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Seasonal Temperature and Precipitation Influenced Holocene Environmental Changes in Qinghai Lake, Northeastern Qinghai-Tibetan Plateau

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Abstract: In the present paper, we reanalyzed the reported paleoenvironmental proxies, in combination with climate-model-simulated summer and winter temperature and precipitation changes, to more comprehensively understand paleoenvironmental changes in the Holocene period in Qinghai Lake. We found that the early Holocene (11-8 ka BP) summer precipitation and surface evaporation was high, but winter precipitation was low, causing widespread aeolian sands in the areas surrounding the lake and the lake water level only a few meters deep. Moreover, the early Holocene climate was not stable; it fluctuated frequently with large amplitudes. The Holocene hydrothermal configuration optimal period persisted from 8 ka to 6 ka BP, and some environmental proxies abruptly changed to indicate warm and wet environments during this period. The Asian summer monsoon weakened since 6 ka BP, while winter precipitation increased simultaneously, and summer temperature and evaporation decreased. These climate changes caused vegetation to transform from forest to grassland and alpine meadow, allowed the lake water level to be maintained at a high level, and caused continuous development of paleosol. Environmental conditions then deteriorated since 1.5 ka BP, summer and winter precipitation over Qinghai Lake declined simultaneously, the lake level dropped, and aeolian activities intensified again.

Key words: Holocene; Qinghai Lake; Qinghai-Tibetan Plateau; Seasonal temperature and precipitation changes

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1 Introduction

The Qinghai-Tibetan Plateau (QTP) is the highest and largest plateau on Earth, and it is sensitive to global climate changes. The QTP is regarded as the "Asian water tower", and its environments and ecosystems are easily damaged, but difficult to recover. Currently, the rivers originating from the QTP satisfy water requirements for over one fifth of the world's population [1-2]. Therefore, climate changes over the QTP have been attracting the attention of many governments and scientists around the world.

There are more than one thousand lakes larger than 1 km^2 spread over the QTP. Lacustrine sediments of these lakes are often used to research lake evolution and Quaternary paleoenvironmental chan-

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ges[3-7]. However, due to the high elevation and harsh environments, lacustrine sediments in QTP lakes contain very low organic matter. Moreover, the carbon reservoir (also called the "old carbon effect") varied spatially and temporally both within one lake and among different lakes, causing the precise and accurate dating of lacustrine sediments to be a major challenge [8-9]. Recently, some researchers dated paleoshoreline sediments from various lakes on QTP by optically-stimulated luminescence dating and uranium-series dating to reconstruct the lake level variation histories of the lakes since the late Quaternary [10-18], and further quantitatively reconstructed the paleo-rainfall amounts during the high lake level periods[19]. These researches are independent of paleoenvironmental information retrieve from lacustrine sediments, and provided additional paleo-hydrological information in QTP. A recent synthesis of existing reports indicates that lakes located at the southern QTP experienced high lake level during the early Holocene, and lake level declined since the middle Holocene, in accordance with the Holocene Indian summer monsoon variations [14,16]. However, lakes on the northern QTP showed diverse variations; some lakes experienced high lake level during early Holocene, whereas others experienced high lake level during the middle and late Holocene[16].

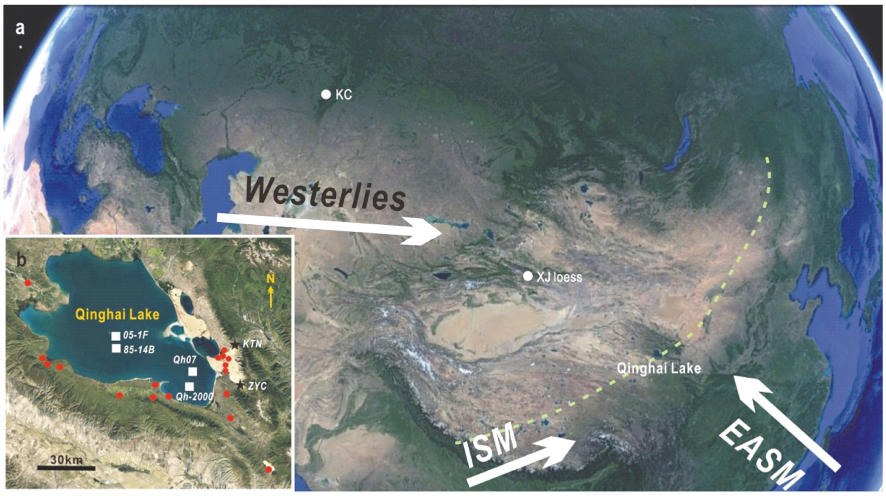

Fig. 1 Geographical location and satellite map of the study area. (a) Locations of Qinghai Lake and other sites mentioned in this study. KC and XJ loess are the approximate locations of the stalagmite oxygen isotope record in Kinderlinskaya Cave (Fig. 4a) and moisture records in Xinjiang (Fig. 4d and 4e), respectively. The Asian summer monsoon (ASM) includes both the Indian summer monsoon (ISM) and the East Asian summer monsoon (EASM). The boundary of the modern summer monsoon (thick green dashed line) was modified from Chen *et al*[20]. (b) Satellite image of Qinghai Lake, where white squares represent drilled cores in the lake, red dots represent the aeolian sections investigated by researchers [21-23], and black stars represent the location of aeolian section of KTN (Ketu North) and ZYC (Zhongyangchang) in Fig. 2i. The map was generated using ESRI ArcGIS v9.1 (www.esri.com/sofware/arcgis), and the satellite image is provided by Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn)

图 1 研究区地理位置(a)和卫星影像图(b)。图(a)中 KC 和 XJ loess 为本文提到的 Kinderlinskaya 石笋和新疆黄土的位置,绿色虚线为现代亚洲夏季风影响区的边界。图(b)中红色点为学者们已报道的风成沉积剖面位置,黑色五角星为 KTN 和 ZYC 风成剖面的位置,白色矩形为已报道湖心钻孔的位置

Qinghai Lake, located on the northeastern QTP at the elevation of ~3 200 m above sea level, is the largest inland closed lake in China (Fig. 1). It is now a brackish lake with salinity of 14 g/L, and the lake area is ~4 400 km^2. The average water depth is 21 m, and the maximum depth is approximately

27 m. It is located at the junction of the Asian summer monsoon (ASM) and the Westerlies (Fig. 1), sensitive to these two atmospheric circulation changes, and is the ideal place to investigate past ASM-Westerlies interactions [24]. Recent research concluded that Qinghai Lake was dominantly controlled by Westerlies during the last glaciation, and was dominantly influenced by the ASM during the Holocene[24].

More than 100 papers that focus on the Holocene paleoenvironmental changes in Qinghai Lake have been published, but there remains controversy over two opposing academic perspectives. Some researchers suggest that the ASM was strong and summer precipitation, summer temperature, and the lake level were high during the early Holocene (9 – 11 ka BP) [24-28]. The ASM weakened since the middle Holocene, and the climate became increasingly arid accordingly. This viewpoint was supported by the assessment of lacustrine organic matter fluxes [24-25], carbonate contents [24-25], δ^{18}O of ostracods [24], carbon and hydrogen isotope of leaf wax [27-28], grain size [25], and the elemental geochemistry of lacustrine sediments [26] (Fig. 2a – 2e). In contrast, other scientists proposed that the environment was harsh in Qinghai Lake during the early Holocene, but the hydrological conditions became better for vegetation to growth since the middle Holocene [15,29-34]. They found that aeolian sands were widely spread around the lake margins [21-23], lake level was low [15,31], the lake was only about ten meters deep[33-34], water salinity was high[26,30], and tree pollen percentages were low during the early Holocene (8 – 11 ka BP)[32]. Since ~8 ka BP, lake level has risen [15], lake water salinity has decreased[30,34], paleosol has developed atop the loess and aeolian sands [21-23], and tree pollen percentages have increased substantially[28]. The climate became warmer and wetter during the middle Holocene (6 – 8 ka BP). This viewpoint was supported by dating of aeolian sediments and paleoshoreline sediments around the lake[15,21-23], δ^{13}C of organic matter [31], δ^{13}C of ostracods [30], and the seeds and remnants of potamogetonaceae within lacustrine sediments[33] (Fig. 2f – 2j).

Recent modeling results revealed that the Holocene precipitation in northeastern QTP was controlled by the interactions between the ASM and Westerlies [35]. During the early Holocene, water vapor from the North Pacific increased, causing the precipitation oxygen isotope in the northeastern QTP to became more negative [35]. Since the middle Holocene, water vapor from the North Pacific have decreased, while those from the Tropical Pacific and Indian Ocean have increased, leading to evolution of the precipitation oxygen isotope towards a positive trend [35]. Model results have also shown that summer precipitation over northeastern QTP increased from 9.5 ka to 6.2 ka BP, and decreased since 6.2 ka BP[35] (Fig. 3b).

In this paper, we reanalyze the reported qualitative and quantitative environmental proxies in Qinghai Lake during the Holocene (Fig. 2), in combination with modeled precipitation and temperature changes in summer and winter seasons (Fig. 3 and 4), with the aim to more comprehensively understand Holocene paleoenvironmental changes in the northeastern QTP.

2 Methods

The transient simulation of Holocene temperature and precipitation was carried out using the Community Climate System Model, version 3 (CCSM3). The CCSM3 is a global, ocean-atmosphere-sea ice-land surface climate model [27]. The CCSM3 is designed to produce realistic simulations over a wide range of spatial resolutions, enabling inexpensive simulations lasting several millennia or detailed studies of continental-scale dynamics, variability, and climate change[36]. Detailed information about the CCSM3 and the forcings used in the transient experiment can be found in He [37], Liu *et al*. [38-39], and Thomas *et al*[23].

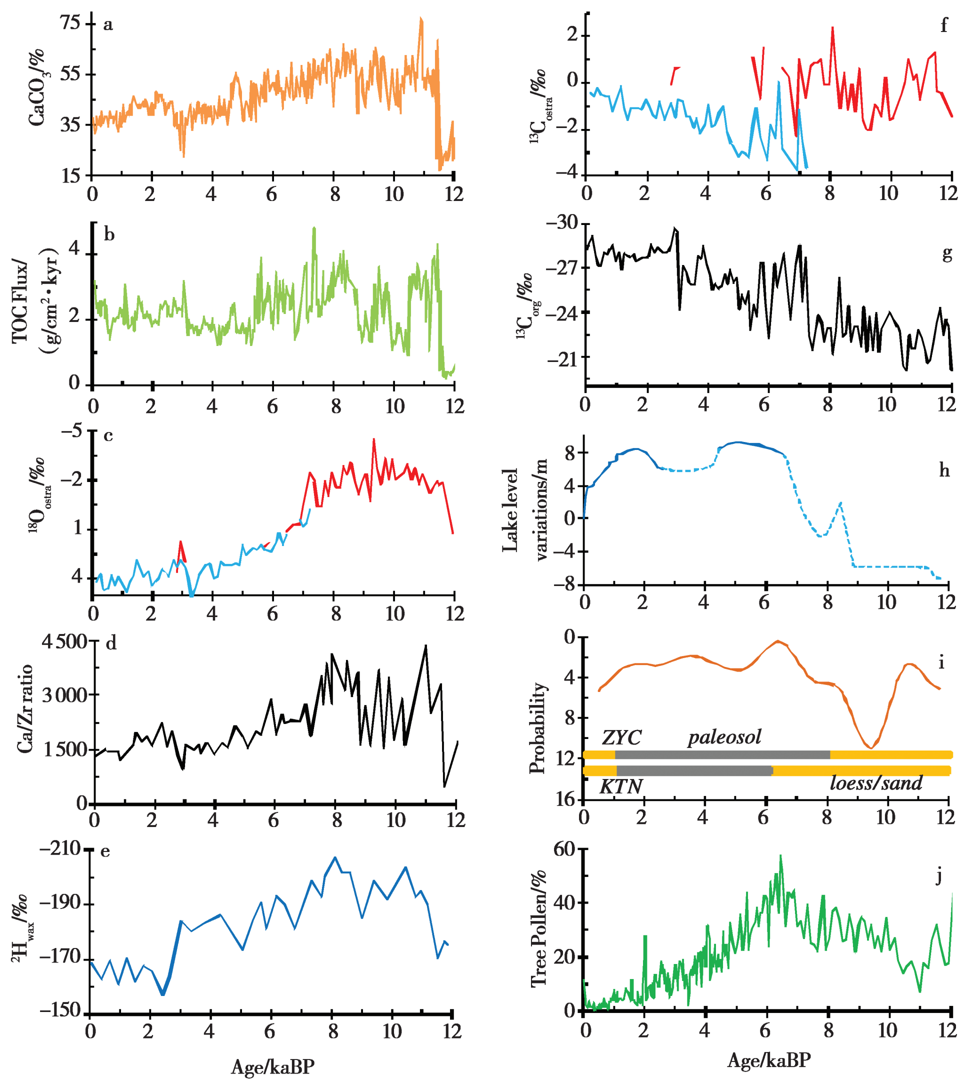

Fig. 2 Reported Holocene paleoenvironmental proxies in Qinghai Lake. Left panel proxies (a – e) show that good environmental conditions appeared in the early Holocene and the right panel (f – j) proxies show that good environmental conditions appeared in the middle to late Holocene. (a) $CaCO_3$ content [24]; (b) total organic carbon (TOC) flux [24]; (c) $\delta^{18}O$ record of ostracods[24]; (d) Ca/Zr ratio [26]; (e) leaf wax hydrogen isotope [28]; (f) $\delta^{13}C$ record of ostracods [30]; (g) $\delta^{13}C$ record of organic matter [31]; (h) lake level variation curve [15]; (i) probability density function plot for ages of aeolian sand sections [29] and sediment strata of ZYC [22] (Zhongyangchang) and KTN [33] (Ketu North) sections dated by optically-stimulated luminescence; (j) tree pollen percentages[32]

图 2 青海湖已报道的古环境指标,左边的指标指示早全新世古环境条件最好,右边的指标指示中晚全新世的古环境条件更好

To generate the Holocene time series of summer/winter temperature and precipitation from the transient simulation for the Qinghai Lake area, we adopt the method described by Thomas *et al.* [27], in which the four closest grid cells' values were averaged to average out random fluctuations from each grid cell and to account for the relatively low resolution of the model and the large topographic gradients in the Qinghai Lake basin. Average temperature and precipitation for the summer season (May-August) and winter season (December-February) were plotted in Fig. 3 and Fig. 4.

The summer season precipitation in northeastern QTP simulated using the Kiel model was obtained from Zhang *et al*. [35].

3 Results

3.1 Summer precipitation and temperature changes

Summer precipitation records reconstructed from the Community Climate System Model, version 3 [27] (CCSM3) and the Kiel model [35] were generally consistent with each other during the Holocene (Fig. 3a and 3b). Summer precipitation was high during the early Holocene, but has decreased since the middle Holocene (6 ~ 7 ka BP) (Fig. 3a and 3b). However, detailed aspects of the two simulations differed considerably. The magnitude of Kiel-model-simulated summer precipitation fluctuation was greater than that of the CCSM3 model. Moreover, the highest summer precipitation simulated by the CCSM3 model was occurred around 10 ka BP, whereas the Kiel-model-simulated highest summer precipitation was appeared ~6.2 ka BP (Fig. 3a and 3b).

The CCSM3-simulated summer temperature record [27] differed considerably from the plankton-community-composition-based [40] and alkenone-based summer temperature records [2,41] in Qinghai Lake. The CCSM3-simulated summer temperature declined between 11 and 1 ka BP, then slowly increased since 1 ka BP, and the highest summer temperature appeared at ~10 ka BP (Fig. 3c). However, plankton-community-composition-based and alkenone-based summer temperature records show that summer temperature (or growing season temperature) varied substantially and frequently during the Holocene, with several high temperature periods isolated by cold stages (Fig. 3d – 3f). Proxies reconstructed summer temperature was unstable during the early Holocene (8 – 11 ka BP), whereas a stable high summer temperature period persisted from 8 ka to 6 ka BP. The summer temperature declined since

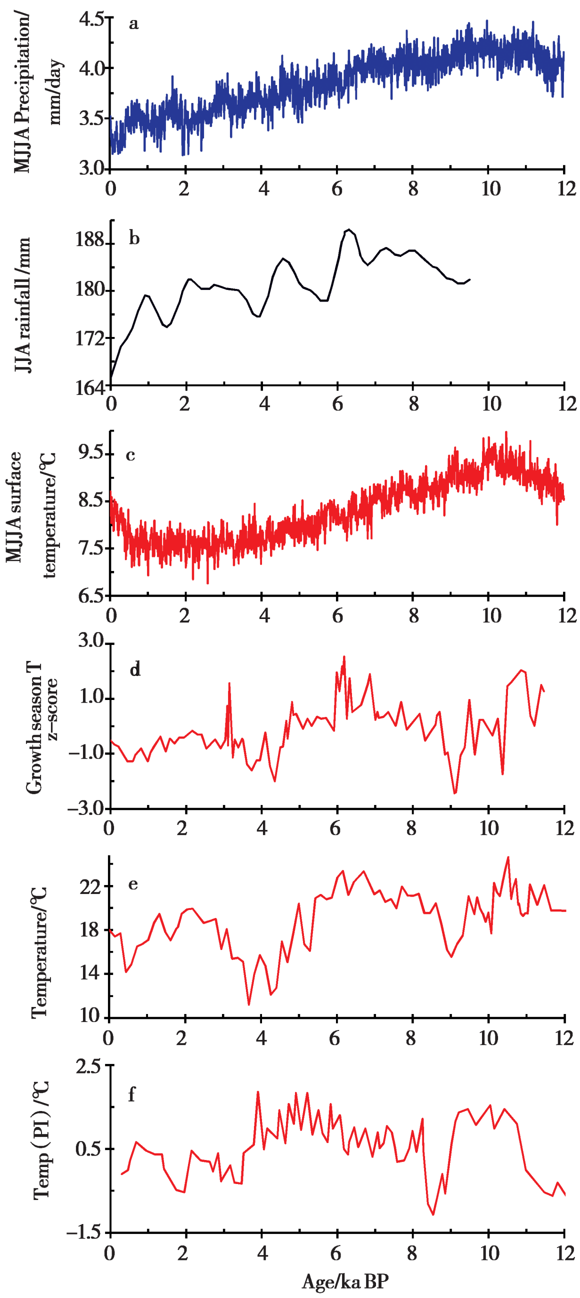

Fig. 3 Summer precipitation (blue lines) and temperature (red lines) changes during the Holocene epoch. (a) CCSM3-simulated summer precipitation over Qinghai Lake [27]; (b) Kiel-model-simulated summer precipitation over northeastern QTP [35]; (c) CCSM3-simulated summer temperature over Qinghai Lake [27]; (d) plankton community composition based summer temperature in Qinghai Lake [40]; (e ~ f) alkenone-based summer temperature in Qinghai Lake[2,41].

图 3 全新世夏季降水(蓝色线)和夏季温度(红色线)变化曲线

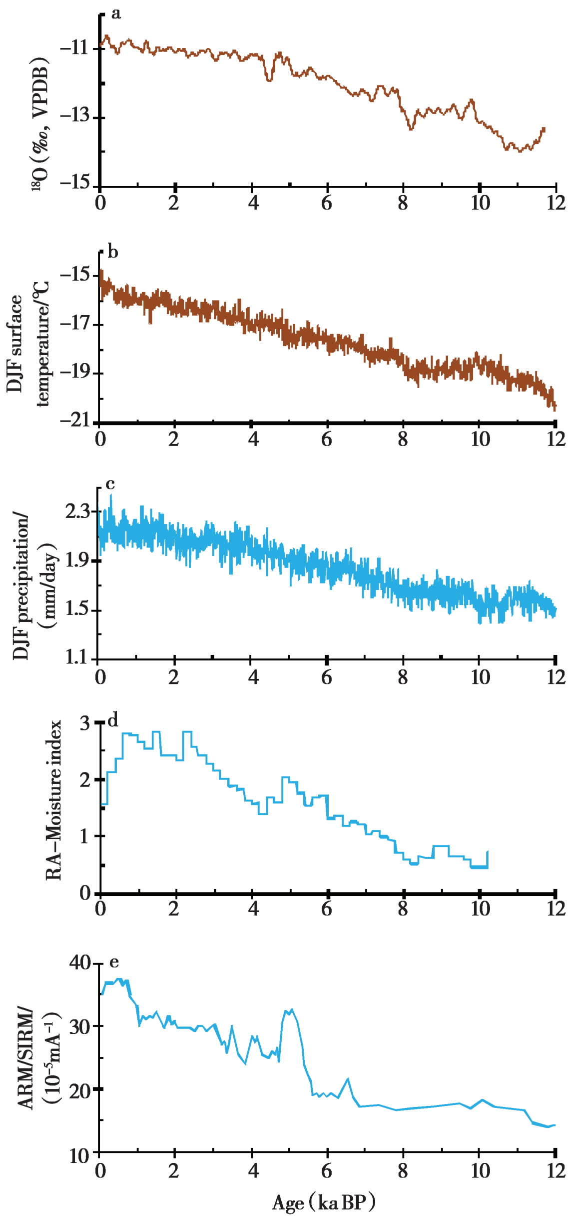

Fig. 4　Winter temperature (brown lines) and precipitation (blue lines) changes during Holocene epoch. (a) Oxygen isotope of stalagmite in Kinderlinskaya cave[42]; (b) CCSM3-simulated winter temperature over Qinghai Lake[27]; (c) CCSM3-simulated winter precipitation over Qinghai Lake[27]; (d) reconstructed moisture index in Xinjiang[43]; (e) Holocene moisture changes represented by χARM/SIRM in the LJW10 section of the Xinjiang Loess[44]

图 4　全新世冬季温度(褐色线)和冬季降水(蓝色线)变化曲线

~6 ka BP, and a relatively cool stage persisted from 5 ka to 3 ka BP, followed by a relatively warm and stable stage between 3 and 1 ka BP (Fig. 3d – 3f). For the last 1 ka, summer temperature dropped first, then risen gradually (Fig. 3d – 3f). The climate-model-simulated summer precipitation appear to be realistic in their general trends, but their detailed variations still need to be further improved (Fig. 3a and 3b). Modeled summer temperature deviated greatly from reconstructed summer temperature records, whereas the three proxies reconstructed summer temperature records had the same variation trends (Fig. 3c – 3f). This suggests that the plankton-community-composition-based and alkenone-based summer temperature records can generally capture the summer temperature variation trends, but the models for summer temperature modelling still require further improvement to produce more credible simulation results.

3.2　Winter precipitation and temperature changes

The CCSM3-simulated winter temperature changes[27] over Qinghai Lake were consistent with the stalagmite oxygen isotope changes[42] controlled by the northern hemisphere high latitude Eurasian continental winter temperature, showing a relatively stable temperature during the early Holocene (before 8 ka BP), followed by a persistent increase of the temperature since 8 ka BP (Fig. 4a and 4b). The CCSM3-simulated winter precipitation changes over Qinghai Lake were consistent with the reconstructed effective humidity index[43] and magnetic susceptibility[44] changes associated with Westerly-related precipitation in the Xijiang region (Fig. 4c – 4e). Winter precipitation was relatively stable in the Holocene before 8 ka BP, and increased steadily since 8 ka BP (Fig. 4c – 4e). These findings suggest that winter temperature and precipitation varied synchronously, with risen temperature accompanied by increased precipitation.

4 Discussion

Recent studies have shown that lake water of Qinghai Lake is saturated with respect to calcite and aragonite, and the carbonate content in recent lake sediments covaries with the observed river discharges [24-26]. It therefore appears that the lake water is calcium-limited, and thus carbonate precipitation is closely related to calcium ions delivered by river runoff, which in turn relates to precipitation in the lake basin, such that high carbonate content is related to a strong ASM[24-26]. This inference is correct if the chemical composition of the water of Qinghai Lake was stable during the Holocene epoch. However, the chemical composition of the water may vary because the size of Qinghai Lake varied greatly during the Holocene[15,31,33-34]. Furthermore, the carbonate content of lake sediments is also potentially influenced by several climate-related factors, such as evaporation, temperature, and primary production in lake systems [25,29]. Hence, the carbonate content may also be influenced by salinity changes of the lake water, with a high carbonate content corresponding to high salinity of the lake water, and vice versa. Total organic carbon (TOC) and TOC flux in lacustrine sediments were regarded to reflect the variations of watershed organic matter input amount or input flux into the lake[24]; the TOC and TOC flux related to watershed biomass changes, and further reflected the changes of ASM precipitation [24]. However, recent researches have reported that TOC mainly represents the organic matter content in Qinghai Lake, and that terrestrial input of organic matter is limited [31,45]. Ostracod shell oxygen isotopes [24] and leaf wax hydrogen isotopes[28] are often reported to change along with ASM precipitation; negative $\delta^{18}O_{ostra}$ and δ^2H_{wax} represent strong ASM and more precipitation within lake basin, and vice versa. However, others suggested that the variations of $\delta^{18}O_{ostra}$ and δ^2H_{wax} reflected the changes of oxygen and hydrogen isotopes in water vapor source regions[29,35], not the ASM intensities. Recent modeling results have revealed that the major water vapor source regions for northeastern QTP changed from the North Pacific to the Tropical Pacific and Indian Ocean during the Holocene, causing early Holocene oxygen isotope in summer precipitation to become more negative than in the middle and late Holocene [35]. Moreover, the water vapor transport distance from the North Pacific is much longer than from the Tropical Pacific and Indian Ocean, also causing the oxygen isotope to become more negative[35]. As discussed above, we suggest that the traditional ASM proxies (carbonate content, TOC, $\delta^{18}O_{ostra}$, δ^2H_{wax} and the Ca/Zr ratio (Fig. 2a - 2e)) used in Qinghai Lake may not fully represent the ASM precipitation variations. However, models simulated summer season precipitation variations only capture the general precipitation change trends, the detailed variations of summer precipitation still need further improvement of the accuracies of the models. Modeled summer temperature changes have even lower credibility than proxies reconstructed summer temperature changes. As the paleoenvironmental proxies and models generated quantitative paleo-parameters all have their limitations, this study we combine them together for the summer and winter season to more comprehensively understand the Holocene environmental changes in Qinghai Lake area.

During the early Holocene (8 - 11 ka BP), previous researches have revealed that the lake water salinity of Qinghai Lake was high [30,34], lake water was shallow (less than 10 m in depth) [15,33], aeolian activities around the lake were intensive[21-23], and tree pollen percentages content were low [32] (Fig. 2f - 2j), implying a relatively arid environment. However, the simulated precipitation shows that summer precipitation was high between 8 and 11 ka BP (Fig. 3a and 3b), but winter precipitation was low (Fig. 4c). Lack of winter precipitation caused lower soil water content during winter and spring, leading to intensive aeolian activities and widespread aeolian sands surround the lake. Even though summer precipitation was high, summer solar irradiance was high [29] and summer temperature was also high in several stages, causing correspondingly high surface evapotranspiration. In response, the terrestrial vegetation primary productivity and lake level were low, but lake biomass was high. The high carbonate content and Ca/Zr ratio in this stage may related to high lake water salinity, which favored carbonate precipitation. Moreover, reconstructed summer temperature records, carbonate content, TOC flux, and Ca/Zr ratio all indicated that the climate in early Holocene is not stable, but fluctuated frequently with large amplitudes [24-26]. The frequent fluctuations of climate in the northeastern QTP during the early Holocene may have been caused by the impacts of residual ice sheets in northern hemisphere high latitudes, which influenced the climate of northern hemisphere mid-latitude through enhanced Westerlies[24,42].

During the early middle Holocene (6 - 8 ka BP), Kiel-model-simulated summer precipitation increased substantially, and peaked at ~6.2 ka BP (Fig. 3b). Moreover, summer temperature reconstructed from alkenone also reached the Holocene highest value during this period (Fig. 3d and 3e). These are the typical characteristics of the ASM that heavy precipitation and high summer temperatures occurred over the same period. During this period, lake water salinity declined abruptly, lake level increased rapidly, aeolian activities surround the lake weakened substantially, paleosols started to form, and tree pollen percentages reached the highest during the Holocene (Fig. 2f - 2j). This indicates that environmental conditions in the Qinghai Lake area improved considerably. The ASM precipitation reconstructed from Gonghai Lake pollen data also show a significant increasing trend between 8 and 6 ka BP [46]. It seems that this period was the optimal period of heat and water configuration in Qinghai Lake during the Holocene (namely the Holocene climate optimum period).

Modeled summer precipitation in the northeastern QTP has decreased since ~6 ka BP (Fig. 3b); summer temperature reconstructed from alkenone has also declined since ~6 ka BP, and experienced a low temperature stage between 5 and 3 ka BP (Fig. 3d and 3e). Tree pollen percentages declined persistently after 6 ka (Fig. 2j), and vegetation compositions in Qinghai Lake basin also transformed from forest steppe to grassland and alpine meadow simultaneously [32]. The ASM precipitation reconstructed from Gonghai Lake pollen data declined rapidly after 3.3 ka [46]. However, between 6 and 1.5 ka BP, Qinghai Lake retained a high water level, paleosols continued to form, and aeolian activities surround the lake were weak [15,21-23,9] (Fig. 2f - 2j), which seems incompatible with the fading ASM. However, the CCSM3-simulated winter temperature has increased since 8 ka BP (Fig. 4b), and the winter precipitation increased simultaneously (Fig. 4c). The climate-model-simulated winter precipitation increasing trend was consistent with increasing trends of effective humidity and precipitation in Westerly-dominated Xinjiang regions[43-44]. In addition, Henderson *et al.* [47] also proposed that the Westerly carried winter precipitation increased in Qinghai Lake during the late Holocene. Winter precipitation falls as snow, which melt only when the temperature rises above 0℃ in the following spring and melt water infiltrates below ground and provides favorable soil moisture content for plants to sprout and grow. Moreover, lower summer temperature and thick grass surround the lake caused the surface evaporation capacity to decline. Although summer precipitation decreased during the mid and late Holocene, increased winter precipitation and decreased summer evaporation maintained Qinghai Lake at a high lake level. Even though forests decreased since 6 ka, grasslands and meadows grew densely in the watershed, causing paleosols to form continuously.

During the last 1.5 ka, lake level dropped continuously and aeolian activities surround the lake strengthened again [13,15,29] (Fig. 2h and 2i). In addition, climate-model-simulated summer precipitation and Westerly-carried winter precipitation all declined persistently (Fig. 3a, 3b, and 4c-4e). Huang et al.[48] also found the environment in Gonghe basin has deteriorated since 1.5 ka BP, and they attributed this deterioration to enhanced human activities. Here, we consider the declined lake level and intensified aeolian activities in Qinghai Lake to be caused by both declined precipitation and enhanced human activities.

5 Conclusions

The results of this study indicate that in the early Holocene (8 – 11 ka BP), summer precipitation and surface evaporation were high, but winter precipitation was low, causing widespread aeolian sands surround the lake and low water level in the Qinghai Lake. Moreover, the early Holocene climate was found to be unstable. The Holocene heat and water configuration was optimal for forest growth between 8 and 6 ka BP. During this stage, lake level increased rapidly, lake water salinity declined abruptly, aeolian activities reduced greatly, paleosols started to develop, and forests were dispersed extensively around the lake. Since 6 ka BP, summer temperature has declined, summer precipitation has begun to decrease, and forests have begun to transform to grasslands and alpine meadows. However, increased winter precipitation and decreased summer evaporation maintained lake level in a high state until 1.5 ka BP, and dense grasslands and alpine meadows caused the paleosol to develop continuously. During the past 1.5 ka, reduced summer and winter precipitation and enhanced human activities led the lake level to decline continuously, and aeolian activities have strengthened again.

Based on the results of this study, we suggest that seasonal temperature and precipitation changes may greatly influenced the Holocene environmental changes in Qinghai Lake. In future research, it is necessary to consider seasonal temperature and precipitation changes to comprehensively decode the paleoenvironmental change information for lakes in high elevation monsoon marginal regions. It is also vital to find proxies that can reliably reflect summer and winter season precipitation and temperature changes, such as some organisms that can record the growing season temperatures.

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冬夏季温度和降水变化对青海湖全新世环境变化的影响初探

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摘　要:青海湖是国内最大的内陆湖泊,位于青藏高原东北缘,因其处在东亚夏季风、印度季风和西风带的交替控制区域,对气候变化十分敏感,成为古环境变化研究的热点地区。有关青海湖的形成演化、环境变化和水文变化的研究也存在多种观点。本研究再分析了青海湖已报道的古环境指标和气候模式模拟的夏季、冬季温度和降水变化,力图更加全面地理解青海湖全新世以来的古环境变化。研究发现早全新世 11 ~ 8 ka 夏季降水量和表面蒸发量较大,冬季降水稀少,湖泊水位只有十余米深,使得青海湖周边风沙活动频繁。并且,早全新世的气候不稳定,经历了频繁和较大幅度的波动。全新世气候适宜期出现在 8 ~ 6 ka,古环境指标指示这一时期为温暖湿润的气候环境,湖盆内植被以森林草原为主,湖泊水位不断上升。青海湖地区的夏季降水自 6 ka 开始减少,然而冬季降水增加,同时夏季温度和蒸发量减少,使得湖区植被组成由森林草原向高山草甸转变,湖区大范围形成古土壤。湖区古环境条件在晚全新世距今 1.5 ka 开始恶化,冬季和夏季降水同时减少,湖泊水位下降,风沙活动再次加强。

关键词:全新世;青海湖;青藏高原;季节温度和降水变化