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Lake evaporation:
A possible factor affecting lake level changes tested by modern observational data in arid and semi-arid China

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Abstract: Qinghai Lake and Zhuye Lake, ~400 km apart, are located in the northwest margin of the Asian summer monsoon. Water of these two lakes mostly comes from the middle and eastern parts of the Qilian Mountains. Previous studies show that the Holocene climate changes of the two lakes implied from lake records are different. Whether lake evaporation plays a role in asynchronous Holocene climate changes is important to understand the lake records. In this paper, we used modern observations beside Qinghai Lake and Zhuye Lake to test the impact factors for lake evaporation. Pan evaporation near the two lakes is mainly related to relative humidity, temperature, vapor pressure and sunshine duration. But temperature has different impacts to lake evaporation of the two lakes, which can affect Holocene millennial-scale lake level changes. In addition, differences in relative humidity on the millennial-scale would be more significant, which also can contribute to asynchronous lake records.

Keywords: Holocene; lake level; lake evaporation; Qinghai Lake; Zhuye Lake; temperature; relative humidity

1 Introduction

The global hydrologic cycle, the circulation of water in the climate system, is an integral part of the earth's climate system, which plays a role in determining the large-scale circulation and precipitation patterns (Hack *et al*., 2006). The lake hydrologic cycle is an important part in the inland hydrologic cycle, in which lake level changes, in response to changes in the hydrologic cycle over the lake and its catchment, are highly sensitive to changes in large atmospheric circulation patterns. Therefore, lake level changes are widely used to reconstruct atmospheric circulation patterns and regional hydrologic cycle changes during the late Quaternary (Street-Perrott and Grove, 1979; Pachur *et al*., 1995; Harrison *et al*., 1996; Qin and Yu, 1998; Herzschuh, 2006). In monsoonal and arid Central Asia, lake level records have been used as a particularly useful indicator to reconstruct Holocene climate history (Morrill 2004; Zhang *et al*., 2004; Chen *et al*., 2008), and the lake level changes are usually

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correlated with the monsoon evolution triggered by low-latitude insolation change (Harrison *et al*., 1996; Qin and Yu 1998; Farrera *et al*., 1999). Furthermore, combined with climate and lake models, the mechanisms of lake level changes are investigated (Yu *et al*., 2003; Li and Morrill, 2010).

The water balance of a lake is governed by many water fluxes (e.g., on-lake precipitation, lake evaporation, surface runoff in the catchment) and these fluxes are controlled by many climatic and hydrologic processes (Morrill 2004). An *et al.* (2006) and Mischke *et al.* (2008) reported some low lake levels in arid and semi-arid China, during the early and middle Holocene, when precipitation is thought to have been high. They ascribed these low lake levels were related to higher evaporation rates and then precipitation rates. In monsoonal and arid Central Asia, Herzschuh (2006) suggested that increased monsoon intensity during the early Holocene caused lake levels in more humid regions to rise, while lake levels in more arid regions fell. She hypothesized that increased summer insolation and air temperature, which were responsible for strengthening monsoon circulation, caused evaporation to increase and that the effects on evaporation were greater in regions where humidity was very low. The author of this paper and Morrill (2010) used a series of models, the NCAR CCSM3, a lake energy-balance and a lake water-balance model to examine the reasons for lake-level changes in monsoonal and Central Asia between the early (8.5 ka), middle (6.0 ka) and late (ca. 1800 AD) Holocene. The model results indicated that the high lake levels at 8.5 and 6.0 ka in the monsoonal regions, and the early Holocene low lake level and mid Holocene high lake level throughout most of Central Asia were highly related with the lake evaporation changes.

In the Qinghai-Tibet Plateau, the Holocene climate change implied by lake records is closely related to the Asian summer monsoon evolution (Lister *et al*., 1991; Morinaga *et al*., 1993; Shen *et al*., 2005; Morrill *et al*., 2006; Liu *et al*., 2007). As a typical research area in the northeast of the plateau, the Holocene lake level change in Qinghai Lake, reaching the high lake level during the early and middle Holocene then declining since the middle Holocene, is similar to other highland lakes (Zhang *et al*., 1989; Lister *et al*., 1991; Shen *et al*., 2005; Liu *et al*., 2007), which is related to the Holocene Asian summer monsoon change (Colman *et al*., 2007). However, in the arid Central Asia and some marginal regions of the Asian summer monsoon, the Holocene lake records show the mid-Holocene high lake level and the dry early Holocene (Xiao *et al*., 2004, 2006, 2009; Chen *et al*., 2008). Zhuye Lake is located in arid China, while the Holocene lake record suggests similar results with the lakes in arid Central Asia (Zhao *et al*., 2008; Li *et al*., 2009a, 2009b). Qinghai Lake and Zhuye Lake are ~400 km apart and divided by the Qilian Mountains, and water of the two catchments is mostly from the middle and eastern parts of the Qilian Mountains (Figure 1). Whether the lake evaporation plays a role for the different lake records is important for understanding the mechanisms governing the millennial-scale lake level changes. The modern observations of lake evaporation and other related climatic factors are very important for understanding the lake evaporation effect to long-term lake evolution. On inter-annual timescales, lake evaporation variability is closely related to modern climatic factors, such as relative humidity, temperature, net radiation, vapor pressure and sunshine duration. On centennial-to-millennial timescales, lake evaporation change is also affected by those climatic factors, and varies according to their long-term fluctuations. The difference is that the mil-

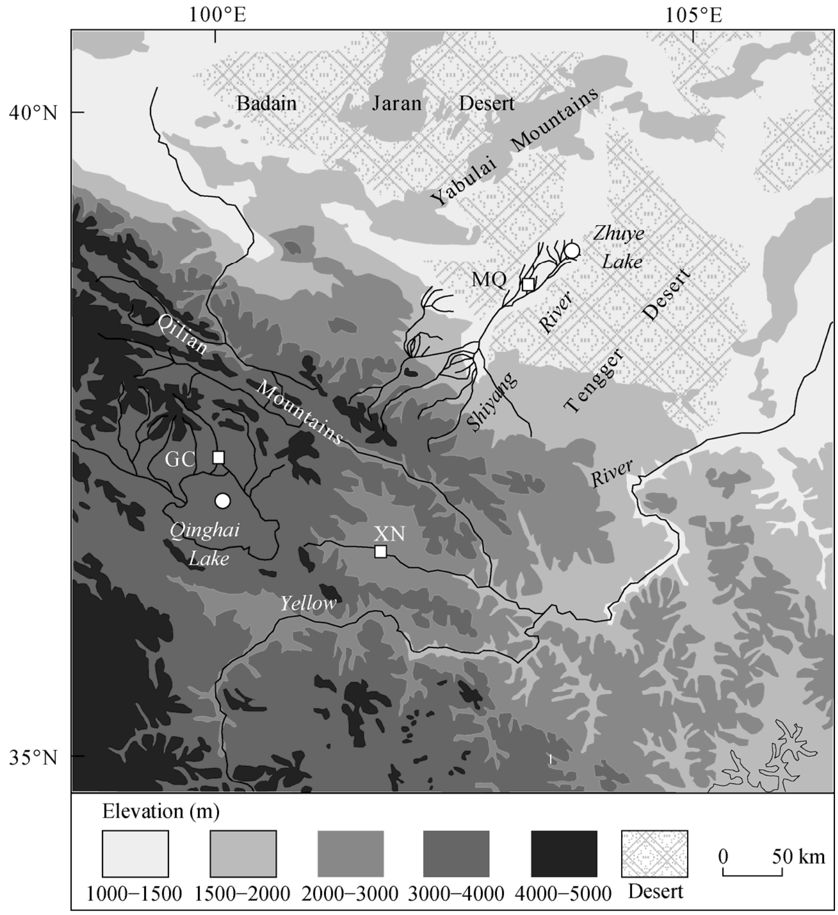

Figure 1 Map of research area showing the elevations (m) and the deserts & rivers distribution around Qinghai Lake and Zhuye Lake (○ means the locations of the two lakes, □ means the locations of the three meteorological stations)

lennial-scale evaporation change is always accompanied by the changes in the atmospheric circulation pattern and the underlying surface, while the interannual-scale evaporation change exhibits variability under a certain circulation pattern and a relatively stable underlying surface. Although the mechanisms governing lake evaporation on different time scales are different, the interannual-scale lake evaporation research can still provide clues for the long-scale evaporation change. In this paper, we selected two meteorological stations (the GC and MQ stations) near the two lakes to collect modern observational data for testing climatic factors that affect lake evaporation. Then, the results, based on modern observational data, are further discussed in order to investigate the relationship between the modern interannual-scale and the Holocene millennial-scale lake evaporation changes.

2 Regional setting

In this study, we focus on a typical arid and semi-arid area (35°N–40°N, 98°E–105°E) in the middle and eastern parts of the Qilian Mountains and the northeast margin of the Qinghai-Tibet Plateau, where the elevation changes from 1000 m to 5000 m above sea level (asl)

(Figure 1). Qinghai Lake (36°15'–38°20'N; 97°50'–101°20'E, Figure 1) is situated on the northeastern Tibetan Plateau and is the largest inland water body of China by surface area. The lake developed within a basin surrounded by three mountain ranges (Bian *et al*., 2000), which are branches of the Qilian Mountains. The lake basin receives its major runoff at its western end from the Buha River, which originates in the middle part of the Qilian Mountains. The lake basin is located at 3194 m asl, with a surface water area of 4400 km^2 and volume of runoff of 1.34×10^9 m^3/yr (Wang, 2003). Zhuye Lake, which is located on the margins of the Tengger Desert, is the terminal lake of Shiyang River, originating from the eastern part of the Qilian Mountains and flowing 300 km from the Qilian Mountains in the south to the Tengger Desert in the north (Figure 1). The Shiyang River originates above 5000 m asl in the Qilian Mountains and has an average runoff of 14.7×10^8 m^3/yr. The Shiyang River Drainage Basin has a catchment area of 41.6×10^3 km^2 (Chen and Qu, 1992). Zhuye Lake has been dry since the 1960s, following construction of the Hongyashan Reservoir and extension of irrigation. At present, the dry lakes that exist in several depressions on the Tengger Desert margins only fill with water in years with sufficient precipitation.

3 Methods

(1) The GC (Gangcha) meteorological station (103°05'E, 38°38'N, 1367 m asl) 15 km apart from Qinghai Lake and the MQ (Minqin) meteorological station (100°08'E, 37°20'N, 3015 m asl) 30 km apart from Zhuye Lake are chosen from 731 basic stations from China Meteorological Administration (Figure 1). The annual and monthly data, including relative humidity (%), average temperature (℃), average vapor pressure (hPa), sunshine duration (h) and average wind speed (m/s) (1960–2005), which are used in this study, were observed by the two stations, and these climatic factors are closely related to evaporation (Penman, 1948). Some monthly data are missing, but the missing ones are rare, which are interpolated by the values of recent 5 years. It is hard to measure the rate of evaporation from a lake; however, a common alternative is to measure the evaporation from a pan. Therefore, pan evaporation from the two stations is used as the lake evaporation. There is a correlation between lake evaporation and pan evaporation. Evaporation from a natural body of water is usually at a lower rate because the body of water does not have metal sides that get hot with the sun, and while light penetration in a pan is essentially uniform, light penetration in natural bodies of water will decrease as depth increases. Most textbooks suggest multiplying the pan evaporation by 0.75 to correct for this (Linacre, 1993, 1994). This study focuses on the relationship between the lake evaporation and its affecting factors, but not the specific values of lake evaporation. Thus, the correction for pan evaporation will not be applied.

(2) Net radiation (mj/m^2) is calculated by the method proposed by Yin *et al.* (2008). The net radiation can be calculated using the following equations:

$$R_n = R_{ns} - R_{nl}$$

$$R_{ns} = (1-\alpha)\left(0.2 + 0.79\left(\frac{n}{N}\right)\right)R_{so}$$

$$R_{nl} = \sigma\left(\frac{T_{\max,k}^4 + T_{\min,k}^4}{2}\right)(0.56 - 0.25\sqrt{e_a})\left(0.1 + 0.9\left(\frac{n}{N}\right)\right)$$

where R_n is the net solar radiation (MJ·m^{-2}·d^{-1}), R_{ns} is the net shortwave radiation, R_{nl} is the net longwave radiation, α is the albedo, R_{so} is the solar radiation, n is the actual sunshine duration (hour), N is the maximum possible sunshine duration, n/N is the relative sunshine duration, R_a is the extraterrestrial radiation, s is the Stefan–Boltzmann constant (4.903×10^{-9} MJ·K^{-4}·m^{-2}·d^{-1}), $T_{\max,k}$ is the maximum absolute temperature during the 24-h period (K), $T_{\min,k}$ is the minimum absolute temperature during the 24-h period, R_{so} is the clear sky solar radiation. N, R_a and R_{so} were calculated by solar constant, latitude, elevation and the number of the day in the year according to the FAO56 Report (Allen *et al*., 1998). All the empirical coefficients in the equations are calibrated by Yin *et al.* (2008) for China. In order to verify the reliability of the calculated net radiation, the observed monthly net radiation data from the XN (Xining) station (101º46'E, 36º37'N, 2262 m asl) (1996–2005), which is ~100 km away from Qinghai Lake, are used to compared with the calculated net radiation. The calculated and observational data are relatively consistent with each other (Figure 2).

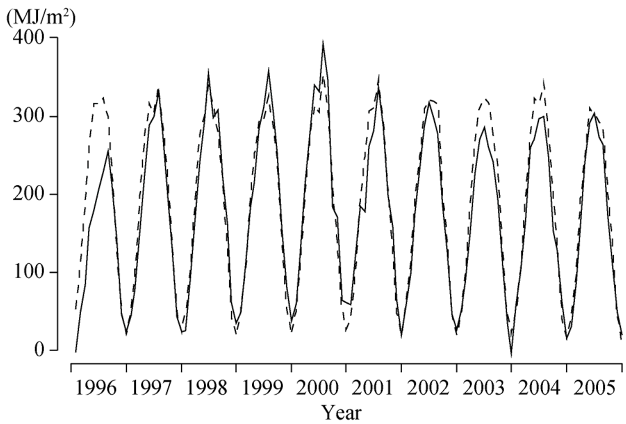

Figure 2 Comparison between the calculated net radiation from the GC (Qinghai Lake) station (the dashed line) and the observational net radiation from the XN station (the solid line)

4 Results

4.1 Annual and seasonal pan evaporation changes from the GC (Qinghai Lake) and MQ (Zhuye Lake) stations (1960–2005)

Pan evaporation from the GC and MQ stations shows a similar trend (1960–2005), while the correlation coefficient between them is 0.355, which is significant at 0.02 level. Since the 1970s, there is an increasing trend in the MQ station. At the same time, the GC station is characterized by a decreasing trend (Figure 3). The 45-year average pan evaporation is 2648 mm in the MQ station, which is much higher than that of the GC station (1457 mm). Figure 4 shows seasonal pan evaporation in the two stations. The average pan evaporation varies according to seasons: 477 mm (32.7%, spring), 528 mm (36.2%, summer), 294 mm (20.2%, autumn) and 156 mm (10.7%, winter) in the GC station; 873 mm (33.0%, spring), 1122 mm (42.4%, summer), 483 mm (18.2%, autumn) and 168 mm (6.3%, winter) in the MQ station. The correlation coefficients between the seasonal pan evaporation of the two stations are 0.393 (spring, significant at 0.01 level), 0.190 (summer), 0.497 (autumn, significant at 0.001

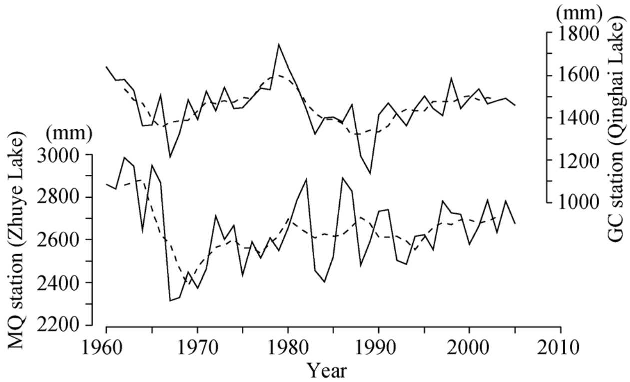

Figure 3 Annual pan evaporation changes from 1960 to 2005 in the MQ (Zhuye Lake) and GC (Qinghai Lake) stations. The dashed lines indicate the 5-year running averages

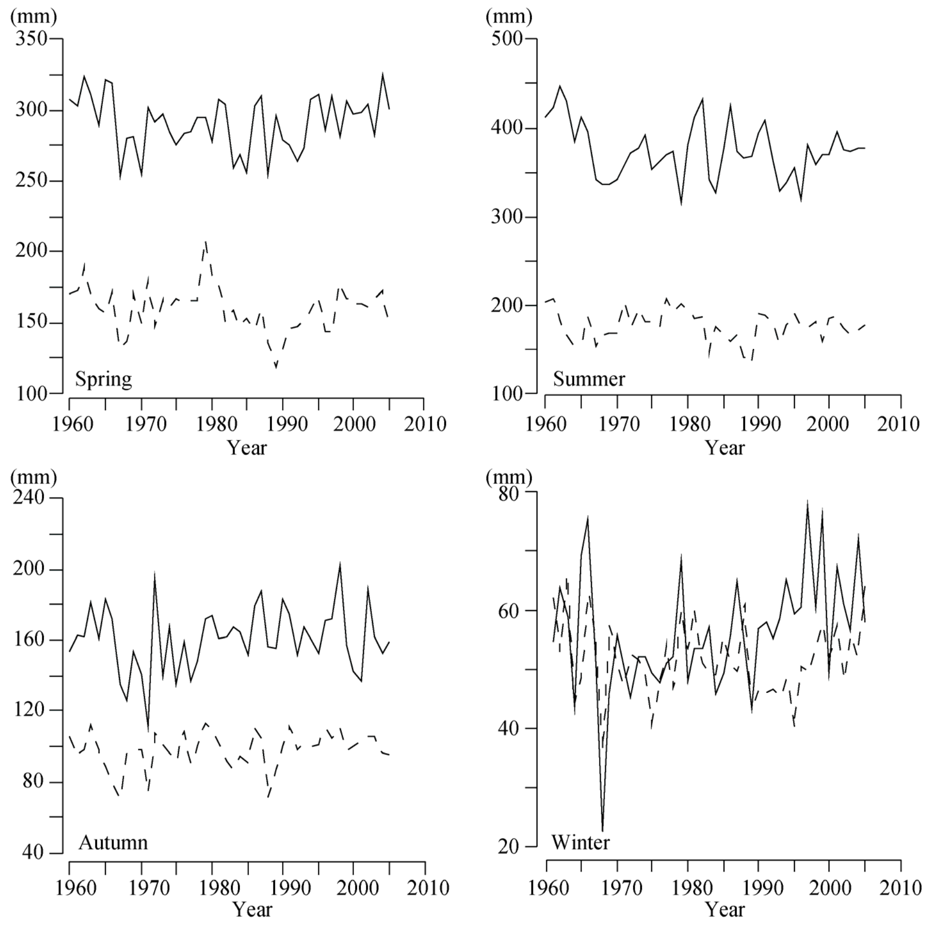

Figure 4 Seasonal pan evaporation changes from 1960 to 2005 in the MQ (Zhuye Lake) and GC (Qinghai Lake) stations. The solid lines indicate pan evaporation in the MQ station, while the dashed lines indicate pan evaporation in the GC station

level) and 0.376 (winter, significant at 0.01 level). The correlation is more significant in autumn, spring, winter, and less significant in summer; however, the summer pan evaporation plays a more important role to the annual pan evaporation. The significant difference in summer pan evaporation may be due to the hot and arid climate in the MQ station. Annual temperature, net radiation, average relative humidity, average wind speed, average water vapor pressure and sunshine duration are related to each other between the two stations (1960–2005), and the correlation coefficients are 0.786 (temperature, significant at 0.001 level), 0.559 (water vapor pressure, significant at 0.001 level), 0.437 (wind speed, significant at 0.01 level), 0.384 (relative humidity, significant at 0.01 level,), 0.289 (net radiation, significant at 0.05 level), and 0.248 (sunshine duration, significant at 0.1 level) (Figure 5). Temperature has the highest correlation coefficient between the two stations corresponding to the global warming in China. Relative humidity shows a slight different trend since the 1970s: the MQ station shows a decreasing trend, while the GC station indicates an increasing trend. Furthermore, sunshine duration is relatively stable from 1960 to 2005 in the GC station, but the MQ station shows an increasing trend. Wind speed, water vapor pressure, and net radiation are relatively close to each other between the two stations.

4.2 Relationships between pan evaporation and climatic factors

As shown in Tables 1 and 2, annual correlation coefficients are generally consistent with the seasonal correlation coefficients. Both on the inter-annual-scale and seasonal-scale, relative humidity is the most important factor affecting pan evaporation in the two stations. While temperature, vapor pressure and sunshine duration are relatively well related to pan evaporation, net radiation and wind speed are less related to pan evaporation. Temperature is the second most important factor affecting pan evaporation in the MQ station, but which is the fourth factor in the GC station. Sunshine duration is the second most important factor affecting pan evaporation in the GC station, which is the fourth factor in the MQ station. Net radiation in the two stations are well related to sunshine duration on the inter-annual-scale and seasonal-scale (Table 3); however, the correlation between sunshine duration and pan evaporation is much higher than the correlation between net radiation and pan evaporation. The increasing trend since the 1970s on pan evaporation may be more connected with the decreasing relative humidity and the increasing temperature in the MQ station. Also, the increasing sunshine duration since the 1960s can affect the increasing pan evaporation since the 1970s (Figure 5). In the GC station, the decreasing trend on pan evaporation since the 1970s may be linked to the increasing humidity, the decreasing wind speed and the increasing vapor pressure (Figure 5).

5 Discussion

Pan evaporation or lake evaporation is a measurement that combines or integrates the effects of several climate elements, such as temperature, humidity, solar radiation, and wind speed. In this study, pan evaporation shows high correlations with these elements: relative humidity, temperature, vapor pressure, and sunshine duration. Relative humidity, usually stated as a percent, describes the ratio of the partial pressure of water vapor in an air-water mixture to the saturated vapor pressure of water at a prescribed temperature. Using the data observed by 62

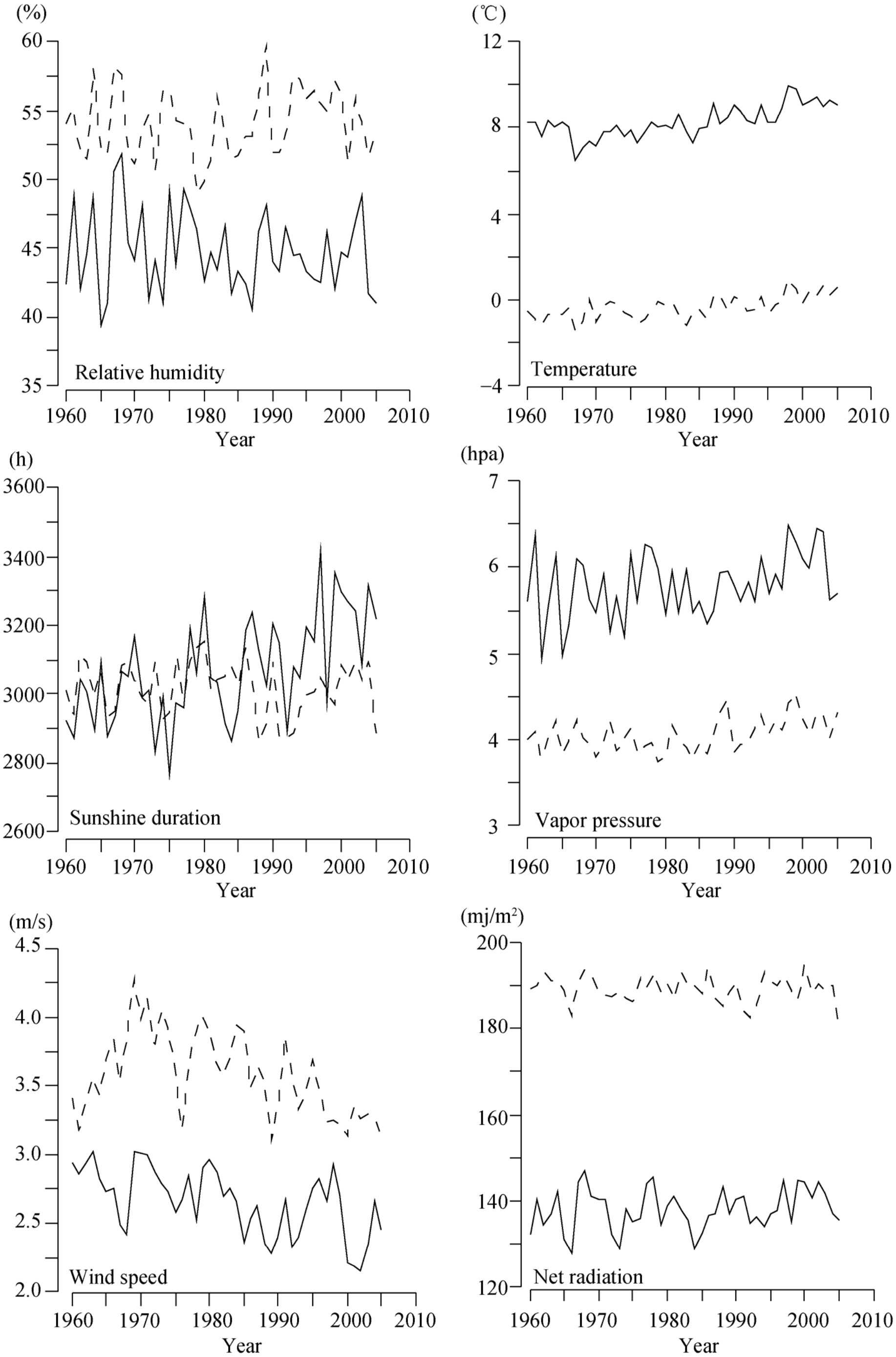

Figure 5 Annual average relative humidity (%), average temperature (℃), average vapor pressure (hPa), sunshine duration (h), average wind speed (m/s) and net radiation (mj/m^2) changes during the period of 1960–2005 in the MQ (Zhuye Lake) and GC (Qinghai Lake) stations. The solid lines indicate the data from the MQ station, and the dashed lines indicate the data from the GC station.

Chinese Routine Meteorological Stations (CRMS) with long-term radiation observation, Zuo *et al.* (2005) also found that relative humidity has a significant role for pan evaporation

Table 1 Correlation coefficients between annual and seasonal pan evaporation and other climatic factors in the MQ station (Zhuye Lake). ** means the correlation coefficient is significant at 0.01 level and * means the correlation coefficient is significant at 0.05 level.

	Relative humidity (%)	Average temperature (℃)	Vapor pressure (hPa)	Sunshine duration (h)	Net radiation (mj/m^2)	Average wind speed (m/s)
Pan evaporation (Annual)	–0.535**	0.470**	–0.340*	0.232	–0.215	0.183
Pan evaporation (Spring)	–0.522**	0.386**	–0.362*	0.362*	–0.055	0.240
Pan evaporation (Summer)	–0.723**	0.570**	–0.471**	0.293*	–0.033	0.125
Pan evaporation (Autumn)	–0.827**	0.333*	–0.639**	0.428**	–0.541**	0.292*
Pan evaporation (Winter)	–0.631**	0.793**	0.122	0.319*	–0.788**	0.329*

Table 2 Correlation coefficients between annual and seasonal pan evaporation and other climatic factors in the GC station (Qinghai Lake). ** means the correlation coefficient is significant at 0.01 level and * means the correlation coefficient is significant at 0.05 level.

	Relative humidity (%)	Sunshine duration (h)	Vapor pressure (hPa)	Average temperature (℃)	Average wind speed (m/s)	Net radiation (mj/m^2)
Pan evaporation (Annual)	–0.577**	0.389**	–0.340*	0.243	0.159	0.051
Pan evaporation (Spring)	–0.749**	0.468**	–0.555**	0.283	0.387**	–0.019
Pan evaporation (Summer)	–0.696**	0.301*	–0.288*	0.335*	0.253	0.177
Pan evaporation (Autumn)	–0.739**	0.682**	–0.463**	0.329*	0.064	0.245
Pan evaporation (Winter)	–0.654**	0.204	–0.272	0.463**	0.242	–0.608**

Table 3 Correlation coefficients between annual and seasonal net radiation and sunshine duration in the MQ (Zhuye Lake) and GC (Qinghai Lake) stations. ** means the correlation coefficient is significant at 0.01 level and * means the correlation coefficient is significant at 0.05 level.

	Net radiation (annual)	Net radiation (spring)	Net radiation (summer)	Net radiation (autumn)	Net radiation (winter)
Annual or seasonal sunshine duration (h) from the MQ station	0.490**	0.687**	0.835**	–0.118	–0.475**
Annual or seasonal Sunshine duration (h) from the GC station	0.707**	0.759**	0.952**	0.525**	0.150

variations. This result indicates that relative humidity is also a key factor for pan evaporation in other parts of China. Temperature: if the air is hotter, then the molecules of lake water have a higher average kinetic energy, and evaporation will be faster. However, the air temperature increases while the pan evaporation decreases in most parts of China in the past 50 years, and we call this phenomenon "the evaporation paradox" (Cong *et al*., 2008; Shen *et al*., 2008). According to the observational data in this study, the evaporation paradox is not apparent in Zhuye Lake, but can be found in Qinghai Lake. Vapor pressure, which is correlated with relative humidity, is used to mean the partial pressure of water vapor in the atmosphere, while sunshine duration means the cumulative time during which an area receives direct irradiance from the Sun, which influences lake evaporation by changing energy that the molecules of water need to escape the water surface. These four climate elements are the main factors that affect evaporation in Qinghai Lake and Zhuye Lake on the interannual-scale. Net radiation is an important factor affecting pan evaporation (Penman, 1948); however, the correlation between pan evaporation and the calculated net radiation is not apparent. In this study, we used the method proposed by Yin *et al.* (2008) for calculating the net radiation. The empirical coefficients in the equations were calibrated for the whole of China. The different regions in China, therefore, were not given different coefficients. Using the same coefficients for different regions had few effects in this calculation, which has been proved by Yin *et al.* (2008). In arid and semi-arid regions, the nighttime air is usually calm near lakes, with a relative humidity often in the vicinity of 75% owing to the temperature difference between day and night. Consequently, the lake evaporation is almost exclusively a daytime process (Linacre, 1993; 1994). However, the energy exchange is not restricted in daytime, which is also obvious in nighttime, while the long-wave radiation is usually from the lake surface to the atmosphere and can't result the evaporation. For the reason, pan evaporation is more related to sunshine duration in this study, but not well related to net radiation.

Previous research also confirmed the findings of this paper. Li *et al.* (2010) studied pan evaporation (1961–2007) and climate elements that affect pan evaporation based on seven meteorological stations over the Qinghai Lake drainage basin. The decreasing trend on pan evaporation is detected over the basin, which is consistent with this study, and the decrease of vapor deficit, which is directly related to relative humidity change, is the most important factor for pan evaporation change. Temperature also plays a less significant role than vapor pressure and sunshine duration (Li *et al.*, 2010). Zhuye Lake is located in the east of the Hexi Corridor that is ~1000 km long and located between the Qilian Mountains and the Gobi Desert. The pan evaporation data (1958–2005) from 20 meteorological stations in the Hexi Corridor show that pan evaporation is relatively high in the 1960s, then declines and reaches the smallest value in the 1970s, and it begins to rise since the 1970s (Guo *et al.*, 2009). These results are similar to the pan evaporation trend in Zhuye Lake. Guo *et al.* (2009) also found that pan evaporation from the 20 stations is highly related to relative humidity, temperature, vapor pressure, sunshine duration, while temperature is one of the most important factors that affect lake evaporation.

On the interannual-scale, the variability of lake evaporation depends on the changes of relative humidity, temperature, vapor pressure and sunshine duration in Qinghai Lake and Zhuye Lake. According to this, the Holocene millennial-scale lake evaporation change can also be related to the long-term fluctuations of these climate elements. However, atmospheric circulation pattern and underlying surface may change a lot on the millennial-scale. Millennial-scale solar radiation in the Northern Hemisphere reaches the peak during the early Holocene and declines sharply since the middle Holocene (Berger and Loutre, 1991). The early and middle Holocene Climate Optimum (the Holocene Megathermal), which is represented by warm and humid climate, was widely reported in China (An *et al*., 2000). During the early and middle Holocene, the air temperature could be much higher in Qinghai Lake and Zhuye Lake. Furthermore, temperature plays different roles on lake evaporation of the two lakes. The temperature impact on lake evaporation is much stronger in Zhuye Lake than that in Qinghai Lake on the modern interannual-scale. If the temperature is higher than present during the early and mid Holocene, the difference in the temperature impact can be greater between the two lakes. As a result, the temperature impact on lake evaporation will be enlarged on the millennial-scale, which eventually triggers the asynchronous lake evaporation change during the early and middle Holocene, then affects lake level changes. In addition to the temperature impact, relative humidity is the most important factor affecting lake evaporation of the two lakes. According to the Holocene Asian summer monsoon history implied by lake records in the Qinghai-Tibet Plateau, the Asian summer monsoon, which can bring more water vapor to the Plateau and lead to humid climate in the northeast of the Plateau, is much stronger during the early and middle Holocene than modern times (Shen *et al*., 2005; Liu *et al*., 2007; Colman *et al*., 2007). However, Zhuye Lake is located on the other side of the Qilian Mountains, although the lake can share the increased precipitation in the mountains, the mountains can intensely keep water vapor from Zhuye Lake. Consequently, the vapor discrepancy between the two lakes can be more intense than present. Water vapor is directly related to relative humidity and vapor pressure that are important climate elements influencing the modern interannual-scale lake evaporation. By this way, the Holocene millennial-scale relative humidity and vapor pressure changes can be very different in the two lakes. Qinghai Lake is characterized by the early Holocene high lake level, which could be contributed by the early Holocene low lake evaporation triggered by the relatively weak temperature impact and the high vapor content. On the other hand, Zhuye Lake shows the middle Holocene high lake level (Climatic Optimum), which could be related to the higher early Holocene lake evaporation that is associated with the strong early Holocene temperature impact on lake evaporation and the low vapor content due to the obstruction of the Qilian Mountains. Totally, the Holocene millennial-scale climate change in the study area can have significant impacts on the climate elements that affect lake evaporation, which can cause the difference in long-term lake evaporation change between the two lakes.

6 Conclusions

Lake evaporation has been considered as a factor affecting millennial-scale lake level changes in East and Central Asia. During the Holocene, the lake records from Qinghai Lake and Zhuye Lake show different millennial-scale climate changes in the northwest margin of the Asian summer monsoon. Using the modern observational data from meteorological stations beside the two lakes, this paper analyzes the relationship between pan evaporation and other climatic factors. The results suggest that climate factors have different impacts on pan evaporation in the two lakes. Temperature has a more significant effect on pan evaporation in Zhuye Lake than that in Qinghai Lake. Different temperature effects can contribute to asynchronous millennial-scale lake level changes. Besides, relative humidity, the most important factor for lake evaporation, can also affect lake level changes on the millennial-scale.

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