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Diurnal and intra-season variation of warm-season temperature in coastal zone of Qinghai Lake

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Abstract
The Qinghai Lake is the largest saltwater lake in the Tibetan Plateau and in mainland China. Effects of the lake on surface climate of the coastal areas, however, are not well understood. This article utilizes hourly observation data of warm season from 17 automatic weather stations to analyze the diurnal and seasonal variations in air temperature in different coastal zones of the Qinghai Lake. The EOS/MODIS data was also used to analyze the surface temperature differences between the lake and its surrounding areas. The results show a few unique characteristics of the plateau lake: (1) based on the satellite data, lake surface temperature is lower than its surrounding areas (4.9~25.1 °C and 12.2~35.6 °C respectively) in the daytime, while it is obviously higher than that in the surrounding areas (1.9~10.5 °C and − 13.1~6.3 °C respectively) at the nighttime. Daily mean water surface temperature is higher than that in the surrounding areas, which is 7.8~17.9 °C and − 2.6~17.9 °C respectively; (2) based on data of meteorological stations, coastal zones closer to the shoreline have a higher air temperature during the warm season largely due to the much warmer nighttime near the shoreline than those in deep inland zones. For the on-shore, near-shore, and far-shore zones, mean daytime air temperature is 8.7~9.6 °C, 9.5~11.1 °C, and 10.0~10.7 °C, respectively, and the mean nighttime air temperature is 2.9~4.1 °C, 1.3~12.3 °C, and − 0.2~0.4 °C respectively. The hourly mean diurnal temperature range (DTR) increases with distance to the shoreline, which is 8.6 °C, 10.9 °C, and 12.3 °C in the on-shore, near-shore, and far-shore zones respectively; (3) differences between maximum and minimum 5-day mean daily maximum (minimum) air temperature during the warm season are 20.3 °C (23.3 °C), 21.7 °C (25.6 °C), and 22.6 °C (26.7 °C) for the on-shore, near-shore, and far-shore zones, respectively, indicating an asymmetrical effect on daytime and nighttime air temperature in the on-shore zone; (4) daily maximum air temperature of the on-shore zone is lower before early October, but it is slightly higher afterward and occurs later; (5) daily minimum air temperature of the on-shore zone is on average higher than that of the far-shore zone, especially after the mid-September, and it also appears later in autumn than in summer.

1 Introduction

Located in the northeastern part of the Tibetan Plateau (TP), Qinghai Lake (QL) is the largest saltwater lake in the high plateau and China, and probably in any of the world high plateaus, with an average lake level altitude 3200 m. Currently, it has a surface area of 4450 km^2, an average depth of 21 m, a maximum depth of 33 m, and a volume of 1050 × 10^9 m^3. The QL basin is surrounded by mountains, with the Datong Mountains in the north, the Riyue Mountains in the east, the Qinghai South Mountains in the south, and the Amuniniku Mountains in the west (Editorial Board of Ecological Environment Protection and Restoration in Qinghai Lake Basin 2008). The terrain within the lake basin is varied, and there are obvious spatial differences in vegetation cover. The major types of vegetation include temperate coniferous forests, plateau and valley shrubs, alpine shrubs, sand shrubs, temperate grasslands, alpine grasslands, alpine meadows, swamp meadows, and alpine rocky slope vegetation (Chen and Peng 1993).

The QL and its surrounding regions have a temperate, semi-arid plateau climate, with a cold winter, warm summer, and meager precipitation. The surface area of the QL is in a

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medium size in view of the global lakes (Crosman and Horel 2010), but the largest in China and East Asia, producing a benefiting condition for a lake climate effect. The vast lake water surface should particularly affect the air temperature of surrounding regions during the warm season, a phenomenon which is worth investigation. The climatic effects of the major lakes of the world have already been extensively explored, especially with regard to North America's Great Lakes (Scott and Huff 1997; Kunkel et al. 1998; Ackerman et al. 2013; Lofgren et al. 2011). There have also been many investigations into the Caspian Sea and Aral Sea of Central Asia (Small et al. 2001; Tursun and Kasim 2002; Guo et al. 2011; Chen et al. 2012), including observational research and numerical simulation analysis. These researches have found that inland lakes with large surface areas have an observable regulatory effect on the climate of the surrounding regions (Scott and Huff 1996; Vincent and Mekis 2006). They decrease spring and summer temperatures, increase autumn and winter temperatures, and buffer the diurnal and seasonal temperature variations. A reduction in diurnal temperature range, for example, is especially conspicuous from April to August in the Great Lakes Region (Eichenlaub 1979; Bates et al. 1993; Angel and Isard 1998). At the same time, lakes also increase precipitation on their windward shores during autumn and winter, especially snowfall (Niziol 1987; Chang and Braham 1991; Kristovich 2009; Barthold and Kristovich 2011).

In recent years, a few groups have used numerical simulation methods to study the lake-land breeze phenomenon. Among these are relatively early research that used lake-land breeze numerical models on the Great Lakes (Moroz 1967; Alpert and Neumann 1983; Ballentine 1982; Maddukuri 1982) and the recent research focused on major lakes in mainland China (e.g. Chen et al. 1994; Lv et al. 2008; You et al. 2016a). Research on the QL lake effect has been concentrated on the characteristics of local circulation and the atmospheric boundary layer, the lake-land breeze, and local precipitation processes (Chen et al. 1995; Lv et al. 2007; Liu et al. 2013; Tang et al. 2016). Existing researches on the climatic effects of lakes using actual meteorological observation data in the Dianshan Lake, Taihu Lake and the Poyang Lake have yielded a few results (Zhang and Wu 1988; Peng et al. 2010; Yang et al. 2013; Cao et al. 2015), but no observational research on the QL climatic effects is referable.

The domestic researches generally reported the similar influence of large inland lakes on nearby surface climate with those shown in other countries, with a cooling effect during summer or warm seasons, and warming effect during the winter or cold seasons. However, the investigations into the Boyang Lake and Taihu Lake in the mid- to lower reaches of the Yangtze River exhibited a different lake effect during summer, in spite of the fact that they did consistently showed a warming effect during winter season (Lin 1985; Lu and Wei 1990; Wang and Fu 1991; Wang 1993; Wan et al. 1994; Ren et al. 2017). The reasons for the difference may result from the datasets and models use, and also may be related to the significant decline of solar radiation in the areas during summer (Ren et al. 2005).

The QL is an exceptionally high-altitude saltwater lake situated in inland mid-latitude. On the one hand, the water surface area of the Qinghai Lake is much larger than other lakes in China, its average depth of water reaches more than two times of other inland lakes in the country, and thus, it may exert a larger effect on the surrounding climates; on the other hand, the westerly circulation above the lake is strong and there is a higher background wind speed in the QH lake region during warm season, which may weaken the climatic effect of the lake in some extent. However, the current research is significantly lacking on the climatic effects of the QH Lake under the influence of various factors, and the level of scientific knowledge on this topic is quite low.

Due to the complexity and diversity of the QL basin surfaces and the relatively big differences in the climatic conditions and climate change of different terrains (Qi and Guo 2007; Li et al. 2008; Chen et al. 2011; You et al. 2016b), the use of modeling techniques alone is somewhat limited and may lead to significant uncertainty. An investigation of temporal and spatial pattern of the climatic effect of the mid-latitude inland plateau lake using observational data of surface meteorological stations is badly needed.

This article utilizes hourly observation data from 17 automatic weather stations around the QL for 6-year observations from 2009 to 2014 to analyze the effects of the lake on the average seasonal and diurnal temperature variations during the warm season. Our analysis overcomes the problems of observational data insufficiency and the poor representativeness of the data in previous investigations, and the reliability of the analysis would be higher. The results would help in deepening our understanding of climatic effects of the huge plateau lake and could also provide scientific information for the future implementation of ecological protection measures in the lake basin.

2 Data and methods

2.1 Data

Data on hourly air temperatures, including hourly mean temperature, maximum and minimum air temperature, and the near-surface wind direction were collected from 17 Automatic Weather Stations (AWS) around the QL from 2009 to 2014. The data have been quality controlled in the Information Center of Qinghai Met Bureau. The locations of the AWSs are displayed in Fig. 1.

The satellite land surface temperature data of MYD11A2 from 2009 to 2014 is provided by the US NASA Data Center (https://earthdata.nasa.gov/search?q=MYD11A2), and the dataset used in this study have been adjusted for cloud effect

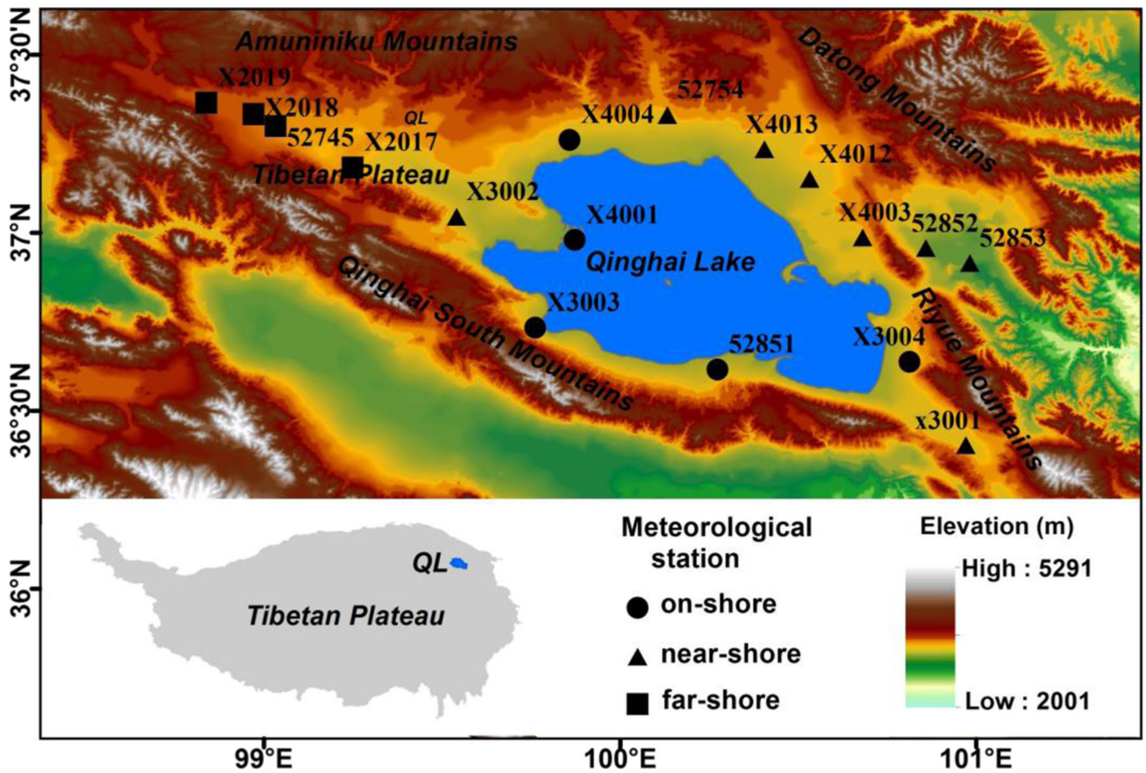

Fig. 1 Distribution of different categories of meteorological stations surrounding the Qinghai Lake (QL)

(Wan et al. 2015). The spatial resolution is 1 km × 1 km, and the time resolution is 8d. The EOS/MODIS Aqua satellite has two transit times per day above the QL, with one around 2:00 am Beijing time, representing the night land surface temperature, and the other around 13:00 pm Beijing time, representing the land surface temperature during the day. The average land surface temperature of the QL and its surrounding areas was calculated according to the arithmetic mean of two temperature observations during the daytime and nighttime.

The satellite NDVI data come from the MOD13Q1 product, available on the NASA website (http://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod13q1) in the United States, and its spatial resolution is 250 m × 250 m, and the time resolution is 16d.

The data of beginning to freeze and complete ablation in the Qinghai Lake come from the MOD09GQ product on the NASALPDA, and its spatial resolution is 250 m × 250 m and the time resolution is 1d.

2.2 Methods

Based on the linear distance from the shoreline, the meteorological stations were divided into three categories: those within 10 km were defined as representing the lakeside or on-shore zone, those within 10–30 km the near-shore zone, and those within 30–105 km the far-shore zone (Table 1). Using the meteorological stations in the far-shore zone as reference sites, the temperature difference between the on-shore and near-shore zones and the reference sites were calculated to indicate the climatic effect of the lake. Table 1 also shows that the average latitude of each of the weather stations in the on-shore, near-shore, and far-shore zones is 36.85°, 37.01°, and 37.29°, respectively, and their average altitudes are 3234 m, 3223 m, and 3408 m respectively. The surface air temperature difference caused by latitudinal and altitude factors would be not large and thus, the method would be effective for analyzing the effects of the lake on the surface air temperature.

The threshold method has been used to determine the beginning and ending dates of lake water freezing and ablating. This method is able to directly distinguish ice and water by using different characteristics of reflectivity and surface temperature (Wei and Ye 2010). Freezing and ablating time was based on the records of 2009–2014. The average dates for the QL to start freezing and to completely freeze over was calculated. It was thus determined that 10th of December to 13th of April of the following year is the climatologically freezing period or cold season, while 14th of April to 9th of December is the climatologically thawing season or warm season.

The 5-day average temperature was calculated starting from the 21st 5-day interval (11–15th of April) and ending on the 68th 5-day interval (6–10th of December), and this way, the averages of every 5 (or 6) days within a month of warm season were obtained.

The temperature is monitored every minute. The hourly mean temperature is the average of the past 60 min. The daily

Table 1 Information of the weather stations used in the study

Zone	Station #	Longitude	Latitude	Altitude	NDVI value	Distance from lake shore (km)
On-shore zone	X4001	99.87°	36.98°	3201 m	–	0.00
	X3003	99.76°	36.73°	3205 m	0.71	1.65
	52851	100.27°	36.62°	3241 m	0.67	2.20
	X4004	99.86°	37.26°	3229 m	0.59	4.18
	X3004	100.81°	36.64°	3296 m	0.62	7.48
	Average		36.85	3234 m	0.65	3.10
Near-shore zone	X4013	100.41°	37.24°	3266 m	0.67	12.98
	X3002	99.54°	37.05°	3241 m	0.72	13.11
	52754	100.13°	37.33°	3302 m	0.59	14.08
	52853	100.98°	36.92°	3010 m	0.72	26.40
	X4003	100.68°	36.99°	3280 m	0.41	16.94
	X4012	100.53°	37.15°	3265 m	0.5	17.60
	52852	100.86°	36.96°	3140 m	0.76	18.50
	X3001	100.97°	36.40°	3283 m	0.62	29.34
	Average		36.99	3223 m	0.62	18.62
Far-shore zone	X2017	99.25°	37.18°	3335 m	0.59	55.00
	52745	99.03°	37.30°	3417 m	0.57	75.92
	X2018	98.97°	37.33°	3421 m	0.58	84.73
	X2019	98.84°	37.36°	3459 m	0.56	102.36
	Average		37.29	3408 m	0.58	79.50

maximum (minimum) temperature is the maximum (minimum) values of the minutely temperature in the past 1440 min (24 h × 60 min), which is utilized in analyzing the spatial pattern of daily maximum temperature, minimum temperature and diurnal temperature range (DTR) during warm period (Fig. 3), and also the intra-seasonal variation of pentad (5-day or 6-day) mean maximum and minimum temperature (Fig. 9). The daily maximum (minimum) hourly mean temperature is the maximum (minimum) values of hourly mean temperature over the past 24 h, which is used in describing the diurnal variation of temperature (Fig. 4). The average maximum (minimum) temperature in the warm season is the average of the daily maximum (minimum) temperatures derived from minutely temperature from April 14 to December 9, while the pentad maximum (minimum) temperature is the average of the daily maximum (minimum) temperatures derived from minutely temperature for every 5 days (or 6 days). Obviously, the average maximum (minimum) temperature for a given period of time as used in this paper is lower (higher) than the traditional maximum (minimum) value. For temporal variation within a day, Beijing time is used consistently; the time difference between Beijing time and the Qinghai Lake local time is about 1.2 h.

The EOS/MODIS NDVI values of each site are synthesized according to the MVC (maximum value composites) method in every month, and the maximum monthly NDVI value is defined as the annual value. The average annual NDVI value from 2009 to 2014 represents the vegetation cover.

3 Results and discussion

3.1 Spatial distribution of temperature

The spatial characteristics of the land surface temperature and the surface air temperature are shown in Fig. 2. During the warm season, the satellite surface temperature of the lake water is obviously higher than that of the surrounding land (Fig. 2a). The lake and land surface temperature has obvious diurnal variation, with the lake surface temperature lower than the surrounding land surface temperature in the daytime (Fig. 2b), but higher than the surrounding land surface temperature during the nighttime (Fig. 2c). The surface air temperature observed from the AWSs has the similar spatial variations, with the higher average air temperature in the warm season found in zone closer to the lake (Fig. 2d). The distribution of daytime and nighttime air temperatures is opposite. On-shore zone witnesses a lower average air temperature in the daytime (Fig. 2e), and a higher average air temperature in the nighttime (Fig. 2f). Similarly, the air temperature observed from the meteorological stations also shows that, the closer to the lake, the higher the average air temperature in the warm season (Fig. 2d). The distribution of daytime and nighttime air temperatures is opposite, with the sites closer to the lake recording a lower temperature in the daytime (Fig. 2e) and a higher temperature in the nighttime (Fig. 2f).

Comparing the observations by satellite and automatic stations, both show that the temperature is lower during the

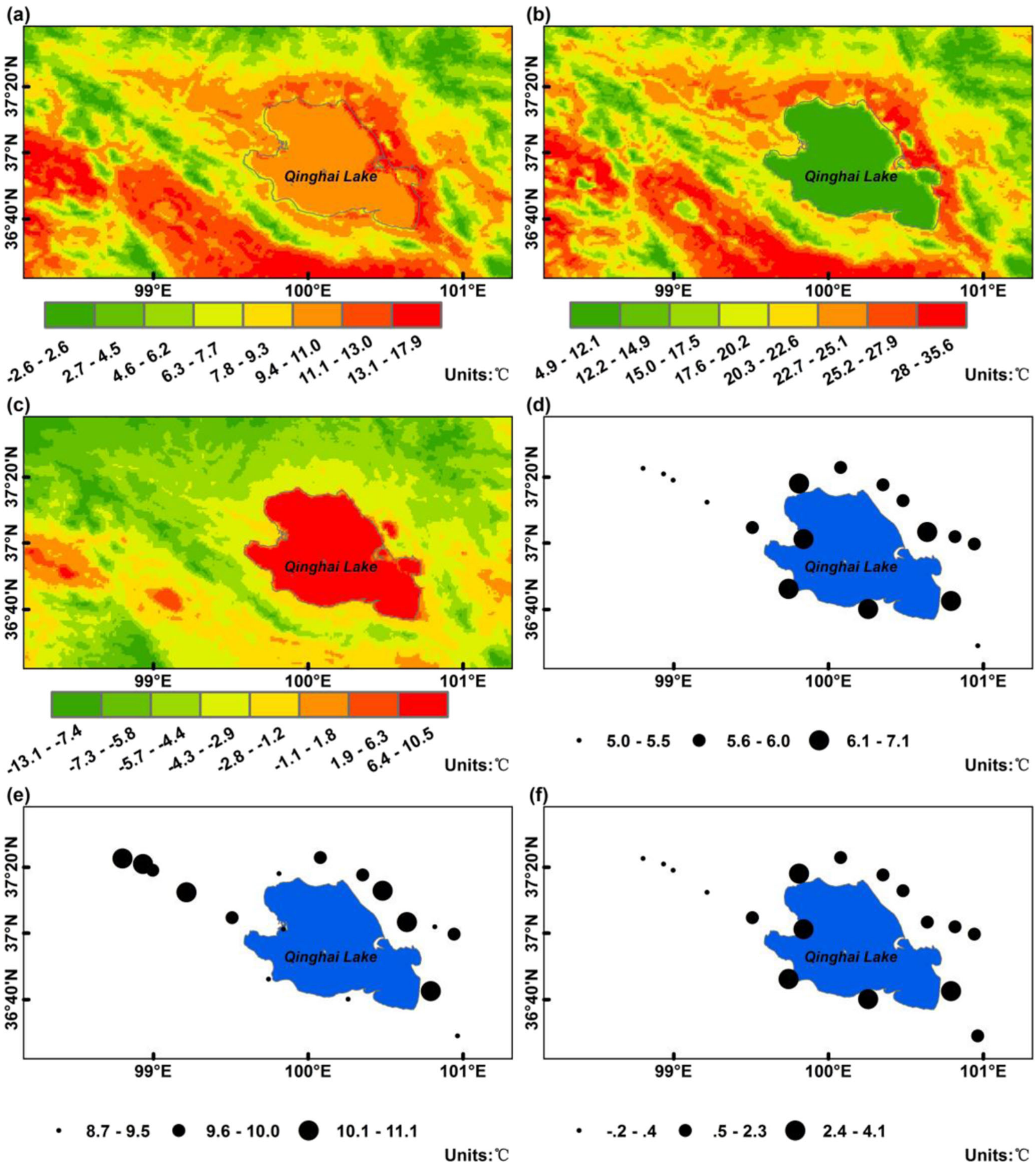

Fig. 2 Distribution of warm-season mean land surface temperature (**a**), daytime mean land surface temperature (**b**), and nighttime mean land surface temperature (**c**) based on satellite data from 2009 to 2014, and warm-season mean air temperature (**d**), daytime mean air temperature (**e**), and nighttime mean air temperature (**f**) based on data of meteorological stations from 2009 to 2014 (unit: °C)

daytime and higher at night near the lake. However, the former is land surface temperature and the latter is surface air temperature, a small difference exists between them, with the data of satellite higher than those of automatic stations. The average land surface temperature during daytime, nighttime and daily mean is 4.9~25.1 °C, 1.9~10.5 °C, and 7.8~17.9 °C respectively in the lake surface, and it is 12.2~35.6 °C, −13.1~6.3 °C, and −2.6~17.9 °C respectively in the surrounding land. The average air temperature in the daytime, nighttime and daily mean is 8.7~9.6 °C, 2.9~4.1 °C, and 6.3~6.7 °C respectively in the on-shore zone, but it is 9.5~11.16 °C, 1.3~2.3 °C, and 5.4~6.5 °C respectively in the near-shore zone, and 10.0~10.7 °C, −0.2~0.4 °C, and 5.0~5.5 °C in respectively the far-shore zone.

Our analysis was focused on surface air temperature as observed from the meteorological stations. It is interesting to note that the warm-season mean air temperature of the on-shore zone is relatively higher, ranging between 5.8 and 6.5 °C, and the mean temperature of the near-shore zone ranges between 5.0 and 5.7 °C. Probably due to the combined effects of the distance from the lake water and the vegetation coverage, the warm-season mean air temperature of the far-shore zone is the lowest, on average between 4.4 and 4.9 °C (Fig. 3a).

The on-shore zone is warmer than other costal zones in terms of warm-season average temperature (Table 2), though the average maximum air temperature in this zone is still lower, and this is unexpected because the phenomenon is opposite those found for the lakes of low-elevation regions during the summer season. The research results on large deep-water lakes of low-altitude areas show that the lakes in the summer have a cold effect along the coastal zone (e.g., Scott and Huff 1997; Small et al. 2001). The larger the area and the deeper the lake water, the more obvious the cooling effect of summertime (e.g., Lu and Wei 1990; Wang 1993; Scott and Huff 1996).

The difference from the previous studies, as shown in this study, cannot be explained by the definition of the warm season (14th of April to 9th of December) used in this analysis, which includes a few months out of the climatologically defined summer (JJA), because the phenomenon of higher air temperature near the lake also appears in summer or even in mid-summer (Fig. 8). It might not have been caused by the difference of the observational elevations either because there is very similar average elevations of the stations between the on-shore zone and the near-shore zone, with the former even 11 m higher than the latter (3234 m:3223 m) (Tables 1 and 2).

The influence of the lake water might have been the best explanation for the difference of the temperature between the different coastal zones. It is plausible that the huge plateau lake is exerting a unique influence on the surface air

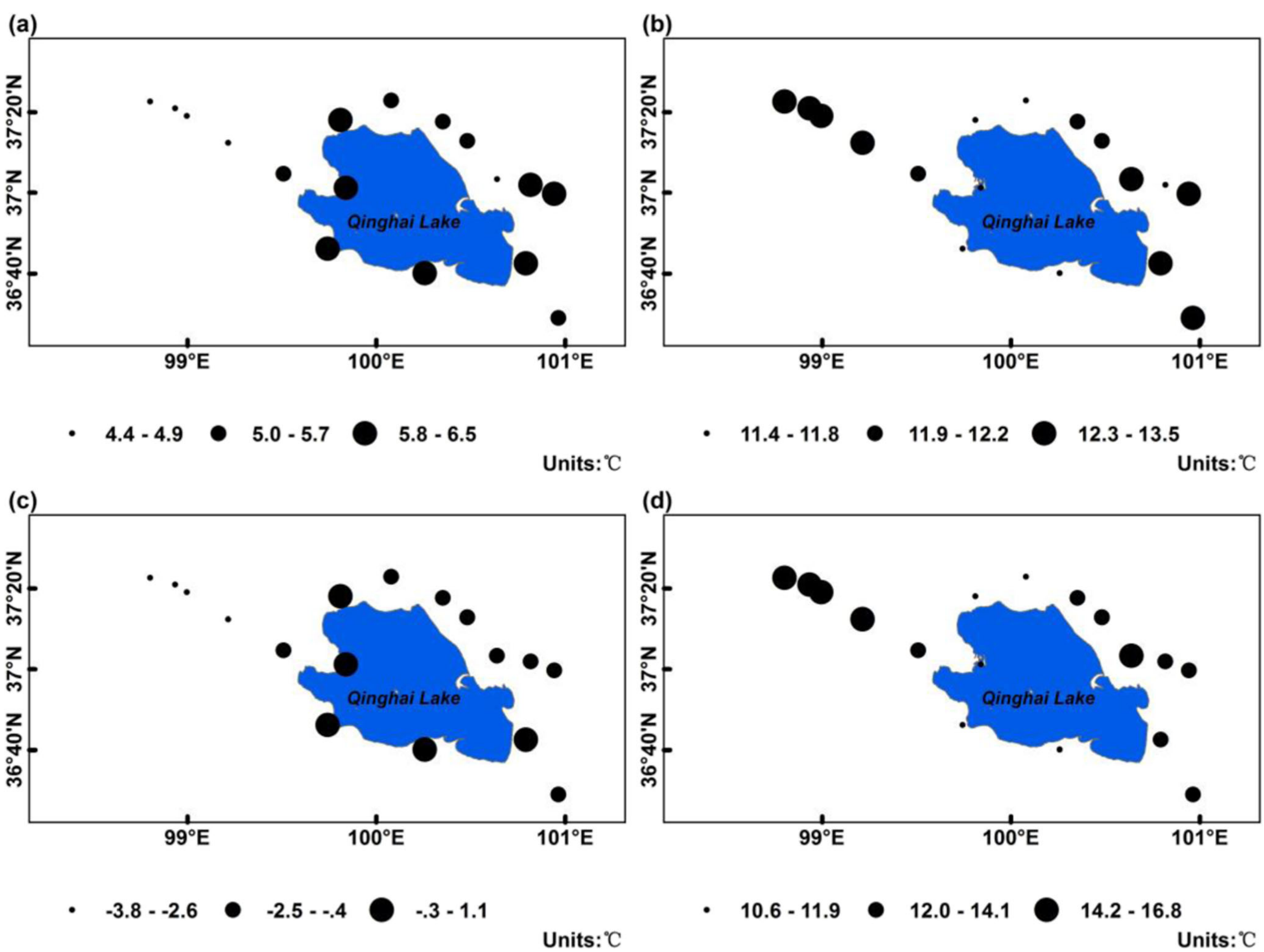

Fig. 3 Distribution of warm-season mean air temperature (**a**), mean maximum air temperature (**b**), mean minimum air temperature (**c**), and the mean diurnal temperature range (DTR) (**d**),based on observational data of meteorological stations from 2009 to 2014 in the Qinghai Lake region (unit: °C)

Table 2 Average geographical and climatic parameters for the on-shore zone, near-shore zone, and far-shore zone of the Qinghai Lake during warm season

Zone	Altitude	Latitude	Longitude	Average temperature in warm season	Average maximum temperature in warm season	Average minimum temperature in warm season	NDVI value
On-shore zone	3234 m	36.85°	100.11°	6.21 °C	11.9 °C	0.74 °C	0.67
Near-shore zone	3223 m	37.01°	100.51°	5.51 °C	12.4 °C	− 1.20 °C	0.62
Far-shore zone	3408 m	37.29°	99.02°	4.85 °C	12.3 °C	− 2.54 °C	0.58

temperature of the costal land areas due to the colder atmosphere and stronger wind of the near-surface layer which is effectively chilling the inland surface air, especially during daytime when the stronger turbulent flow in boundary layer cause a larger downward transfer of momentum and a stronger near-surface wind.

It is also possible that, in the high plateau region, the lake water is with higher salinity, and its specific heat capacity is smaller than that of fresh water, absorbing more heat during the daytime and the temperature increases faster. Though the lake is located in the low temperature area, the lake water temperature is not too lower than surrounding land during the daytime. At night, the infrared radiation emitted into the atmosphere from the surface is strong due to the thinner atmospheric layer and less water vapor, and the air temperature in the on-shore zone is obviously higher, causing the daily and season mean temperature to be obviously higher than that of the near-shore and far-shore zones.

Certainly, the causes of the higher average air temperature in on-shore zone than that in the other costal zones need to be further investigated in the future.

From the warm-season mean maximum and minimum temperatures of each weather station, it can be seen that, the closer to the shore, the lower the mean maximum temperature (Fig. 3b) and the higher the mean minimum temperature (Fig. 3c). The effects cause the DTR of the on-shore zone to be the lowest, about 10.6 to 11.9 °C. The mean DTR of the near-shore zone is about 12.0 to 14.5 °C, and the largest mean DTR of 14.6 to 16.8 °C occurs in the far-shore zone (Fig. 3d). Therefore, the warming effect of the lake in the on-shore zone seems to dominantly occur during nighttime, and the daytime sees a similarly cooling effect of lake to those found in other regions.

3.2 Diurnal temperature variation

Figure 4 shows diurnal air temperature variation of warm season for the three zone averages and the individual sites of the zones in the QL region. The QL has a clear effect on the surface air temperatures of the nearby observational sites. The closer the sites are to the shoreline, the higher the nighttime hourly mean temperature, the lower the afternoon hourly mean temperature, and the smaller the diurnal temperature variation. These are typical diurnal characteristics resulting from the general lake effect. However, it is also clear that the hourly mean temperature of the on-shore zone at nighttime is much higher than that of the near-shore zone and far-shore zone, and the daytime mean temperature differences among the zones is very small, indicating that the warmer warm-season climate near the shoreline dominantly results from the obviously higher nighttime temperature. Although the lake does somehow cool the on-shore zone during daytime, the cooling effect is rather weaker than those found surrounding the large likes of other regions.

Lakes have a greater heat capacity, and the diurnal temperature variation at the surface of the lake and in locations nearby is generally smaller. During the daytime, especially in the afternoon, the on-shore site temperature rises more slowly and the maximum temperature is lower, and in the evening the temperature drops more slowly and the minimum temperature is higher, causing diurnal temperature range to be noticeably smaller than that of the far-shore zone. The day-to-night conversion of lake-land wind circulation is likely also one of the direct causes of the smaller diurnal temperature fluctuations in the on-shore and near-shore zones.

Taking July as an example, we calculated the average hourly wind direction frequency and drawn the monthly mean wind rose diagram for the period 2009–2014. The meteorological stations 52754, 52851, 52852, and X4001 are located respectively in the north, south, east, and west sides of the QL. Figures 5 and 6 show the distribution of wind direction frequency at different time of a day at stations 52754 (north) and 52851 (south). The wind direction in the north and south shores of the lake had obvious changes, which was the manifestation of the lake-land breeze. At station 52754, the north wind is dominant at nighttime, which is land breeze from the land southward to the lake, and the south wind is dominant during daytime, which is the lake breeze from the lake northward to the land. Similarly, there are also wind direction shifts at stations 52853 and X4001, and the lake-land breeze is obviously notable. It can also be found that the land breeze during nighttime is more obvious than the lake breeze during daytime. Take station 52754 (north) as an example, the northerly wind (land breeze) is dominant, and the maximum wind direction frequency is 37.8%; meanwhile, the frequency of other wind directions is very low at night; while during the

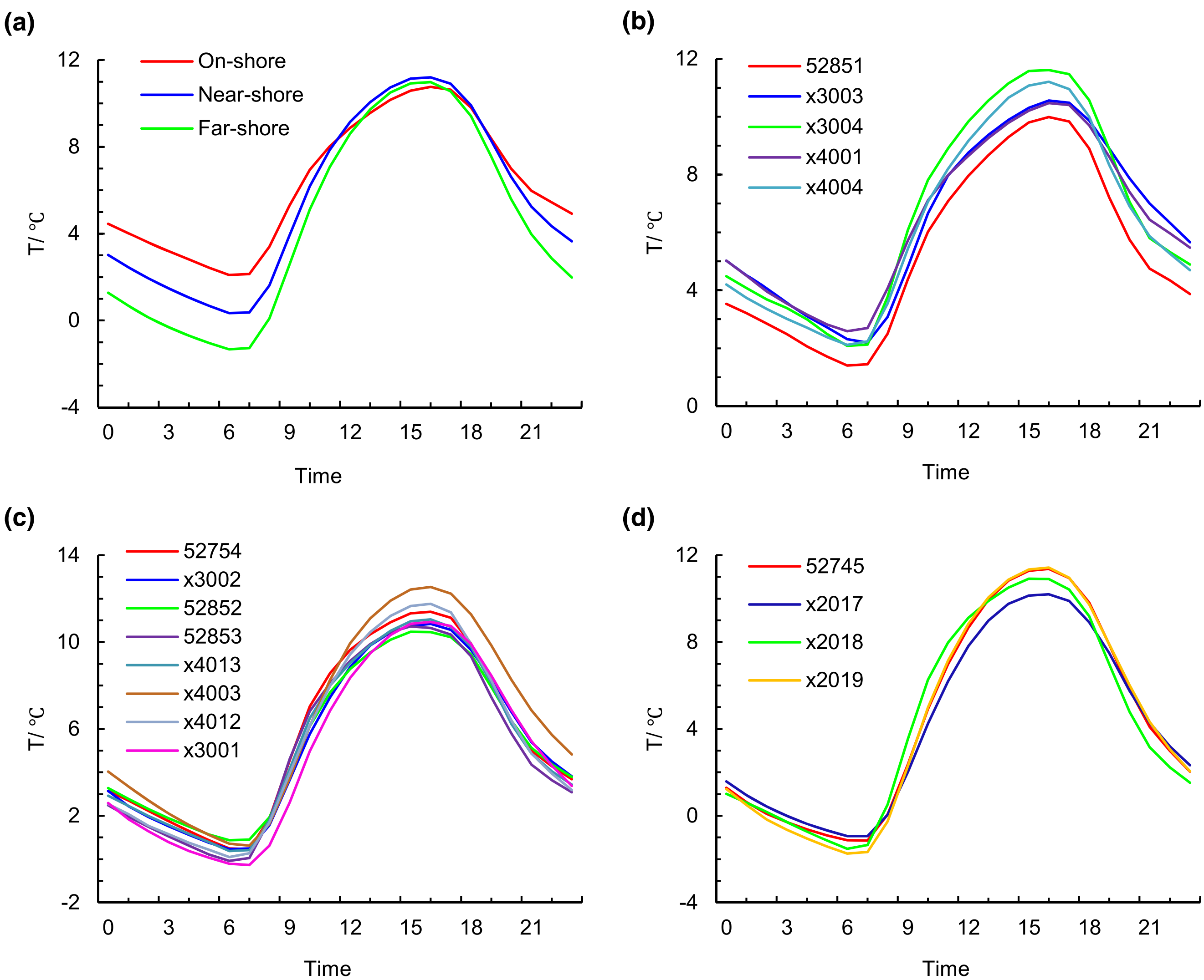

Fig. 4 Average warm-season diurnal temperature variation for the on-shore, near-shore, and far-shore zones (**a**), and individual stations of the on-shore (**b**), near-shore (**c**), and far-shore zones (**d**), in the Qinghai Lake region

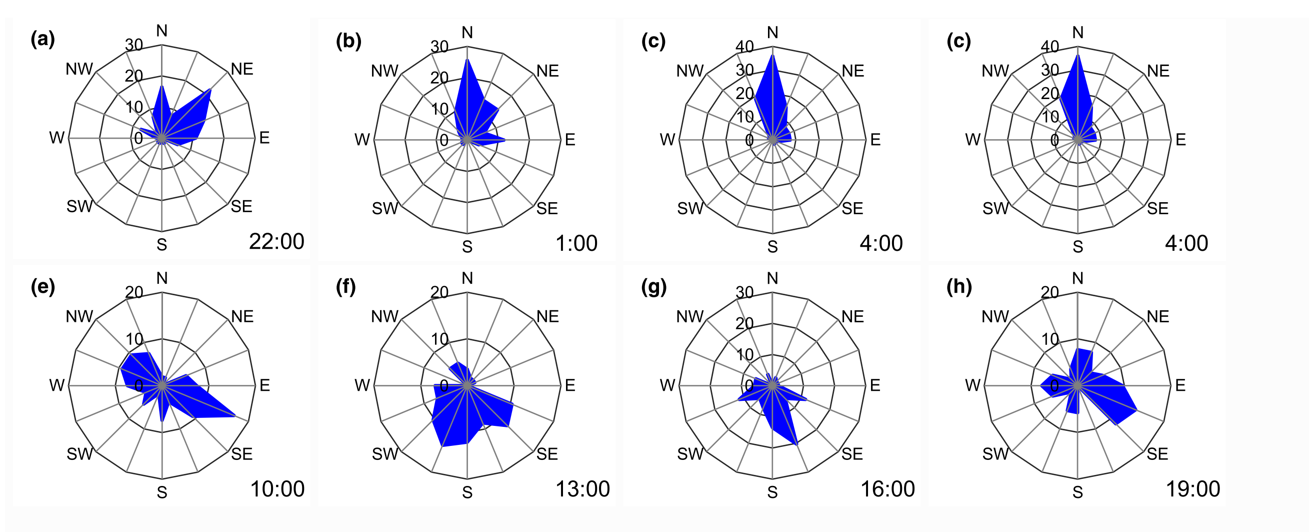

Fig. 5 The distribution of mean near-surface wind direction frequency at different time (Beijing time) in July from 2009 to 2014 at station 52754 (unit: %)

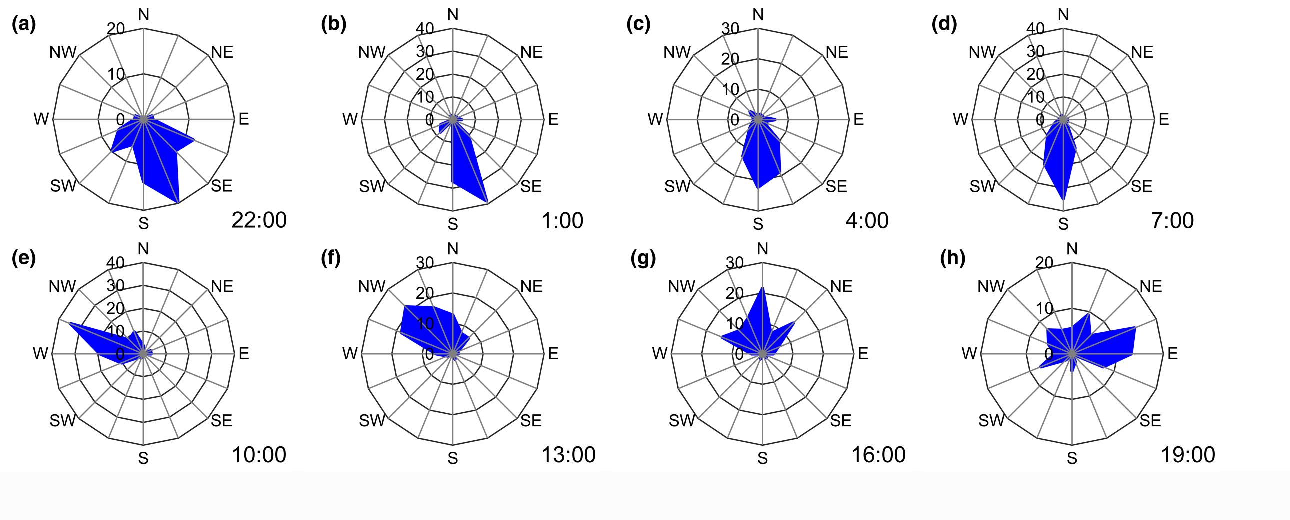

Fig. 6 The distribution of mean near-surface wind direction frequency at different time (Beijing time) in July from 2009 to 2014 at station 52851 (unit: %)

daytime, although the southerly wind (lake breeze) is dominant, the maximum wind frequency is only 20.3%, and the frequency of other wind directions is relatively higher.

This may be because the mid-tropospheric high-speed westerly currents are closer to the surface on the plateau, and the near-surface wind speed would be much larger, leading to a generally non-benefiting background circulation field for the formation and development of the daytime lake breeze due to the downward transfer of momentum by the turbulence. At nighttime, however, the stronger surface cooling due to the upward long-wave radiation from the surface results in the formation of a temperature inversion layer, which may have effectively prevented the upper westerly momentum from downward transportation, and thus benefited the development of the land breeze within a thin boundary layer. This suggested mechanism could be further investigated in further research by using a numerical model.

In zones with varying distances from the lake shoreline, diurnal temperature variations display different characteristics for specific sites. Temperature variations at the sites of the on-shore zone are mostly slower and smaller. The smallest hourly mean DTR among all the weather stations of the zone is 7.9 °C, while the greatest DTR is 9.5 °C. In analyzing the diurnal temperature fluctuations in all of the weather stations of the on-shore zone, it is evident that the lake exerts a clear effect on diurnal temperature variations. Located from the nearest to the furthest distance from the lake shoreline, the hourly mean DTR of the 5 on-shore zone weather stations X4001, X3003, 52851, X4004, and X3004 are 7.9 °C, 8.4 °C, 8.6 °C, 9.1 °C, and 9.5 °C respectively (Fig. 4b).

The smallest diurnal fluctuation in temperature among all the weather stations of the near-shore zone is 9.6 °C, while the greatest is 11.9 °C. Located from the nearest to the furthest distance from the lake shoreline, the near-shore zone weather stations X4013, X3002, X4012, 52754, X4003, 52852, 52853, and X3001 register the DTR values of 10.7 °C, 10.4 °C, 11.7 °C, 10.9 °C, 11.9 °C, 9.6 °C, 10.8 °C, and 11.2 °C respectively. It is possible that, apart from the lake effect, the state of vegetation cover at the sites also had an effect on the temperature of the near-shore zone. NDVI can represent vegetation cover, and the high NDVI value indicates high vegetation coverage. At stations 52852 and 52853, which had a relatively high NDVI values (0.76 and 0.72 respectively), witness smaller DTR, whereas station X4003, which was relatively lacking in vegetation cover (NDVI value was 0.41), had a larger DTR (Fig. 4c). However, the possible influences from vegetation around the stations need to be investigated in the future.

The far-shore zone (Fig.4d) is mostly distributed to the northwest of the QL; it is in the alluvial plains between the Qinghai South Mountains and the Amuniniku Mountains. Located from nearest to furthest distance from the shoreline, the meteorological stations X2017, 52745, X2018, and X2019 have DTRs of 11.1 °C, 12.5 °C, 12.4 °C, and 13.2 °C respectively. It can be seen that the diurnal temperature variations was large in the far-shore than that in the on-shore and near-shore areas, and the regulating effect of water on air temperature is obviously weakened with distance from the shoreline.

Figure 7 shows the relationship of warm-season mean maximum temperature, minimum temperature and diurnal temperature range of all the stations with the straight-line distances of the AWSs from the shoreline. It can be seen that, within 30 km (i.e., within the on-shore and near-shore zones), the lake had a clear effect on the mean maximum and minimum temperatures. The maximum temperature and DTR sharply increase and the minimum temperature rapidly decrease with the distance from the shoreline in the two zones. In the far-shore zone, which is approximately 50 km or more from the shoreline, however, the lake effect is not as conspicuous. The fluctuations in diurnal temperature are more subject to the lake

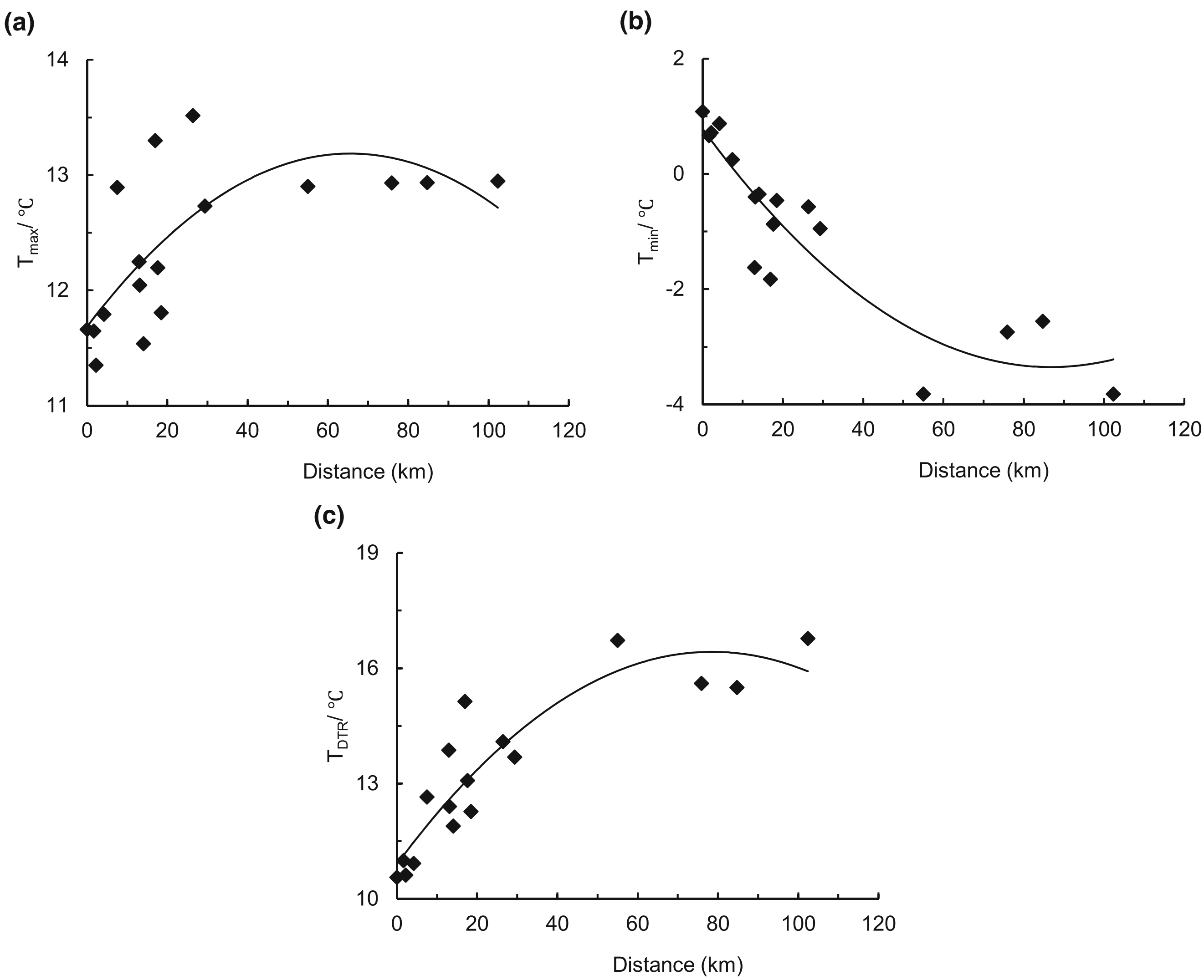

Fig. 7 The relationship between mean maximum temperature (**a**), mean minimum temperature (**b**), and mean diurnal temperature range (**c**) of the observational stations and their straight-line distance from the shoreline in the warm season

effect within about 50 km of the shoreline, while the lake effect on DTR is inconspicuous for most sites of the far-shore zone.

Table 3 shows that, when the daily average maximum and minimum temperatures and diurnal temperature range are fitted to a curve, they form a half-parabola pattern. The fitted equation passes the test with a significance level of 0.01. It is thus evident that, within a certain distance, the lake exerts a significant effect on the maximum and minimum temperatures, and the DTR, but after exceeding a certain distance, the lake effect gradually disappears.

3.3 Intra-seasonal temperature variation

For the on-shore, near-shore and far-shore zones, the intra-seasonal cycles of the 5-day average temperatures all represent a single-peak variation type, with the maximum value occurring at the 42nd 5-day interval (26th–31st of July) and the

Table 3 Fitted equations for the daily mean maximum temperature, minimum temperature, and diurnal temperature range versus distance from the lake shoreline

Meteorological element	Fitted curve	R^2	Significance level
Maximum temperature	$Y = -0.000\ X^2 + 0.046\ X + 11.686$	0.492	**
Minimum temperature	$y = 0.001\ X^2 – 0.095\ X + 0.784$	0.827	**
DTR	$y = -0.001\ X^2 + 0.141\ X + 10.897$	0.822	**

Y represents the temperature and *X* represents the distance from the lake shoreline. Double asterisk represents passing the test of 0.01 significance level minimum value at the 68th 5-day interval (6th–10th of December) (Fig. 8). During the warm season, the 5-day average temperature ranges (maximum–minimum) for the on-shore, near-shore, and far-shore zones are respectively 19.7 °C, 22.1 °C, and 22.9 °C. From Fig. 7a, it can be seen that the difference of the 5-day average temperatures of the on-shore and near-shore zones from the far-shore zone are all positive, indicating that, compared to the far-shore zone, the average temperatures of the on-shore and near-shore zones are always higher during the warm season. The temperature difference between the on-shore zone and far-shore zone slowly rises from the 36th 5-day interval (26th–30th of June) to the 52nd 5-day interval (16th–20th of September), but only by about 1.0 °C. From the 53rd 5-day interval (21th–25th of September), however, the difference rises rapidly peaking at around 4.0 °C near the end of the warm season. The temperature decrease for the on-shore zone is therefore particularly slow after mid-September when it is clearly subject to the

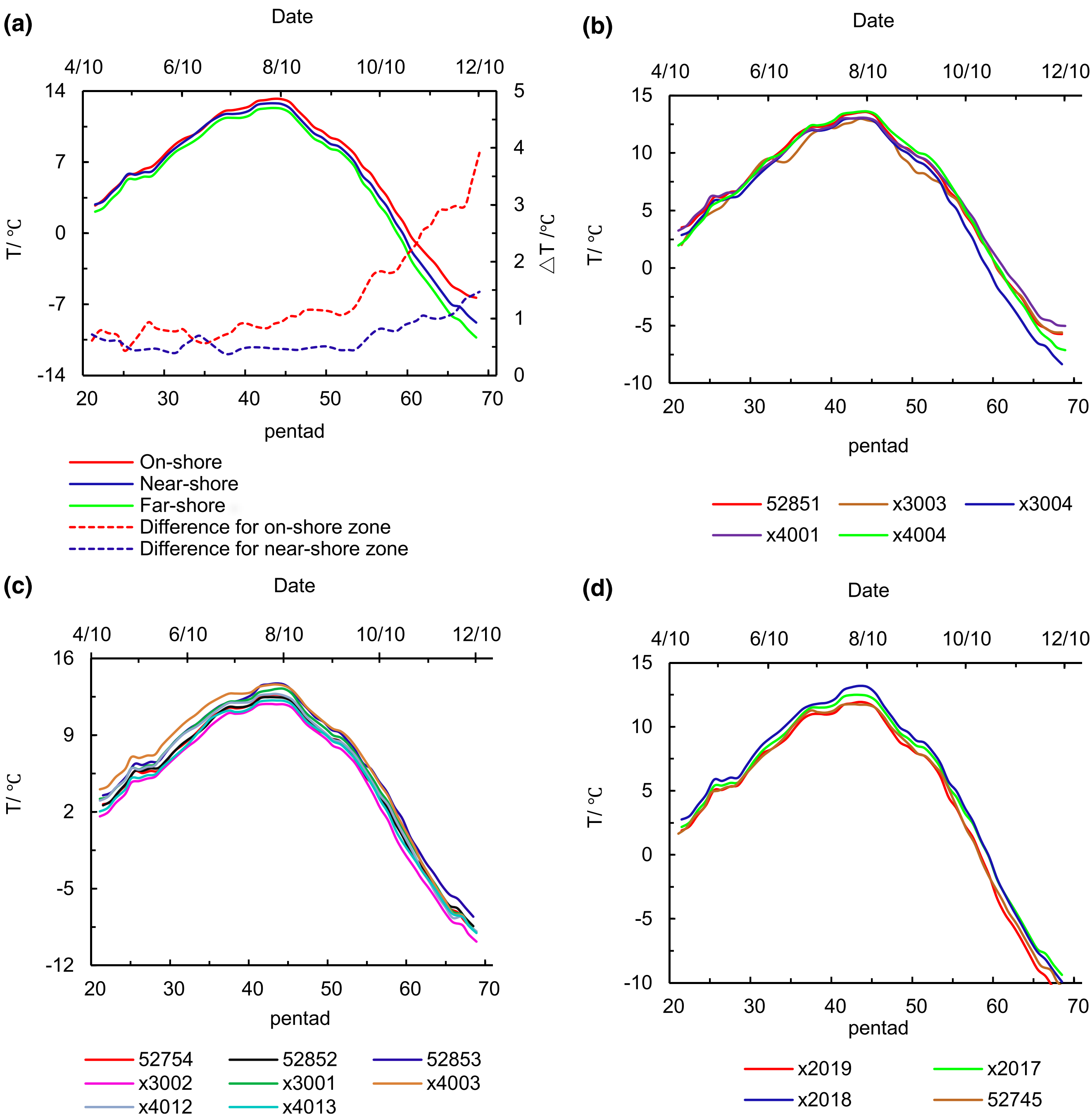

Fig. 8 Five-day average temperatures for different zones and the differences of 5-day average temperature of the on-shore zone and near-shore zone from the far-shore zone (**a**), and the 5-day average temperature variations for individual stations for the on-shore zone (**b**), near-shore zone (**c**), and far-shore zone (**d**)

buffering effects of the lake water, whereas the regulatory effect of the lake on the near-shore zone starts to become prominent beginning in mid-October.

It is obvious that the 5-day average temperature for the on-shore zone always remains at a relatively higher value than that of the near-shore or far-shore zones during the warm season, a result well consistent with the abovementioned seasonal mean temperature spatial pattern (Fig. 3 and Table 2). The temperature difference of the on-shore zone from the far-shore zone is especially large after the late September, with the largest difference found in the end of the warm season (Fig. 8a), indicating that the most remarkable lake effect occurs in late autumn and early winter. The larger lake effect may be because the deep lake usually stores heat in summer and releases it in autumn and winter. It is also likely that the development of inversion layer and the more frequent calm weathers at night in the transitional season benefit the lake-land surface air temperature contrast.

As observed with the diurnal temperature change, the closer the site of the on-shore zone is to the lake, the smaller the fluctuations in the 5-day average temperature will be. For example, the closest station to the lake shoreline(X4001) had a 5-day average temperature range of 18.3 °C during the warm season, while the station furthest from the lake shoreline in the on-shore zone(X3004) has a 5-day average temperature range of 21.6 °C (Fig. 8b).

In the near-shore zone, apart from being subject to the lake effect, vegetation cover likely has an additional influence on seasonal temperature variations. The temperature rise is inhibited by the vegetation transpiration and soil evaporation during daytime. The soil moisture can also reduce the decreasing rate of air temperature during nighttime. These can all result in a reduced diurnal air temperature variation. For example, although the station nearest to the lake shoreline (X4013) has a moderate NDVI value of 0.67, the 5-day average temperature range is relatively small at 21.6 °C because it is relatively close to the lake. Station 52852 has a high NDVI value of 0.76, and it has the smallest 5-day average temperature range at 21.3 °C (Fig. 8c).

For the far-shore sites, the 5-day average temperature ranges (maximum–minimum) at stations X2017, 52745, X2018, and X2019 are 22.3 °C, 22.6 °C, 23.3 °C, and 23.4 °C respectively. It can be seen that, compared to the on-shore and the near-shore area, the 5-day average temperature ranges at the far-shore stations increase greatly with the disappearance of the lake regulation (Fig. 8d).

Figure 9 shows the average 5-day maximum temperatures of various zones and the differences of the on-shore and near-shore zones from the far-shore zone (Fig. 9a), along with the diurnal time (Beijing time, h) when the average 5-day maximum temperature occurs and the differences of the occurrence time of the on-shore and near-shore zones from the far-shore zone (Fig. 9b). The intra-season 5-day average maximum temperature ranges in the on-shore, near-shore, and far-shore zones are 20.3 °C, 21.7 °C, and 22.6 °C respectively. Compared to the sites far away from the lake shoreline, the 5-day average maximum temperature of the on-shore zone is always smaller than that of the other zones before early October. After early October, the 5-day average maximum temperature in the on-shore zone is slightly higher than that

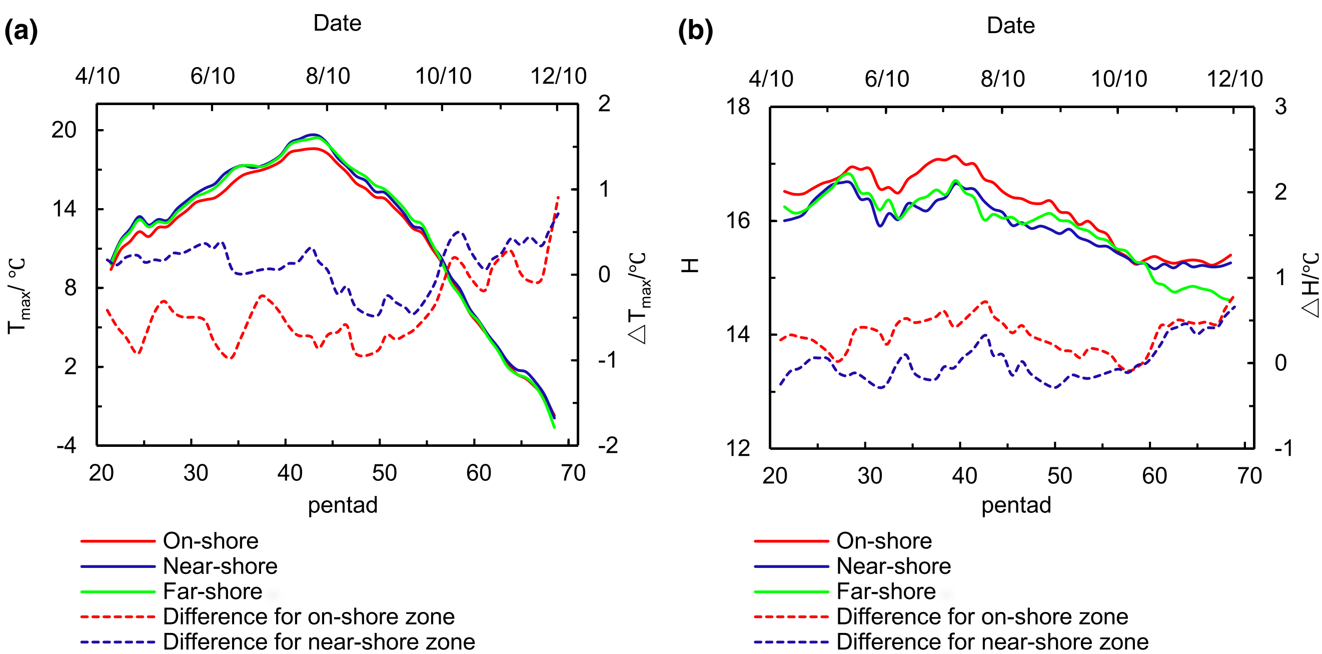

Fig. 9 Five-day average maximum temperatures for different zones and the differences of 5-day average maximum temperature of the on-shore zone and near-shore zone from the far-shore zone (**a**), and the diurnal time at which the 5-day average maximum temperature occurs (Beijing time) and the difference of the occurrence time of the on-shore zone and near-shore zone from the far-shore zone (**b**)

of the far-shore district and the 5-day average maximum temperature of the near-shore zone is almost the same with that of the far-shore zone.

As the lake water can absorb a great deal of solar radiation heat between April and September, the daily maximum temperature of the on-shore zone rises relatively more slowly than that of the other zones due to the lower lake surface temperature and the warmer inland surface, and the 5-day average maximum temperature is correspondingly lower. By early October, the inland surface temperature has begun to drop, but the lake water still keeps warmer, and the on-shore maximum temperature is relatively higher due to the lake effect. The maximum temperature of the on-shore zone drops relatively more slowly as well (Fig. 9a).

Compared to the far-shore zone, the daily maximum temperature occurs relatively later in the on-shore zone, particularly from late May to late August and also after the beginning of October, with the delayed occurrence time of about 1 h. The occurrence time of the daily maximum temperature for the near-shore zone is also generally later than that of the far-shore zone, but the difference is very small (Fig. 9b). Due to the regulatory effect the lake on the nearby air temperature, the occurrence time of the daily maximum temperature for the lake surface and the on-shore zone is obviously delayed during summer and autumn, displaying a typical feature of lake and oceanic climate.

The 5-day average minimum temperature ranges of the warm season for the on-shore, near-shore, and far-shore zones are 23.3 °C, 25.6 °C, and 26.7 °C respectively. Figure 10a shows that the 5-day average minimum temperature for the on-shore and near-shore zones is generally higher than that of the far-shore zone. Starting from the middle of September, the minimum temperature for the on-shore zone is clearly higher than that of the far-shore zone, while the near-shore zone sees a narrowing difference from the far-shore zone probably due to the effects of other factors like vegetation withering. Compared to the far-shore zone, the occurrence time of the daily minimum temperature is a little later for the on-shore and near-shore zones, but the delay is smaller than that of the daily maximum temperature, especially for the period before September (Fig. 10b). After September, the difference of the occurrence time of the minimum air temperature becomes larger, probably because of the increased surface thermal contrast between the lake and the inland area.

4 Conclusions

Using the satellite data of land surface temperature and vegetation coverage and the hourly observation data from meteorological stations situated around the Qinghai Lake, the spatial contrast of land surface temperature in Qinghai Lake and its surrounding and the seasonal and diurnal variations in air temperature of the coastal zones during warm season were analyzed. The following conclusions were drawn:

1. During the warm season, lake water surface temperature derived from remote sensing was lower than that in the surrounding land areas in the daytime, while it was obviously higher than that in the surrounding land areas at

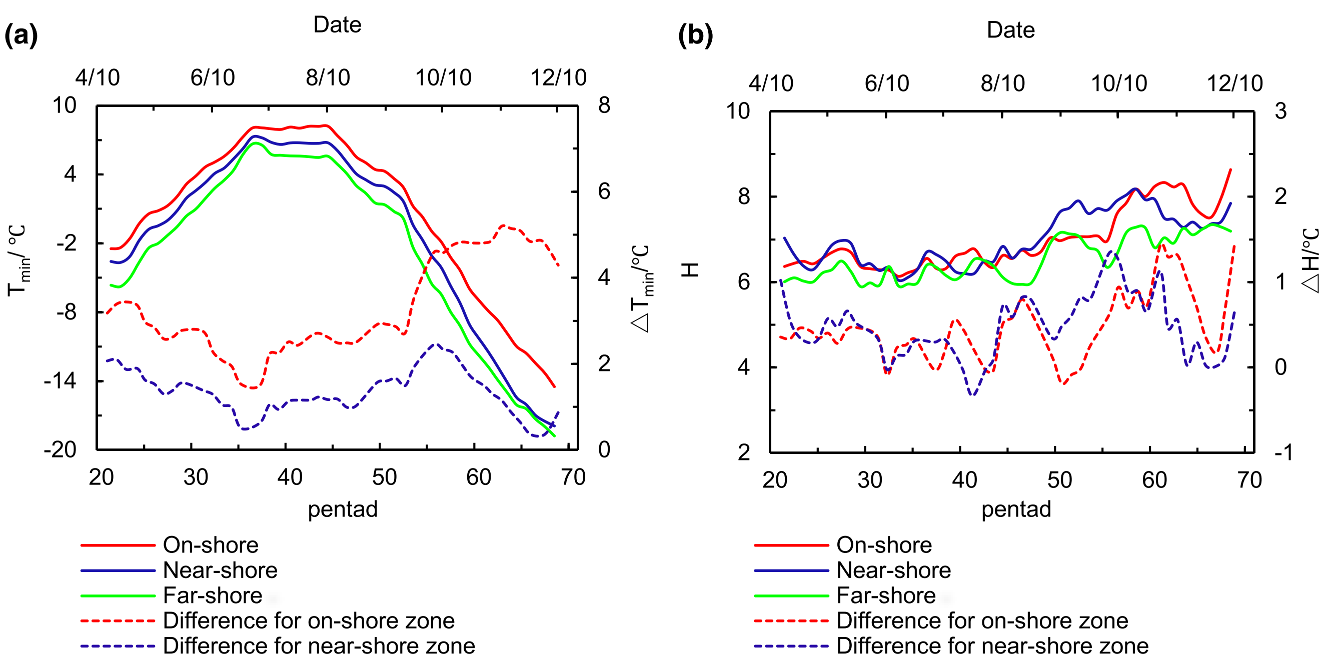

Fig. 10 Five-day average minimum temperatures for different zones and the differences of 5-day average minimum temperature of the on-shore zone and near-shore zone from the far-shore zone (**a**), and the diurnal time at which the 5-day average minimum temperature occurs and the difference of the occurrence time of the on-shore zone and near-shore zone from the far-shore zone (**b**)

nighttime. The daily mean the lake water surface temperature was higher than that in the surrounding areas.

2. The sites closer to the shoreline experience higher average air temperature and smaller diurnal temperature variations. This results from a slight cooling of 0.26 °C during daytime and a much larger warming of 3.17 °C during the nighttime in the on-shore zone as compared to the far-shore zone. The diurnal temperature ranges of the on-shore, near-shore, and far-shore zones are 8.7 °C, 10.9 °C, and 12.3 °C respectively.
3. The 5-day average temperature ranges of the warm season for the on-shore, near-shore, and far-shore zones are 19.7 °C, 22.1 °C, and 22.9 °C respectively. Compared to the far-shore zone, the 5-day average temperature for the on-shore and near-shore zones is generally higher during the whole warm season.
4. The 5-day average maximum temperature ranges of the warm season for the on-shore, near-shore, and far-shore zones are 20.3 °C, 21.7 °C, and 22.6 °C respectively. The 5-day average maximum temperature for the on-shore zone is always lower than that of the far-shore zone before early October, but it is slightly higher after early October probably due to the frequent invasion of cold air in autumn. The occurrence time of the diurnal maximum temperature is delayed in the on-shore zone, especially after early October.
5. The 5-day average minimum temperature ranges of the warm season for the on-shore, near-shore, and far-shore zones are 23.3 °C, 25.6 °C, and 26.7 °C respectively. The minimum temperatures for the on-shore and near-shore zones are generally higher than that of the far-shore zone. The occurrence time of the diurnal minimum temperature is generally later in the on-shore and near-shore zones than that of the far-shore zone.

Therefore, the effect of the QH Lake on surface air temperature is unique in diurnal variation of warm season compared to those of inland big lakes in the lower altitude, with the obviously asymmetrical effect. The lake effect on night-time air temperature in the on-shore zone is much higher than that of daytime. The mechanism for this asymmetrical effect needs to be further investigated in future studies. The thinner and leaner plateau atmosphere which allows a stronger daytime downward radiation and a larger absorption of heat in lake water, the stronger near-surface wind speed during daytime due to the combined influence of daytime turbulent mixing and unusual altitude, and the huge water body and heat capacity as the largest lake in mainland China, however, may have been the main reasons for the distinctive characters as found in this analysis.

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References

Ackerman SA, Heidinger A, Foster MJ, Maddux B (2013) Satellite regional cloud climatology over the Great Lakes. Remote Sens 5(12): 6223–6240

Alpert P, Neumann J (1983) A simulation of Lake Michigan's winter land breeze on 7 November 1978. Mon Wea Rev 111(9):1873–1881

Angel JR, Isard SA (1998) The frequency and intensity of Great Lakes cyclones. J Clim 11(1):61–71

Ballentine RJ (1982) Numerical simulation of land-breeze-induced snow bands along the western shore of Lake Michigan. Mon Wea Rev 110(11):1544–1553

Barthold FE, Kristovich DAR (2011) Observations of the cross-lake cloud and snow evolution in a lake-effect snow event. Mon Wea Rev 139(8):2386–2398

Bates GT, Giorgi F, Hostetler SW (1993) Toward the simulation of the effects of the Great Lakes on regional climate. Mon Wea Rev 121(5):1373–1387

Cao JH, Liu XM, Li GP, Zou HB (2015) Analysis of the phenomenon of lake-land breeze in Poyang Lake area. Plat Meteorol 34(2):426–435

Chang SS, Braham RR (1991) Observational study of a convective internal boundary layer over Lake Michigan. J Atmos Sci 48(20):2265–2279

Chen GC, Peng M (1993) Types and distribution of vegetation in Qinghai Lake region. Acta Phytoecologica Geobotanica Sinica 17(1):71–81

Chen WL, Chen J, Chen YN, Peng JY (1994) A numerical simulation of the effect of vegetation with the lake breeze. J Nanjing Inst Meteorol 17(1):64–72

Chen WL, Sun WG, Zhou JN, Chen J (1995) A numerical study of Qinghai Lake lake land breeze. J Lake Sci 7(4):289–296

Chen L, Chen KL, Liu BK, Hou GL, Cao SK, Han YL, Yang L, Wu YP (2011) Characteristics of climate variation in Qinghai Lake basin during the recent 50 years. J Arid Meteorol 29(4):483–487

Chen QC, Xia ZQ, Guo LD, Wang JC (2012) Characteristics of temperature variation in lake zones of Central Asia. J Hohai Univ (Nat Sci) 40(1):88–94

Crosman ET, Horel JD (2010) Sea and lake breezes: a review of numerical studies. Bound-Layer Meteorol 137(1):1–29

Editorial Board of Ecological Environment Protection and Restoration in Qinghai Lake Basin (2008) Ecological environment protection and restoration in Qinghai Lake Basin, Qinghai People's Publishing House. Xining

Eichenlaub VL (1979) Weather and climate of the Great Lakes region. University of Notre Dame Press, p 335

Guo LD, Xia ZQ, Wang ZJ (2011) Comparisons of hydrological variations and environmental effects between Aral Sea and Lake Balkhash. Adv Water Sci 22(6):764–770

Kristovich DAR (2009) Climate sensitivity of Great Lakes–generated weather systems. Climatology, variability, and change in the Midwest. Indiana University Press, 236–250

Kunkel KE, Changnon SA, Croley TE, Quinn FH (1998) Transposed climates for study of water supply variability on the Laurentian Great Lakes. Clim Chang 38(4):387–404

Li XY, Xu HY, Ma YJ, Wang JH, Sun YL (2008) Land use/cover change in the Qinghai Lake watershed. J Nat Resour 23(2):285–296

Lin ZG (1985) The climate of the middle and lower reaches of the Yangtze River and the possible climatic effects of the Three Gorges Reservoir. Meteorology 11(12):24–28

Liu X, Long X, Zhang WY, Zhang BK, Tian M (2013) Numerical simulation research into atmospheric characteristics influenced by Qinghai Lake in the process of local snowfall. J Lanzhou Uni (Nat Sci) 49(3):347–353

Lofgren BM, Hunter TS, Wilbarger J (2011) Effects of using air temperature as a proxy for potential evapotranspiration in climate change scenarios of Great Lakes basin hydrology. J Great Lakes Res 37: 744–752

Lu HB, Wei GL (1990) Analysis of air temperature effect of Taihu Lake. Oceanol Et Limnol Sinica 43(3):80–87

Lv YQ, Yang XY, Ma YM (2007) Numerical simulation of summer circulation and atmospheric boundary layer characteristics over Qinghai Lake. Plat Meteorol 26(4):686–692

Lv YQ, Ma YM, Li MS, Yang XY (2008) Numerical simulation of typical atmospheric boundary layer characteristics over Lake Namco Region, Tibetan Plateau in summer. Plat Meteorol 27(4): 733–740

Maddukuri CS (1982) A numerical simulation of an observed lake breeze over southern Lake Ontario. Boundary-Layer Meteorol 23(3):369–387

Moroz WJ (1967) A lake breeze on the eastern shore of Lake Michigan: observations and model. J Atmos Sci 24(4):337–355

Niziol TA (1987) Operational forecasting of lake effect snowfall in western and Central New York. Weather Forecast 2(4):310–321

Peng HQ, Qian PD, Zhu LY (2010) Local microclimate characteristics near Taihu Lake. J Meteorol Environ 26(1):27–31

Qi WL, Guo LY (2007) Climate and its variation in the Qinghai Lake Basin ecological environment impact analysis. Prataculture& Animal Husbandry 7:33–43

Ren GY, Guo J, Xu MZ, Chu ZY, Zhang L, Zou XK, Li QX, Liu XN (2005) Climate changes of China's mainland over the past half century. Acta Meteorol Sinica 63(6):942–956

Ren X, Wang YW, Zhang Z, Yang YC, Hu C, Kang HQ (2017) Simulation studies for Lake Taihu effect on surrounding cities thermal environment. Acta Meteorol Sinica 75(4):645–660

Scott RW, Huff FA (1996) Impacts of the Great Lakes on regional climate conditions. J Great Lakes Res 22(4):845–863

Scott RW, Huff FA (1997) Lake effects on climatic conditions in the Great Lakes Basin. SWS Contract report 617

Small EE, Sloan LC, Nychka D (2001) Changes in surface air temperature caused by desiccation of the Aral Sea. J Clim 14(3):284–299

Tang Y, Huang AN, Tian LR, Sun H, Qi PD, Shen PF (2016) Numerical study on summer local climatic effect over Taihu Lake. J Meteorol Sci 36(5):647–654

Tursun LASO, Kasim APIZ (2002) Study on the shift of Aral Sea and its effects on environment. J Xinjiang Uni (Nat Sci) 19(4):492–494

Vincent L, Mekis E (2006) Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. Atmosphere-Ocean 44(2):177–193

Wan JS, Lv DM, Liu FJ (1994) Summer temperature field and its temperature effect in Poyang Lake. Quart J Appl Meteorol 5(3):374–379

Wan Z, Hook S, Hulley G (2015) MYD11A2 MODIS/aqua land surface temperature/emissivity 8-day L3 global 1km SIN grid V006 [data set], NASA EOSDIS LP DAAC

Wang H (1993) A preliminary study about the different climatic effects of deep and shallow water body. J Nanjing Uni (Nat Sci) 29(3):517–522

Wang H, Fu BP (1991) The effects of water body on temperature. Scientia Meteorol Sinica 11(3):233–243

Wei QF, Ye QH (2010) Review of lake ice monitoring by remote sensing. Prog Geogr 29(7):803–810

Yang JB, Liu HN, Fei S, Zhang N, Jiang WM (2013) The impact of urbanization on the urban heat island in Suzhou under the influence of Taihu lake-land breeze. J Meteorol Sci 33(5):473–484

You Y, Guo JX, Chen YZ, Shen XF, Jin LJ, Zhong ZHH (2016a) Observation experiment and simulation evaluation of influence of non-frozen water body on air temperature. Plat Meteorol 35(2):495–506

You QL, Min JZ, Kang SC (2016b) Rapid warming in the Tibetan Plateau from observations and CMIP5 models in recent decades. Int J Climatol 36(6):2660–2670

Zhang XB, Wu SF (1988) Influence on local climate in Dianshan Lake. Trans Oceanol Limnol 4:26–32