviolet–visible spectrophotometer (D5000, Hach, USA) and a fluorescence analyzer (Hitachi, F7000, Japan) respectively according to the method of Wang et al. (2018). Ultrapure water was scanned synchronously for the baseline correction. The EEM data were calibrated and the fluorescence components were determined through the PARAFAC technology according to the methods of Wang et al. (2018). Fluorescence intensity (FI) of the fluorescence component was used to represent the relative concentration in the WEOM.

**δ¹³C**

The sediment sample pretreated with 3 mol/L HCl (AR, SCR, SINOPHARM, China) and 2–3 g of CuO wire were placed into a quartz tube (preheated to 850 °C for 2 h). The tube was then welded, sealed in a high-vacuum system, and burned (850 °C, 5 h), and then the CO₂ was purified in a vacuum system. The δ¹³C was analyzed using an isotope mass spectrometer (MAT252, Finnigan Mat, Germany). The Pee Dee Belemnite of Cretaceous in South Carolina, USA, was used as the standard substance, with an analytical error of 0.2‰. The δ¹³C values were calculated using Eq. (1):

\[
\delta^{13}C = \left( \frac{R_t}{R_s} - 1 \right) \times 1000\text{‰},
\]

where \( R_t \) is the \(^{13}\text{C} / ^{12}\text{C} \) natural abundance ratio of the sample, and \( R_s \) is that of the standard substance.

**Relative contribution of SOM sources**

The relative contribution rates of the terrestrial (\( P_T \)) and autochthonous (\( P_A \)) sources for SOM on the basis of C/N were calculated using a binary model (Qian et al. 1997). \( P_T \) and \( P_A \) based on \( \delta^{13}C \) were calculated using Eqs. (2) and (3) (Piotr et al. 2018):

\[
\delta^{13}C = \delta^{13}C_1 \times P_1 + \delta^{13}C_A \times P_A,
\]

where

\[
\delta^{13}C_1 = \left( \frac{R_t}{R_s} - 1 \right) \times 1000\text{‰},
\]

\[
\delta^{13}C_A = \delta^{13}C_{13} \times P_{13} + \delta^{13}C_{12} \times P_{12},
\]

and

\[
\delta^{13}C_{13} = \left( \frac{R_{13}}{R_{12}} - 1 \right) \times 1000\text{‰},
\]

\[
\delta^{13}C_{12} = \left( \frac{R_{12}}{R_{13}} - 1 \right) \times 1000\text{‰}.
\]
δ₁³Cₜ is the δ₁³C value of the terrestrial organic matters in the sample, and δ₁³Cₐ is that of the autochthonous organic matters in the sample.

**Chronology calculation of sediments**

Radionuclide ²¹⁰Pb and ¹³⁷Cs have been widely used in the chronology determination of sediments in water bodies (Abbasi 2019; Kumar et al. 2016; Nie et al. 2016). In practice, the two dating methods are usually combined and verify each other to improve the accuracy and reliability of dating results. A composite model based on the combination of ²¹⁰Pb and ¹³⁷Cs was used to calculate the sediment chronology of Hulun Lake. The sediment age (Tₛ), sedimentation rate (Rₛ), and organic carbon burial rate (OCBR) in the sediments were calculated according to the method of Zhang et al. (2018a).

**Statistical analysis**

All the indexes were analyzed in parallel three times, and the test results were expressed as the average value of the three parallel analyses with the error range of the three analysis results < 5%. The Pearson correlation coefficient method was used for correlation analysis in the SPSS 17.0 software. Excel 2010, Origin 8.0, SPSS 17.0, ArcGIS 10.2, Matlab 7.0, and Surfer 14.0 were used for the statistical inspection, analysis, and plotting of experimental data.

**Results**

**Depth-chronology model of the sediment cores of Lake Hulun**

The excess ²¹⁰Pb (²¹⁰Pbₑₓ) in the HLH16 and HLH26 cores in Hulun Lake ranged from 8.6 to 520.9 Bq/kg and 11.0 to 334.2 Bq/kg, with the mean values of 165.6 and 120.5 Bq/kg, respectively. The ²¹⁰Pbₑₓ values in the two cores all showed serrated distributions in the vertical direction. The distribution decreased gradually and then stabilized with the increase of the sediment depth (Fig. 2).

The ¹³⁷Cs values in the HLH16 and HLH26 cores were in 0–61.7 Bq/kg and 0–48.9 Bq/kg ranges, with mean values of 13.8 and 13.7 Bq/kg, respectively. The vertical distributions of ¹³⁷Cs in the sediment cores presented typical single-peak distribution characteristics (Fig. 3), which are similar to the results of previous research on Hulun Lake (Zhang et al. 2018a) and other lakes (Lan et al. 2020; Pempkowiak et al. 2006). According to the sedimentary characteristics of ¹³⁷Cs in the northern hemisphere, the maximum peak of the ¹³⁷Cs distribution curve corresponds to the peak of the nuclear explosion test in 1963, which can be used as an important time scale for the sediment dating of Hulun Lake.

The corresponding relationship between the sediment core depth and the chronological sequence of Hulun Lake is shown in Fig. 4. The average sedimentation rates of the HLH16 and HLH26 cores since 1950 were 0.44 and 0.61 cm/a, respectively. The sedimentation rate of the
HLH26 core in the middle of the lake was higher than that of the HLH16 core. This result may be attributed to the relatively stable hydrodynamic conditions in the middle of the lake, which is more conducive to the formation of sediment. The sedimentation rate of the HLH26 core was similar to the study results of Gao (2017) (0.72 cm/a) and Zhang et al. (2018a) (0.58 cm/a), indicating that the dating results are relatively accurate.

**Sedimentary evolution characteristics of organic matter in Hulun Lake**

**TOC**

The TOC contents in the HLH16 and HLH26 cores were in the 27.9–43.1 and 30.4–49.0 g/kg ranges, with mean values of 32.6 and 36.7 g/kg, respectively. The average OCBR values in the HLH16 and HLH26 cores were 1.60 and 1.83 g/(m²·a), respectively. The TOC contents in the sediment cores in Hulun Lake have shown a fluctuant and increasing trend in recent years, and the annual TOC variation can be roughly divided into four stages (Fig. 5).

Before 1920, the TOC contents in the sediment cores were relatively stable and the OCBR values were low, with mean values of 0.85 and 0.37 g/(m²·a) in the HLH16 and HLH26 cores, respectively. Years 1920 to 1979 can be considered the transition period of organic matter sedimentary evolution in Hulun Lake. The TOC contents in the HLH16 and HLH26 cores varied within 27.9–37.6 and 30.4–41.4 g/kg, and the average OCBR values were 2.37 and 2.77, respectively. Since 1980, the TOC content in the sediment cores has shown an obviously increasing trend. From 1980 to 1999, the averages of TOC contents in HLH16 and HLH26 were 32.8 and 37.8 g/kg, with the OCBR averages of 1.59 and 2.68 g/(m²·a), respectively. Since 2000, the TOC contents have increased further and remained at a high level in recent years, the average values increased to 36.5 and 41.6 g/kg for HLH16 and HLH26, respectively. The OCBR values increased to 1.74 and 3.30 g/(m²·a), respectively.

The variation trend of the TOC contents in the sediment cores in Hulun Lake over the years indicates that the TOC and the OCBR have an overall increasing trend. The TOC increased significantly after 1980, especially since 2000, and the OCBR reached its maximum value, indicating that the climate, water, and hydrological conditions of Hulun Lake may have changed significantly during this period.

**C/N**

The C/N values in the HLH16 and HLH26 cores in Hulun Lake fluctuated within 11.9–19.7 and 8.6–16.1, with mean values of 15.6 and 12.7, respectively. The C/N in the sediment cores in Hulun Lake has shown a fluctuant and decreasing trend in recent years (Fig. 6).

Similar to the variation characteristics of the TOC content over the years, the variation of C/N could be also roughly divided into four stages. Before 1920, the C/N in the sediment cores was relatively stable, and the mean C/N values of HLH16 and HLH26 were 16.7 and 13.6, respectively. From 1920 to 1979, the C/N values in the sediment cores fluctuated greatly, and the C/N values of the HLH16 and HLH26 cores varied from 11.9 to 19.7 and 11.8 to 16.1, with mean values of 15.6 and 13.6, respectively. Since 1980, C/N has shown an obvious decreasing trend. In 1980–1999, the
mean C/N values of the HLH16 and HLH26 cores were 15.6 and 12.4, respectively. From 2000 to 2019, the C/N value decreased further, and the mean C/N values of the HLH16 and HLH26 cores were 13.8 and 10.2, respectively, reaching the lowest average values in recent years.

\[ \delta^{13}C \]

The \( \delta^{13}C \) in the sediment cores of Hulun Lake has shown an overall increasing trend in recent years, and experienced four stages, namely, relative stability, fluctuation, gradual increase, and rapid increase successively (Fig. 7). Before 1920, \( \delta^{13}C \) was relatively stable, and the mean values for HLH16 and HLH26 cores were \(-27.40\%e\) and \(-27.20\%e\), respectively. In 1920–1979, the mean \( \delta^{13}C \) values for HLH16 and HLH26 cores were \(-27.46\%e\) and \(-27.23\%e\), respectively. From 1980 to 1999, \( \delta^{13}C \) showed an obvious and stable increasing trend, and the mean values for the HLH16 and HLH26 cores reached \(-27.39\%e\) and \(-26.99\%e\), respectively. From 2000 to 2019, the average \( \delta^{13}C \) values of HLH16 and HLH26 were \(-26.62\%e\) and \(-26.34\%e\), respectively, reaching the highest level in recent years.

The isotopic signal of organic matter in sediments may be affected by the preferential degradation of protein-like organic matter after being buried in sediments. In general, the \( \delta^{13}C \) values in sediment cores should show a decreasing trend from the bottom to the top if they are influenced by the early degradation of organic matter. Therefore, it can be concluded that the \( \delta^{13}C \) in the sediment cores of Hulun Lake was little affected by the early degradation and diagenesis, and can effectively indicate the changes of source and environment.

**Protein-like component in WEOM**

The SOM components mainly include WEOM, humic acid (HA), fulvic acid (FA), and humin (HM) (Zhang et al. 2017). WEOM is the most easily degraded by microorganisms and has the highest bioactivity among these components (Hur et al. 2014). The WEOM in the sediment cores of Hulun Lake contained four fluorescence components, including three humic-like components and one protein-like component. The protein-like components reflect the tryptophan components generated by microbial and phytoplankton degradation and mainly come from autochthonous sources (Bai et al. 2017; Chari et al. 2013, Rochelle-Newall and Fisher 2002). Therefore, the sedimentary evolution characteristics of protein-like components in the WEOM of sediment cores can reflect the historical changes of the source of organic matter and the aquatic ecological environment in the lake.

The FI values of the protein-like components in WEOM in the HLH16 and HLH26 cores varied in the ranges of 0.35–1.05 and 0.39–1.06 R.U., respectively, and have shown an overall increasing trend in recent years (Fig. 8). Before
1920, the FI values of the protein-like components in the HLH16 and HLH26 cores were basically stable, with mean values of 0.39 and 0.41 R.U., respectively. In 1920–1999, the FI values of the protein-like components increased insignificantly and the mean values were 0.55 and 0.48 R.U., respectively. Since 2000, the FI values of the protein-like components in the HLH16 and HLH26 cores have shown an obviously increasing trend, with mean values of 0.97 and 0.86 R.U., respectively, which are nearly one time higher than those of before 1920. The protein-like components in the WEOM mainly came from autochthonous sources, and their FI values changed significantly around 2000, indicating that the compositions of SOM sources in Hulun Lake may have changed greatly. Therefore, the historical change of the compositions of SOM sources in Hulun Lake must be analyzed further and verified.

**Historical variation of the compositions of SOM sources in Hulun Lake**

The main components of terrestrial plants are cellulose and lignin, so terrestrial plants have a high C/N value. The main component of aquatic phytoplankton is protein, and the C/N value of aquatic plants is lower than that of terrestrial plants (Meyers 1994). The C/N value has been widely used to determine the organic matter sources in lake sediments (Bouton et al. 2020; Carrizo et al. 2019; Pu et al. 2020). The results calculated by the binary model based on C/N indicated that the $P_T$ and $P_A$ varied within 70.5–98.2% and 1.8–29.5% for the HLH16 core, and within 43.3–89.6% and 10.4–56.7% for the HLH26 core, respectively. $\delta^{13}C$ can also be used to analyze the sources of SOM. The $\delta^{13}C$ values of the sediments were near those of the C3 plants, aquatic plants, and terrestrial materials of Hulun Lake (Zhang et al. 2018b), indicating that the SOM in Hulun Lake was influenced by both terrestrial and autochthonous sources. The $P_T$ and $P_A$ values calculated by $\delta^{13}C$ were within 58.5–83.4% and 16.6–41.5% for the HLH16 core, and within 53.9–81.5% and 18.5–46.1% for the HLH26 core, respectively.

The SOM in Hulun Lake generated from both terrestrial and autochthonous sources, but mainly came from terrestrial source. However, the relative contribution of the terrestrial source has shown a decreasing trend in recent years. Similar to the historical variation characteristics of other organic matter indicators, the historical changes of organic matter sources could also be roughly divided into four stages (Fig. 9). Before 1920, the compositions of SOM sources in Hulun Lake were relatively stable, and the terrestrial source was dominant. The mean values of $P_T$ and $P_A$ were 82.4% and 17.6%, respectively. In 1920–1979, $P_T$ and $P_A$ fluctuated with mean values of 80.7% and 19.3%, respectively. In 1980–1999, $P_T$ showed an obviously decreasing trend, with a mean value of 76.3%. In 2000–2019, $P_T$ decreased further and has remained in a relatively low level in recent years, and the mean value was 63.1%. However, the mean value of $P_A$ increased to 36.9%, which is 19.2% more than that before 1920.

**Discussion**

When organic matter enters the lake water from sources and is deposited at the bottom of the lake, it is affected by human activities, the climatic conditions of the basin, the hydrological conditions of the lake, and other factors. The sedimentary evolution of lake organic matter is also affected by diagenesis (Leonova et al. 2019; Melenevskii et al. 2015). Compared with marine diagenesis, the early diagenesis in lacustrine environment is relatively weak for the lower sulfate content. The SOM in lake was generated from terrestrial (such as terrestrial plants) and autochthonous inputs (such as algae). Terrestrial higher plants are more abundant than algae in aromatic compounds, such as lignin, tannin, resin, and suberin, which are very stable and have a strong resistance to bacterial decomposition and are easy to be preserved in sediments (Harfmann et al. 2019). Previous results also showed that the dominant component of SOM in Hulun Lake was HM, which is difficult to be degraded, and the average proportion of HM to TOC was as high as 75.1% (Wang et al. 2021b). The influence of early diagenesis on the SOM...
of Hulun Lake may be relatively small and will not be discussed this time. Given its special geographical location and climate conditions, the aquatic environment of Hulun Lake is sensitive to climate change. Some results showed no significant correlation between the burial rate of organic carbon and human factors, including population, cultivated area, livestock, and fish (Zhang et al. 2018a). Therefore, this study focused on the impacts of climate factors on the sedimentary evolution of organic matter in Hulun Lake.

The annual mean changes of temperature, precipitation, and evaporation in Hulun Lake Basin from 1951 to 2018 are shown in Fig. 10. The average annual temperature fluctuated between −2.9 and 2.7 °C. Overall, the temperature in the Hulun Lake Basin showed an increasing trend (Fig. 10a). The annual average precipitation and evaporation of the basin were within 137.9–590.1 mm and 612.3–1256.3 mm, with mean values of 285.9 and 906.6 mm, respectively. The precipitation in the basin showed a gradually decreasing trend (Fig. 10b), while the evaporation showed an increasing
trend (Fig. 10c). The climate in the Hulun Lake basin has been warming and drying in recent years.

The correlation relationships between climate factors (temperature, precipitation, evaporation) and SOM-related indexes (TOC, C/N, δ13C, FI of protein-like components of WEOM, PA) are shown in Table 1. The correlation between SOM-related indexes and temperature is the best, showing significant correlation (P < 0.01), followed by evaporation. The relatively poor correlation between precipitation and the organic matter related indexes may be due to the fact that the evaporation in the Hulun Lake basin is much greater than the precipitation, and the strong evaporation effect is one of the important reasons for the reduction of water volume and level in Hulun Lake in recent years (Li et al. 2019, Liu and Yue 2017). Therefore, the effect of evaporation on the occurrence and sedimentary evolution of organic matter in Hulun Lake may be more obvious than that of precipitation.

Temperature can affect the content, composition, migration, and transformation of organic matter at the sediment–water interface, which is of great significance to the sedimentary evolution of organic matter (Dadi et al. 2016, Luff and Moll 2004). Hulun Lake is located in the Hulun Buir steppe, and the vast steppe provides many terrestrial organic matters for Hulun Lake. Meanwhile, due to the low temperature and long ice period in the basin, the growth of aquatic algae is greatly restricted, and the aquatic biomass of the lake is small, resulting in the small contribution of the autochthonous source to the SOM in Hulun Lake. Hence, terrestrial source has an absolute advantage over autochthonous source in the contribution to SOM in Hulun Lake. However, since the 1980s, especially since 2000, the basin has been exhibiting an obvious warming trend, the eutrophication degree in Hulun Lake has increased, the lake bloom has regularly broken out in summer, and the aquatic biomass has increased. Studies also show that the land around Hulun Lake has seen serious desertification, and the desertification area exceeds 100 km² due to the significant warming and drying of climate (Zhao et al. 2008). In addition, the warm and dry climate has also led to the decrease in grassland vegetation height and grassland degradation, resulting in the relative decrease of organic matter input from terrestrial sources. Therefore, the compositions of SOM sources changed significantly as PT gradually decreased and PA gradually increased.

The change in compositions of sources can also cause the change in SOM composition. Organic matters from terrestrial sources mainly consist of hard-degraded humic-like substances, and autochthonous organic matters mainly consist of protein-like components (Hu et al. 2019; Lu et al. 2019). WEOM is a highly active component of SOM and is

![Fig. 10](image)

**Table 1** Correlation relationships between climate factors and SOM related indexes of Hulun Lake

| SOM-related indexes | Temperature | Precipitation | Evaporation |
|---------------------|-------------|---------------|-------------|
| TOC                 | 0.420**     | −0.096        | 0.357*      |
| C/N                 | −0.694**    | 0.213         | −0.528**    |
| δ13C                | 0.754**     | −0.331*       | 0.595**     |
| FI of protein-like components of WEOM | 0.431** | −0.261 | 0.597** |
| PA                  | 0.707**     | −0.269        | 0.586**     |

* significantly correlated at 0.05 level, ** significantly correlated at 0.01 level
closely related to microbial activities. Protein-like components mainly come from the metabolic activities or degradation of plankton and microorganisms (Chen et al. 2017; Li et al. 2020). Hence, the FI values of the protein-like component in the WEOM of the SOM in Hulun Lake showed an increasing trend with the increase of $P_A$.

The carbon isotope composition of SOM is also affected by temperature, and the change in carbon isotope composition can reflect the level of the lake’s primary productivity. The $\delta^{13}C$ values of terrestrial plants are more negative than that of planktonic algae. The SOM in Hulun Lake mainly came from terrestrial sources during the lower temperature period, so the $\delta^{13}C$ was low, while the $\delta^{13}C$ increased with $P_A$ and the water primary productivity increased gradually. The temperature and evaporation in the basin have increased, the precipitation and lake inflow have decreased, and the surface area of Hulun Lake has shrunk rapidly since 2000. The increase in temperature and evaporation leads to the decrease in CO$_2$ concentration and the increase of the Ca$^{2+}$, CO$_3^{2-}$, and HCO$_3^-$ concentrations in water. The $\delta^{13}C$ value is inversely proportional to the water CO$_2$ supply during the synthesis of organic matter by phytoplankton, indicating that the lower the $\delta^{13}C$ value is, the higher the dissolved CO$_2$ concentration is (Wang et al. 2003). Hence, the CO$_2$ concentration in the lake decreased with the increase in temperature, and the algae preferentially used HCO$_3^-$ to increase the $\delta^{13}C$ value. The evaporation concentration also resulted in enhanced isotopic fractionation in Hulun Lake, and $\delta^{13}C$ was more easily enriched in the water, maintaining the $\delta^{13}C$ values in the sediments remaining at a high level.

The sedimentary evolution of TOC in Hulun Lake had a good response and indicator effect on the changes in temperature, evaporation, and lake surface area. From 1951 to 1979, the climate of the basin was dry and cold, which was not conducive to the vegetation growth of the basin, and the inputs of terrestrial and autochthonous organic matters were small. Moreover, the water surface area of Hulun Lake was relatively large, and the evaporation and concentration effects were relatively weak, so the TOC content that accumulated in the sediments of this period was small. From 1980 to 1999, evaporation and water surface area fluctuated with an unobvious trend, but the TOC content also presented a fluctuating and increasing trend due to the rising air temperature, primary productivity, and organic matter inputs. The TOC contents increased significantly from 2000 to 2008. On the one hand, the increase of the TOC content in this stage was due to the increase of organic matter inputs caused by the temperature increase. On the other hand, the increase of the TOC content from 2000 to 2008 was due to the strong evaporation concentration effect. During this period, the evaporation increased significantly, the water level dropped sharply, and the lake area shrank seriously. Hulun Lake became a closed lake that could only enter and not exit. The strong evaporation effect led to the enrichment and concentration of organic matters in the water body, and the concentration remained at a high level, which was conducive to the settlement and accumulation of organic matters from the overlying water to sediments, resulting in the increase of the TOC contents in the sediments.

From 2009 to 2013, the evaporation of the basin decreased, and the water inflow and water level of Hulun Lake showed a fluctuant increasing trend with the operation of the river diversion project to the lake since 2012. The changes of water level and climate had a combined effect on SOM. On the one hand, the reduction of evaporation and the increase of water volume led to the weakening of the concentration effect of the organic matter in overlying water. On the other hand, the changes of water level could affect the sedimentation and release behaviors of organic matters between water and sediments. The increase of the water level led to the increase of the concentration distance of organic matters from the water body to the sediments and the increase of the decomposition consumption of organic matters. When the lake water level rose, the concentration of organic matter in the overlying water would be diluted by the inflow water, which could promote the release of organic matters in the sediment interstitial water (Gao et al. 2017). Hence, the TOC contents in the sediments showed a decreasing trend in this period. From 2014 to 2018, the water level kept in a relatively stable state, while the temperature and evaporation increased, the climate was warm and dry, the primary productivity increased, and concentration effect was strong, resulting in the increasing trend of the TOC contents in the sediments.

The result of this study is consistent with previous results; that is, temperature increase will lead to the increase in SOM content. However, the temperature increase will also enhance the SOM mineralization effect. Therefore, further studies on the effects of temperature rise on the stability of the SOM of Hulun Lake and other similar lakes located in cold and arid areas should be conducted in the future, and the two-way feedback mechanism between climate change and lake carbonaceous organic matters should be further explored.

**Conclusion**

The sedimentary evolution of the TOC, C/N, and $\delta^{13}C$ in the Hulun Lake sediment cores could be roughly divided into four periods. Before 1920, the indexes were relatively stable. From 1920 to 1979, the indexes fluctuated, and the change trend was not obvious. From 1980 to 1999, the TOC and $\delta^{13}C$ increased, while C/N decreased. From 2000 to 2019, the TOC and $\delta^{13}C$ increased significantly and has remained at high levels in recent years, while C/N continued to decrease and has remained at a low level in recent years. After 2000, the FI of the protein-like component in WEOM increased significantly. The compositions of SOM sources also changed significantly. Although terrestrial input was
still the main source, the contribution rate of the autochthonous source increased gradually and by approximately 20% from 2000 to 2019 compared with that before 1920.

Since 1950, the temperature and evaporation in the Hulun Lake basin have been increasing, precipitation has been decreasing, and climate has been warming and drying. The mean annual temperature and evaporation were significantly correlated with the SOM indexes, and the historical variation trends were relatively consistent. The temperature rise and the evaporation concentration were the important driving factors of the deposition evolution of the organic matters in Hulun Lake. Temperature rise led to the increase of the primary productivity, the autochthonous contribution rate, and the FI of the protein-like component. The strong evaporation concentration effect led to the enrichment and concentration of the organic matters in the overlying water, which led to the increase of the TOC and δ13C in the sediments.

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Author contribution Wenwen Wang collected and analyzed samples and was a major contributor in writing the manuscript. Li Zhao and Junyi Chen collected and analyzed the samples. Wei Li checked the quality of the paper. Shuhang Wang formulated the sampling and experimental schemes. All authors read and approved the final manuscript.

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Data availability The datasets used and/or analyzed in the study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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