Spatiotemporal characteristics of lake breezes over Lake Taihu, China

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ABSTRACT

Lake Taihu is a shallow lake located in the Yangtze River delta region in eastern China. Lake breezes and their interactions with urban heat islands are of great importance to air quality and weather forecasting. In this study, surface observations at a dense network and Wind Profile Radar measurements were utilized to characterize the lake breezes at Lake Taihu and assess the impact of geophysical factors on the development and intensity of the lake breezes. The lake breezes were characterized by a low occurrence frequency of 12%–17% (defined as the percentage of days with lake breezes in a given month), weak speed (annual mean ranging from 1.5 to 3.3 m s^{-1}), late onset [average onset around 1110 local standard time (LST), with a range of 0900–1300 LST], short duration (annual mean 3.5 h), and low circulation depth (average depth of 400 m from 1200 to 1400 LST). The lake breezes were greatly suppressed when the geostrophic winds were higher than 4.1 m s^{-1}. The low heat capacity of shallow water (mean depth 2.0 m) led to small temperature differences between the land and the lake, which was the main factor responsible for the low occurrence frequency along Lake Taihu. All of the characteristic parameters showed distinct seasonal variations. Increased frequencies, earlier onset times, and longer durations on the northern lakeshore were indicative of the impact of the urban heat island on the lake breezes.

1. Introduction

Lakes occupy about 1% of the global continental area (Segal et al. 1997) but display disproportionately large societal importance (Lee et al. 2014). Lake breezes frequently occur near inland water bodies because of large thermal contrasts between the water and the adjacent land surface. The intensity of lake breezes for large lakes with width larger than 80 km tends to resemble that of sea breezes (Segal et al. 1997). However, the majority of lakes are small, with a typical width of less than 50 km (Segal et al. 1997). The difficulty in characterizing lake breezes of small- and medium-sized lakes stems from the diversity of lake shapes, the complexity of the surrounding terrain, and the lack of

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high-spatial-resolution observations (Segal et al. 1997). As compared to sea breezes, whose characteristics have been extensively investigated (e.g., Pielke 1974), the lake breezes over the small- and medium-sized lakes are not well documented.

Characteristics of lake breezes are highly dependent on weather conditions and geophysical variables. Sensible heat flux H, background geostrophic winds V_g, atmospheric stability N, lake geometry (e.g., lake diameter and curvature), and surrounding terrain are the most important factors in determining the occurrence and intensity of lake breezes (e.g., Segal et al. 1997; Drobinski and Dubos 2009; Crosman and Horel 2012). Of these factors, surface sensible heat flux over the surrounding land is the prime factor affecting the intensity of lake breezes for a given lake width (Segal et al. 1997). Many studies showed that the horizontal and vertical velocity and the depth of the sea breeze increase with increasing land surface heat flux (e.g., Segal et al. 1997; Porson et al. 2007; Antonelli and Rotunno 2007; Kala et al. 2010). Crosman and Horel (2012) used a large-eddy simulation (LES) model to investigate the sensitivity of thermally driven circulations to varying surface sensible heat fluxes and atmospheric stability, and their results indicated that lake-breeze circulations are less sensitive to heat flux and more sensitive to atmospheric stability than sea-breeze circulations. Land–lake air temperature differences, closely associated with the contrast between land and water sensible heat flux, are a local driving force in the development of lake-breeze circulations. For example, approximately 70% of lake breezes over Lake Michigan occur with a daily maximum temperature difference of $\Delta T \leq 12.0°C$ (Laird et al. 2001).

Geostrophic wind is another driving factor affecting the occurrence and intensity of sea and lake breezes. The impact of geostrophic wind on lake breezes for small or shallow lakes is not well understood. In comparison to offshore-perpendicular geostrophic winds, the low-level lake-breeze flows are intensified with the onshore-perpendicular geostrophic winds, and the horizontal land–water temperature gradients are diminished (Crosman and Horel 2010). For small- and medium-sized lakes, the critical value of geostrophic wind for the lake-breeze development is not known precisely but likely ranges from 3 to 5 $m\,s^{-1}$, which is smaller than that for sea breezes or for lake breezes at large lakes (6–11 $m\,s^{-1}$; Crosman and Horel 2010). The development and intensity of lake breezes can be affected by interactions with upslope and downslope flows, as occur within the Salt Lake valley (Zumpfe and Horel 2007). Both numerical simulations and field experiments suggested that summertime lake-breeze circulations are destroyed when the opposing wind speeds are higher than 5–7 $m\,s^{-1}$. In addition, increase in offshore geostrophic winds is associated with decreases in breeze speeds and inland penetration distances (Crosman and Horel 2012); the same study also indicates that stability has a large impact on the vertical extent of the circulations.

The urban heat island (UHI) can also influence lake breezes. Yoshikado (1992) used a numerical model to investigate the impact of the UHI on a sea-breeze circulation and found that the sea-breeze advancement is slowed because of the convergence of the sea breeze with the UHI-induced thermal flow. Sarkar et al. (1998) found that the UHI slightly decreased the inland penetration of the sea-breeze front. Subsequently, Freitas et al. (2007) used the Town Energy Budget (TEB) model coupled with the Regional Atmospheric Modeling System (RAMS) to simulate the wintertime urban circulation in the metropolitan area of São Paulo, Brazil, and confirmed that the UHI accelerates the sea-breeze front movement toward the center of the city and decelerates the sea-breeze front after it has propagated beyond the urban area. The UHI is expected to impose a similar impact on lake breezes.

Lake Taihu is situated at the southern part of the Yangtze River delta (YRD) region, approximately 120 km west of Shanghai, China (Fig. 1). It is the third largest lake in China and has a total surface area of approximately 2340 km^2. The average depth is approximately 2.0 m, with the maximum depth of 3.4 m (Shen et al. 2011). It is a shallow lake according to the definition given by the Minnesota Department of Natural Resources (2012). Lake breezes occur in the surrounding areas under favorable weather conditions (Pang and Pu 1995; Qin et al. 2015). The Lake Taihu basin has experienced rapid urbanization over the past several decades, and several large cities with populations greater than one million each are situated near the lakeshores (Lee et al. 2014). The impact of the UHI on lake breezes is not well understood in the Lake Taihu basin and surrounding regions.

In this study, surface observations at a dense network and Wind Profile Radar (WPR; China Aerospace Science and Industry Corp.) measurements over one full year (2012) were presented to characterize the lake breezes in the Lake Taihu catchment. The goals of this study were to 1) quantify the general characteristics of lake breezes around Lake Taihu, 2) identify the key physical driving factors, and 3) assess the impact of the UHI on the occurrence frequency, intensity, and spatial distribution of the lake breezes.

2. Observational data and data quality control

The conventional surface weather observations included hourly air temperatures at 1.5 m above ground

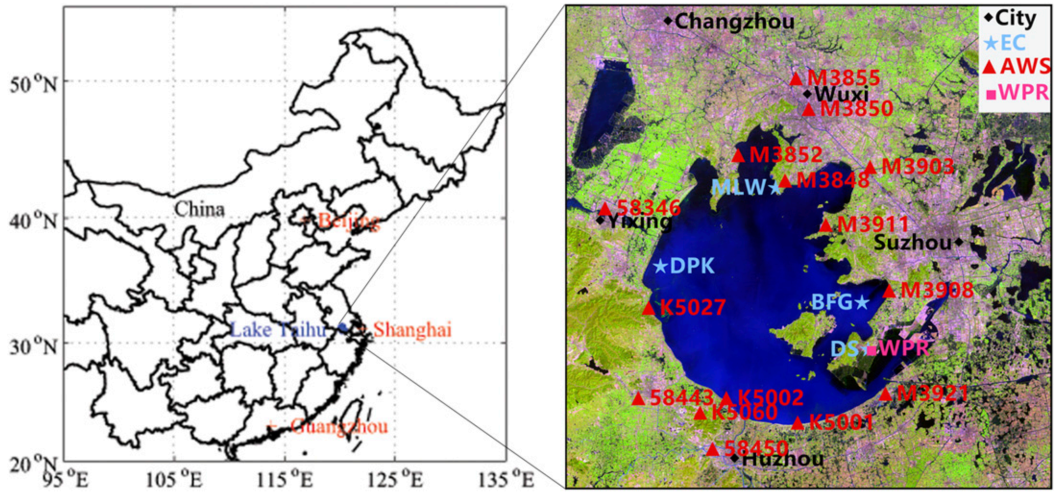

FIG. 1. Locations of meteorological observational sites, eddy covariance monitoring sites, WPR, and major cities along Lake Taihu.

level (AGL) and 10-m wind speeds and wind directions observed at 15 surface automatic weather stations (AWSs; Jiangsu Radio Scientific Institute Co., Ltd.). The Lake Taihu Mesoscale Eddy Flux Network (Xiao et al. 2013; Lee et al. 2014) used standard micrometeorological systems. An on-site wind profiler with a sampling frequency of six minutes provided further information on the lake breezes. The locations of the observational sites are shown in Fig. 1. The AWSs provided real-time measurements of air temperature, wind speeds, and wind directions. The air temperature over the lake was measured by the moored buoy stations positioned in Lake Taihu. The CFL-03 boundary layer WPR, located at Dongshan (DS) weather station (Fig. 1), was used to measure the vertical profiles of wind speed and wind direction up to a height of 5000 m. The observational wind speed and wind direction biases of the CFL-03 WPR were less than 1 $m s^{-1}$ and 10°, respectively (Wei et al. 2014). The Lake Taihu eddy flux network consisted of five lake sites and one land site. A micrometeorological system (Dynamet system from Dynamax, Inc., Houston, Texas) was used to measure air temperature, wind speed, and wind direction at these lake sites.

All of the observational data used in this study followed a strict quality control procedure. The historical extreme values along with the spatial and temporal continuity were used as the quality control criteria to exclude data outliers. For example, the observed temperatures higher than 45°C or lower than −10°C or wind speeds larger than 30 $m s^{-1}$ were excluded from the analysis. The observed winds with speed lower than 0.1 $m s^{-1}$ for several hours to one day were excluded because they were likely caused by instrument errors. It is noted that the low wind case (<0.1 $m s^{-1}$) with duration less than one hour was not considered as an outlier. Four surface observational sites on land were excluded because of a large amount of missing data. Twelve percent of the wind profiler measurements below the 3-km layer were missing because of power outage or other instrument errors. An automatic quality control algorithm developed by Lambert et al. (2003) was used to ensure the data quality of the wind profiler measurements. The lake breezes were characterized at the heights above 60 m because the WPR could not provide reliable measurements near the surface.

3. Methods and a case study

a. *Lake-breeze identification*

Certain meteorological conditions are critical for the development of lake breezes. Hourly surface wind observations at the AWS sites M3908, K5001, K5027, and M3848 were used to identify the occurrence of a lake breeze on eastern, southern, western, and northern shores of Lake Taihu, respectively. The criteria were established by following the method developed by Laird et al. (2001) with a few necessary modifications. The four criteria for identification of lake-breeze occurrence are as follows:

1) Shore-perpendicular onshore winds were observed on the three or four sides of the lake in any hours during the period 1100–1300 local standard time (LST).
2) The 1.5-m air temperature difference between the moored buoy station Meiliangwan (MLW) and the

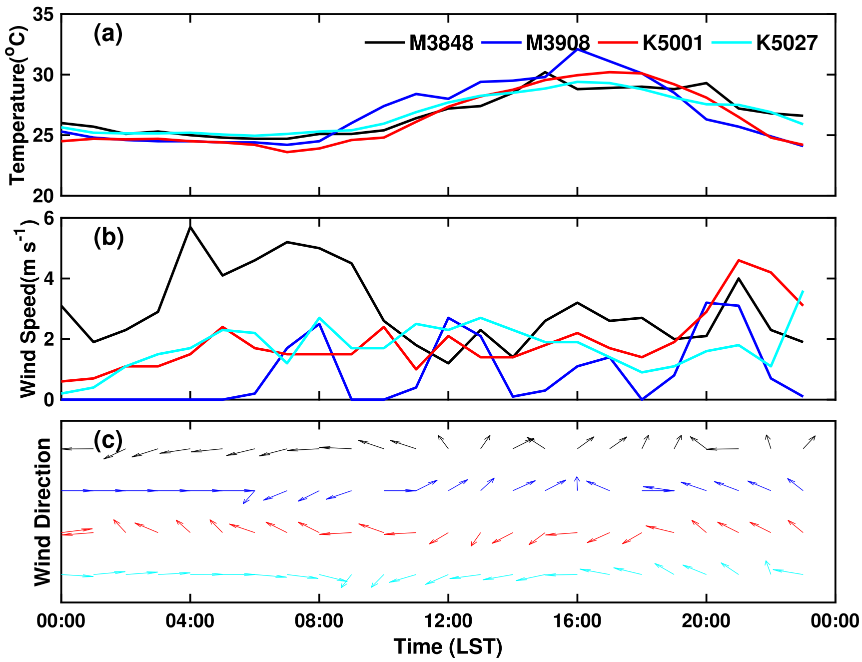

FIG. 2. Time series of (a) 1.5-m temperature, (b) 10-m wind speed, and (c) wind vectors observed at stations M3848 (north side; black), M3908 (east side; blue), K5001(south side; red), and K5027 (west side; cyan) on 12 Jun 2012.

inland site M3850 was larger than 0.5°C during the period 0700–0900 LST.

3) An average wind speed in the morning (0700–0900 LST) was less than 3.0 m s^{-1}.
4) The geostrophic wind V_g at the height of 1500 m as measured by the WPR was lower than 4.5 m s^{-1} during the period 0700–0900 LST.

The second criterion was designed to confirm the occurrence of a lake breeze when background winds were very weak (e.g., lower than 0.5 m s^{-1}). In this case, the surface winds were easily affected by the surrounding complex terrain, and the typical characteristics of lake breezes (i.e., shore-perpendicular surface winds) were not evident. A total of 54 lake-breeze days were identified manually from the 1-yr observational data in 2012 based on the identification criteria defined above. These identification criteria need further refinement and evaluation with long-term observational datasets before they can be used for lake-breeze forecasting in the future.

Two parameters are used here to quantify the characteristics of lake breezes. Onset is defined as the time when the wind shifts to be perpendicular to the lakeshore and the land air temperature or its time rate of change decreases in the following hour. Cessation is defined as the time when the wind direction changes back to the direction of the geostrophic wind on the shore where the lake breeze has been opposite to the geostrophic wind.

b. A lake-breeze case

In this section, a typical case, which occurred on 12 June 2012, is presented to demonstrate an application of the method defined in this study for identification of the occurrence of a lake breeze. Then the life cycle of the breeze circulation is discussed to highlight the spatiotemporal evolution of the observed breezes. On that day, the Lake Taihu region was governed by an anticyclone system with the center in Shanghai, China (weather chart not shown). The weather was clear, and the prevailing winds were easterly with wind speed lower than 3 m s^{-1} before 0900 LST (Fig. 2; except for the site M3848). The maximum sensible heat flux of 27.8 W m^{-2} was observed at the lake site Bifenggang (BFG) around noon time, which was consistent with the surface heat flux over other lakes (<50 W m^{-2}; Segal et al. 1997). Meanwhile, the maximum sensible heat flux measured at the land site DS was 93.2 W m^{-2}, which was much smaller than the typical value of the land sensible heat flux of 200 to 450 W m^{-2} (Segal et al. 1997). Since the DS island was covered by dense vegetation, the sensible heat flux measurement at DS cannot well represent the land sensible heat flux around the lake. The

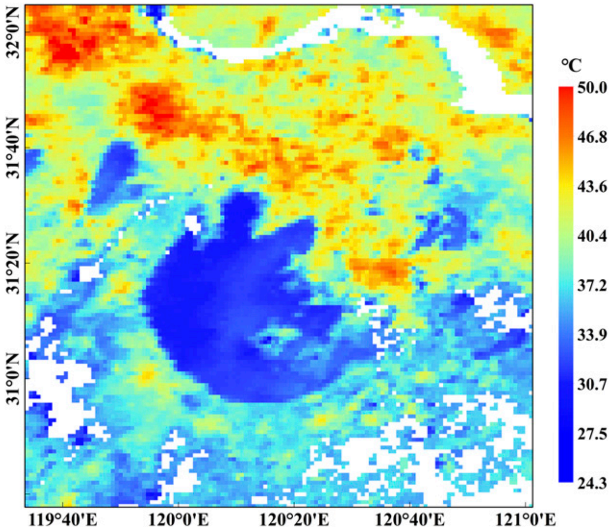

FIG. 3. Satellite-retrieved land and lake surface temperature (°C) at 1330 LST 12 Jun 2012.

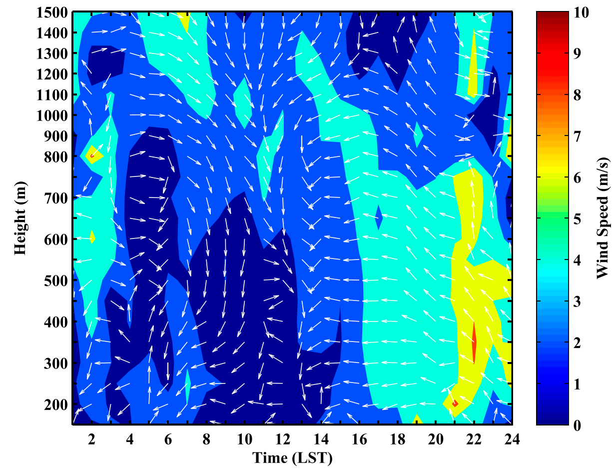

FIG. 4. Time–height cross section of wind speed (m s^{-1}; shaded) and wind directions (arrows) on 12 Jun 2012.

differences in satellite-derived skin surface temperature in the early afternoon (data available at 1330 LST; Fig. 3) thus were used as a proxy of the differences in surface heat fluxes between the lake and the land surface. The largest lake–land surface thermal contrast was observed on the north lakeshore (14.7°C; Fig. 3). In addition, the WPR measurements showed that the wind speeds within the atmospheric boundary layer, extending from the surface to the 1500-m height, were less than 4.0 m s^{-1} (Fig. 4). All these meteorological conditions indicated the occurrence of a lake breeze.

Figure 2 shows the time series of 1.5-m air temperature, 10-m wind speed, and wind direction at four sites on different lakeshores on 12 June 2012. The 1.5-m air temperature increased gradually after 0800 LST, and the wind shifted toward the lakeshores as the air temperature continually increased. As shown in Fig. 5, all the winds shifted to be perpendicular to the lakeshores, indicating that the lake breezes were well established along the lakeshores at 1300 LST.

Several unique features deserve attention from the lake-breeze case. First, the onset time of the lake breeze on the northern and the eastern shores was about 2 h earlier than that on the southern and the western shores (around 1000 LST vs around 1200 LST), and the cessation time on the northern shore was much later than that at the other lakesides (i.e., around 2000 LST on the northern shore vs 1500 LST on the southern shore; Fig. 2c). This was likely due to the difference in land use along the lakeshores although the geometry of the northern and the eastern shores was more complicated than that of the southern and the western shores (see Fig. 1). The urban heat island effect coupled with the shoreline curvature effects likely played an important role in the spatial and temporal variations of the lake-breeze characteristics along the different lakeshores, a point that will be discussed in detail in section 4 of this paper. Second, the lake-breeze speeds on the northern lakeshore were higher than that on the southern lakeshore. The lake-breeze speeds were about 2 to 4 m s^{-1} on the northern lakeside during 1000–2000 LST, whereas the wind speeds were about 1 to 2 m s^{-1} on the southern lakeside. As indicated by the satellite image (Fig. 3), the higher sensible heat flux over the urban areas on the northern shore than that over the forested southern shore likely accounted for the difference of the lake-breeze speeds between the northern and southern shores. Third, the parallel geostrophic flow (easterly) strengthened the lake breeze on the western lakeshore. As a result, the wind speeds of combined lake breezes over the western lakeshore were higher than that over the southern lakeshore.

4. General characteristics of lake breezes along Lake Taihu

a. Frequency of lake-breeze occurrence

The monthly frequencies of the lake-breeze occurrence on the four lakeshores are presented in Table 1. The frequency is defined as the percentage of days with lake breezes for a given month. Several features are identified. First, the lake-breeze occurrence exhibited a large seasonal variation, with the highest frequency (up to 40%) occurring in summer months (i.e., June) and the lowest occurring in winter months (less than 4% in December). The spring and fall months' frequency (around 7%–20%) ranked in between the other two

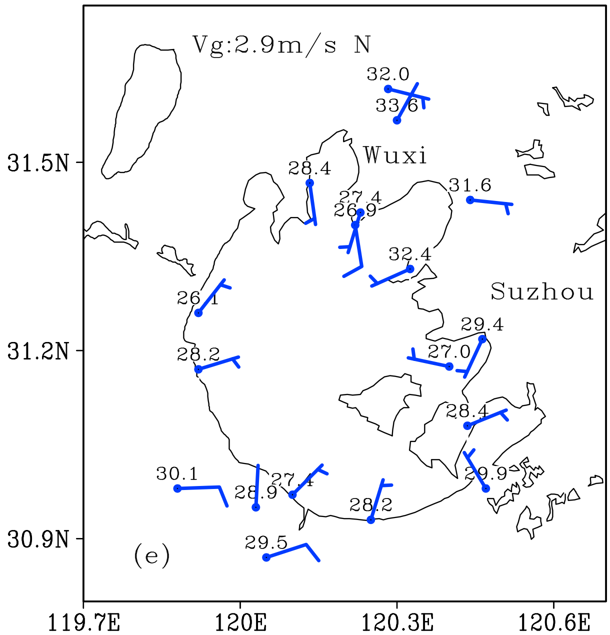

FIG. 5. Spatial distribution of lake breezes and 1.5-m air temperature (°C) observed at 1300 LST 12 Jun 2012.

seasons. The low frequency in July 2012 was caused by two landing typhoons that were accompanied by cloudy and rainy weather as well as geostrophic wind speeds higher than 5 $m\,s^{-1}$.

Second, the frequency of lake-breeze occurrence exhibited large variations among the four shores, with the highest annual frequency of 17% occurring on the northern shore and the lowest frequency (12%) occurring on the western shore. Several factors were hypothesized to account for this difference. The distance between the urban areas and the lakeshores could be an important factor for lake-breeze development. Because of the shorter distance to the large city of Wuxi, China (Fig. 1), the lake–land temperature difference on the northern shore was larger than that on the other shores. Consequently, the occurrence of the lake breeze on the northern shore was higher than that on the other shores. The surrounding topography and shoreline curvature effects likely played another important role in modulating the lake–land interactions, with the complex terrain on the eastern shore inhibiting the occurrence of the lake breezes and the smooth lakeshore terrain on the southern shore promoting the development of the lake breezes. The role of these topographical factors partly offset the impact of the UHI on the eastern shore although the frequency on the southern shore (15%) was slightly higher than that on the eastern shore (13%). A similar argument has been presented in other studies (Boybeyi and Raman 1992; Gilliam et al. 2004). Moreover, the difference could also be related to the prevailing winds with respect to orientation of the lakeshores (Sills et al. 2011).

Third, the frequency of lake-breeze occurrence at this shallow lake was much lower than that observed at deep lakes but higher than that at small- and medium-sized lakes. For example, the occurrence frequencies of lake breezes at Lake Taihu were 22.6% to 40.0% in the summer months (except July). The frequency for Lake Taihu during the summer months was much lower than that of Lake Michigan, where the occurrence frequency reaches up to 46% on the eastern shore and 62% on the western shore during the summer months (Lyons 1972; Laird et al. 2001), but higher than that of the Great Salt Lake (GSL; Zumpfe and Horel 2007) and other small-sized lakes (Segal et al. 1997; Table 2). Moreover, the mean frequency (18.5%) for Lake Taihu was much lower than the frequency (30%) observed at Lake Ontario during the same period from April to September (Comer and McKendry 1993) but almost 2 times of that over the GSL during 1948–2003. The generally low frequency of lake-breeze occurrence at Lake Taihu was probably caused by the low heat capacity of the shallow lake (Zumpfe and Horel 2007).

b. *Lake-breeze speed, onset, cessation, and duration*

The lake-breeze speed is a useful parameter for describing the intensity of the lake-breeze thermal circulation. Figure 6 shows the monthly mean 10-m wind speed at stations M3908 (east), K5001 (south), and M3848 (north) along the shores of Lake Taihu. No western site is presented because of a lack of observational data. The values represented the average wind speeds during the hours of lake-breeze occurrence. The annual mean lake-breeze speeds ranged from 1.5 to 3.3 $m\,s^{-1}$, and these speeds were weaker than those

TABLE 1. Monthly frequency of lake breezes along all lakeshores.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
East shore	13.3	13.8	12.9	10	12.9	26.7	12.9	22.6	16.7	16.1	6.7	3.2	13.5
West shore	10.0	10.9	9.7	6.7	9.7	33.3	9.7	25.8	16.7	6.5	3.3	0.0	11.7
South shore	13.3	17.2	9.7	13.3	12.9	30.0	12.9	25.8	20.0	16.1	6.7	3.2	15.1
North shore	16.7	17.2	12.9	13.3	16.1	40.0	9.7	28.6	16.7	19.4	6.7	6.5	16.8

TABLE 2. A comparison of breeze characteristics for Lake Taihu and other lakes during summer months (depth: average value; frequency: average value; Z: the maximum upward vertical distance; L: the maximum onshore penetration distance; U: horizontal average wind speed at land sites near the shoreline; and ΔT: monthly mean of maximum land–water temperature difference).

Location	Reference	Lat	Depth (m)	Frequency (%)	Duration (h)	Z (m)	L (km)	U (m s^{-1})	ΔT (°C)
Lake El Dorado	Segal et al. (1997)	37°50′N	5.8	9–16	5–8	—	0.2–0.5	—	—
Lake Okeechobee	Segal et al. (1997)	26°56′N	2.7	5–17	4–5	—	11–25	—	—
Lake Eufaula	Segal et al. (1997)	35°16′N	7.0	11	5	—	3	—	—
Lake Winnipeg	Segal et al. (1997)	52°07′N	12	7	6	—	0.3	—	—
Lake Ontario	Comer and McKendry (1993)	43°N	85	30	/	500–750	30–80	>5	—
Lake Michigan	Laird et al. (2001)	41°47′–43°06′N	84	40.6	7	500–750	>20	3.2–4.8 5–7	5.5–16.0
Lakes Erie/Huron	Sills et al. (2011)	41°–43°N	18/59	82/84	9	—	100–185	—	—
Great Salt Lake	Zumpfe and Horel (2007)	41°10′N	4.9	6–15	6–11	400–700	—	4–12	1–5
Lake Taihu	This study	30°50′–31°40′N	2.0	22.6	3.5	405	—	1.5–3.3	2.5–2.9

observed on the shores of deep lakes, such as Lake Michigan, where a majority of lake-breeze events occur with inland wind speeds of 2–4 m s^{-1} (Laird et al. 2001). The lake-breeze speeds on the three shores exhibited similar seasonal variations, with the largest monthly means (1–6 m s^{-1}) occurring in summer months (June to August) and the lowest monthly means (1–3 m s^{-1}) occurring in the winter months (December to February). Furthermore, both the mean and maximum breeze speeds exhibited obvious differences among the four lakeshores, with the highest wind speeds occurring on the northern shore and the lowest wind speeds occurring on the southern shore. The higher lake-breeze wind speeds on the northern and eastern shores may have resulted from the larger lake–land thermal contrast associated with several large cities, such as Suzhou, China, Wuxi, and Changzhou, China. The larger lake–land temperature differences likely resulted in a stronger thermal-driving force that strengthened the lake breezes.

The onset and cessation times are another two parameters that can be used to characterize lake breezes. Figure 7 shows the starting and ending times of lake breezes. The lake breezes started between 0900 and 1300 LST, with a median time of 1100 LST. In general, the onset time gradually shifted earlier from winter to summer. A total of 6%, 30%, and 31% of lake breezes occurred between 0800 and 0900 LST, between 0900 and 1000 LST, and between 1000 and 1100 LST, respectively, from June to September. The earliest starting time of lake breezes occurred between 0700 and 0800 LST, and the latest starting time was between 1300 and 1400 LST although these times varied with the seasons and local weather conditions. The onset time in July was later than in other summer months, and the onset time in October was earlier than in other fall months. The month of July was associated with more frequent convective local weather, which was not favorable for the occurrence of lake breezes, whereas the month of October was related to dry, hot, and cloudless weather conditions. However, the onset time of lake breezes at deep lakes is much earlier. For instance, the onset time of lake breezes at Lake Michigan ranges from 0600 to 1830 LST, with the most frequent start time from 0800 to 0900 LST (Lyons 1972).

The cessation time of lake breezes ranged from 1500 to 1645 LST, with a median value of 1530 LST. Most of the lake breezes (76%) ended between 1500 and 1600 LST. The earliest monthly median cessation occurred at 1300 LST (January) and the latest occurred at 1800 LST (June). The ending time of the lake breezes indicated an opposite seasonal variation compared with the starting time. The lake breezes stopped earlier in the months when they started later, and vice versa. In addition, the cessation time indicated a clear seasonal trend. The mean ending time of the lake breezes moved gradually later from February to June and then moved earlier from July to December.

The lake-breeze duration at Lake Taihu was shorter than that at large lakes and exhibited a pronounced seasonal variation. The annual mean breeze duration over Lake Taihu was 3.5 h. The maximum monthly mean duration (5.9 h) occurred in June, and the minimum duration (3.0 h) occurred in December. The longest duration for a lake breeze was 9 h in August, and the shortest duration for a lake breeze was 2 h in February. As a comparison, the median lake-breeze duration in the southern Great Lakes region is approximately 9 h in the summer (Sills et al. 2011).

Vertical extent is also an important parameter used to quantify the intensity of lake-breeze circulations although it is not as well studied as other characteristics because of a lack of observational data. Table 3 shows

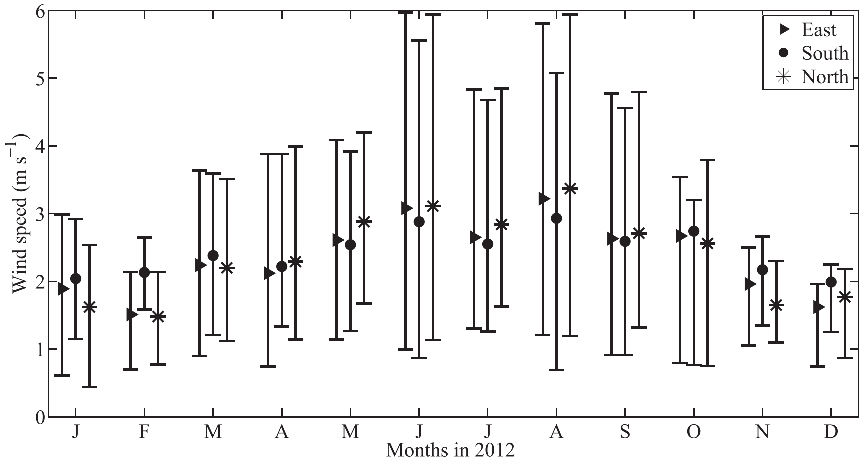

FIG. 6. Monthly mean and range of the lake-breeze speeds along the eastern, southern, and northern shores of Lake Taihu in 2012 (top and bottom bars represent the maximum and minimum of the monthly mean lake-breeze speeds, respectively).

the monthly mean vertical height of the lake breezes in the inflow region from 1200 to 1400 LST based on the wind radar profiler observational data at the DS station (see Fig. 1 for the location). The vertical depth of lake breezes is defined as the height where steep changes of wind direction are observed. The annual mean depth of the lake breezes at Lake Taihu was approximately 400 m, and the depth ranged from 300 to 500 m during the peak of the lake-breeze period (i.e., 1200–1400 LST). The lake-breeze circulation demonstrated obvious seasonal variation, with the largest depth (500 m) occurring in July and the smallest depth (220 m) occurring in December.

In summary, because it is a shallow lake, Lake Taihu exhibited several noticeable features that are different from those of the deep lakes in North America, such as a weaker lake breeze, later onset times (average start at 1112 LST), and relatively shorter duration (annual mean of 3.5 h). All of these characteristic parameters exhibited pronounced seasonal variations.

5. Physical factors impacting the lake breezes

a. Geostrophic wind

Geostrophic flow, also referred to as the background wind, exerts an important constraint on the development of lake breezes. Earlier studies have found that the critical offshore geostrophic winds that suppress the occurrence of lake breezes are 6–11 m s^{-1}, depending on the land–water temperature gradient (Arritt 1993; Porson et al. 2007; Crosman and Horel 2010). However, the critical values are not well quantified for small- and

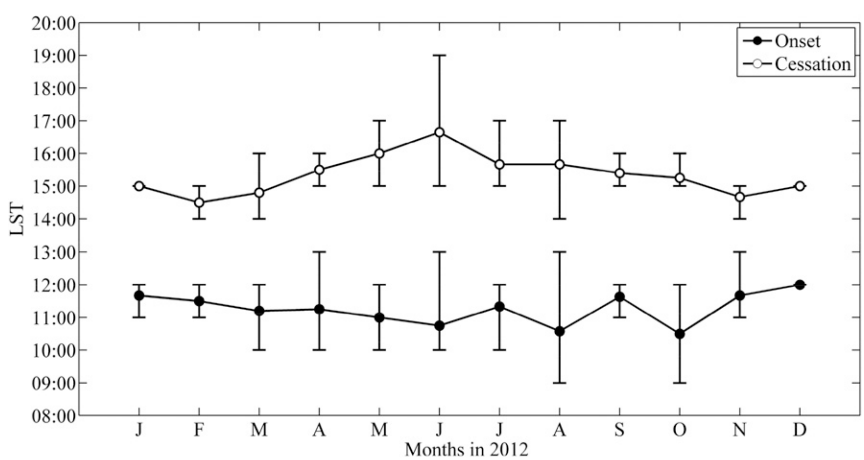

FIG. 7. Monthly median and range of the maximum lake-breeze onset and cessation time over Lake Taihu in 2012.

TABLE 3. Monthly mean lake-breeze heights observed over Lake Taihu.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
h (m)	300	387.5	400	387.5	425	503.1	500	489.3	425	495	328.1	224.1

medium-sized lakes. In this section, the WPR-measured winds at the 1500-m layer AGL were used as a proxy of the background wind.

Table 4 presents the monthly mean and maximum background winds during the period of three hours before the onset of lake breezes. As shown in Table 4, the background wind thresholds for the occurrence of lake breezes exhibited large seasonal variability. Lake breezes only developed when the background winds were less than 1.5 m s^{-1} in the morning from November to February. In other months, lake breezes were able to establish under relatively high background winds (i.e., 2–4 m s^{-1}). For example, the average and maximum critical background winds that prevented the development of lake breezes was approximately 4.1 and 4.6 m s^{-1}, respectively, in September, which partly accounted for the higher occurrence frequency in summer and early fall compared with that in the winter months. This result is consistent with the inference of Segal et al. (1997), who indicated that lake breezes on small- and medium-sized lakes were likely to be suppressed when background wind are higher than 3–5 m s^{-1}.

b. *Effects of lake–land temperature differences*

Although geostrophic winds exert an important impact on lake breezes, the lake–land temperature gradient is crucial to the occurrence of sea breezes and lake breezes. Figure 8 shows the monthly mean land–lake temperature difference, calculated as the difference in 1.5-m air temperatures above the land and water surface, from 0800 to 1600 LST. The annual mean difference was 1.3°C, with the monthly maximum value (2.3°C) occurring in August and the minimum value (0.3°C) occurring in February. The corresponding frequencies of lake-breeze occurrence were 25.6% and 17.8% in August and February, respectively. The lake–land temperature difference at Lake Taihu was lower than that at deep lakes. For instance, monthly mean of the maximum lake–land temperature difference (i.e., difference between the inland maximum temperature and the water surface temperature) at Lake Michigan varied from 5.5° to 16.0°C (Laird et al. 2001), which was much higher than that at Lake Taihu (2.5°–2.8°C) during May–August. The smaller lake–land temperature differences could be one of the reasons causing a lower occurrence frequency at Lake Taihu than at other large and deep lakes (e.g., 46%–64% at Lake Michigan; Lyons 1972; Laird et al. 2001).

c. *Impact of the urban heat island*

In recent decades, the Lake Taihu catchment experienced rapid urbanization, and several large cities have been developed near the lake shorelines. Among these cities, Wuxi is located on the northern lakeshore and has an urban population of 3.4 million, Suzhou is located on the eastern lakeshore and has an urban population of 5.5 million (Fig. 1), and Huzhou, China, is located on the southern lakeshore and has an urban population of 1.3 million. The urbanized area is relatively smaller on the western lakeshore. Yixing, China, is the largest city located on the western lakeside and has an urban population of less than 1 million. In this section, two representative lake-breeze cases in the summer and the fall season are presented to reveal the impact of urbanization on lake breezes.

TABLE 4. Monthly mean wind speeds, wind directions, and maximum speed of background winds V_g over a 3-h period prior to the onset of lake breezes as well as monthly mean wind speed and dominant wind directions in the Lake Taihu region during 2012.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean V_g over LBs (m s^{-1})	0.9	0.8	1.8	1.8	3.3	4.4	4.5	4.6	3.1	3.8	2.5	1.9
Mean direction over LBs	264	251	207	192	110	207	263	356	344	204	184	220
Max V_g over LBs (m s^{-1})	1.8	1.5	4.4	5.3	5.0	7.7	6.8	5.7	4.6	4.2	3.7	2.5
Monthly mean V_g (m s^{-1})	5.0	6.7	7.8	7.1	6.3	5.9	8.2	7.8	6.7	6.8	7.6	9.1
Monthly dominant wind direction	Westerly	Northerly	Westerly	Southerly	Westerly	Easterly	Westerly	Easterly	Southerly	Northerly	Northerly	Easterly

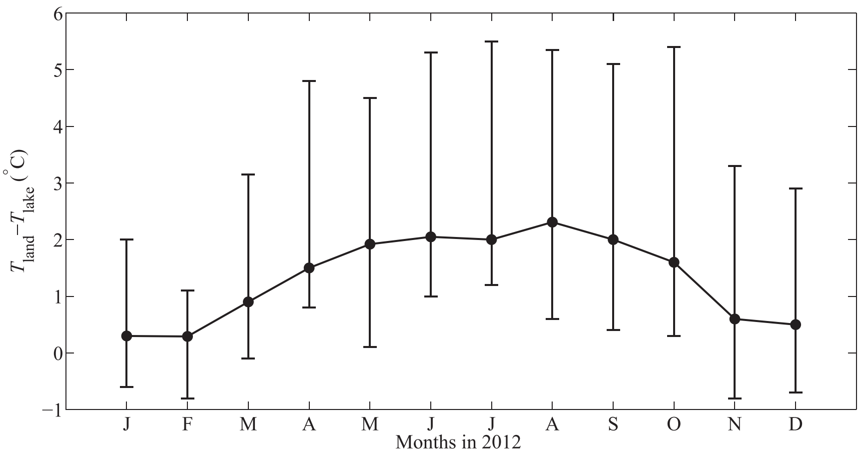

FIG. 8. Monthly mean and range of the temperature differences over a period from 0600 to 1800 LST in different months of 2012.

Figure 9 is a wind vector plot of the hourly mean lake breezes observed at several lakeshore locations from 0800 to 1400 LST 20 July 2012. The weather conditions were conducive to the development of lake breezes with clear skies, weak background winds (4.1 m s^{-1}), and strong land–lake temperature differences (0.9°C). At 0800 LST, the prevailing wind based on the 1500-m wind measured by the WPR was easterly, and the surface wind speed was lower than 0.5 m s^{-1}. Lake breezes were not observed at 0900 LST. With an increasing land–lake temperature difference, lake breezes were established first along the northern and southern lakeshores after 0900 LST. At 1000 LST, the surface winds shifted to southerly, and the breeze speed increased to 1.2 m s^{-1} on the northern lakeshore (Fig. 9b). In addition, the northeasterly lake breeze developed on the southern lakeshore, and the wind speed was approximately 0.9 m s^{-1} (Fig. 9c). However, on the eastern side, the lake breeze was not established until 1100 LST, approximately one hour later than on the other lakeshores. The lake-breeze speed reached the peak values at approximately 1300 LST on all the lakesides. Overall, the lake breezes on the northern lakeshore were more vigorous and had earlier onset times and quicker shifts of wind direction compared with those on other lakeshores, indicating that the northern lakeshore experienced a greater impact of the UHI than other sides, as evidenced by higher land temperature (Fig. 3) and thus higher land surface sensible heat flux on the north shore of the lake.

Figure 10 shows the evolution of wind vectors in another case that occurred on 25 October 2012. The prevailing background winds were northerly to northwesterly, and the surface wind speeds were less than 0.5 m s^{-1} before 1000 LST. Similar to the summer case illustrated in Fig. 9, this lake-breeze event started first on the northern lake shoreline, the onset time was around 1100 LST, approximately 1 h later than in the summer

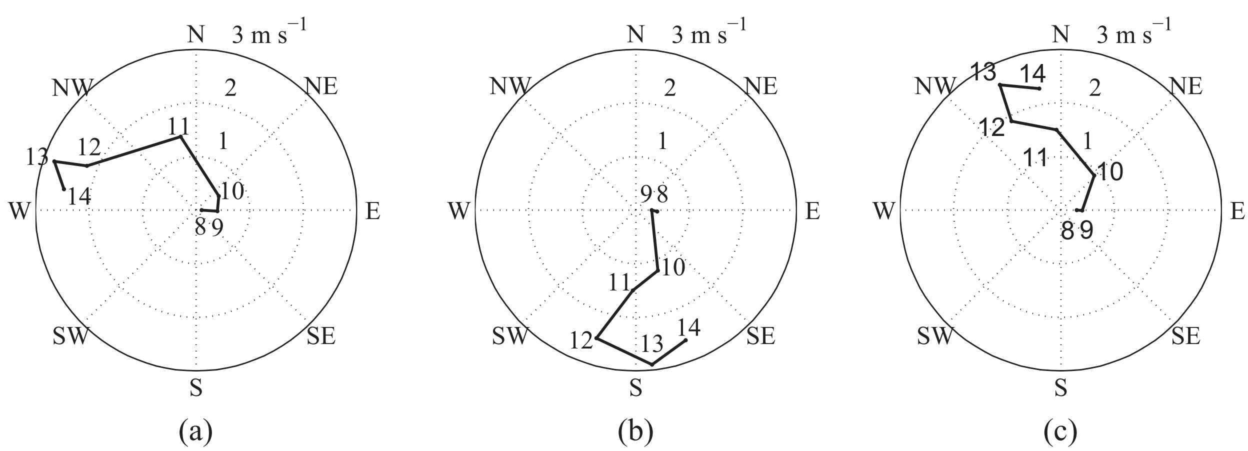

FIG. 9. Wind vector plots of lake breezes on the (a) east, (b) north, and (c) south lakeshores from 0800 to 1400 LST 20 Jul 2012.

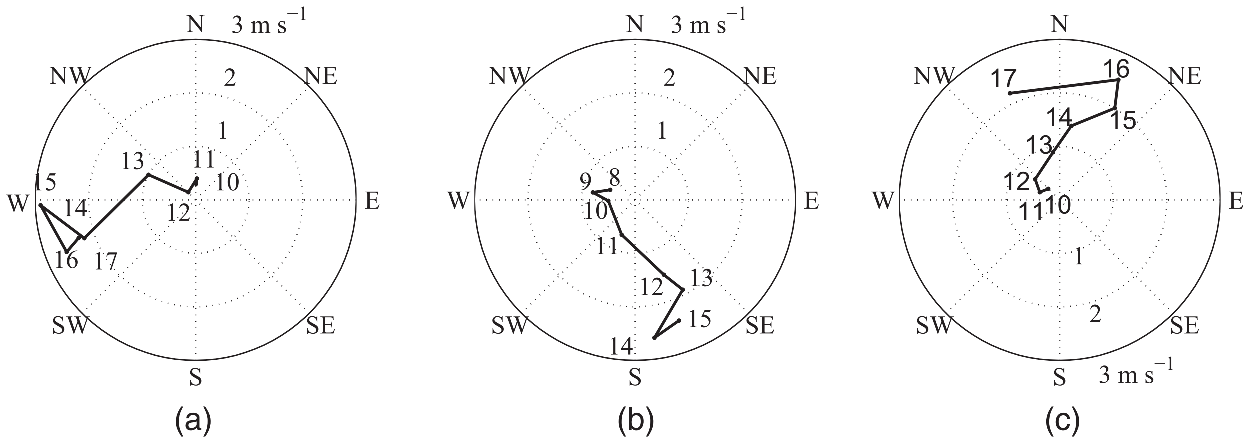

FIG. 10. As in Fig. 9, but from 0800 to 1700 LST 25 Oct 2012.

case, and the breeze peak hour was also delayed by 1–2 h. The maximum wind speed was lower than that of the summer case. This case suggests that the UHI may have a great impact on the intensity and onset time of lake breezes, which partly explains the occurrence of stronger breezes along the northern lakeshore (Zhang et al. 2011).

The UHI effect may enhance the lake–land temperature gradient and lead to a more active thermally driven local circulation. It is worth mentioning that hot and dry climate conditions may increase the chance of heat island circulation development. This is because dry climate is usually associated with less perturbed weather and a higher sensible heat flux over land, which may lead to more pronounced lake breezes (Segal et al. 1997). Moreover, according to the arguments of Keeler and Kristovich (2012), interactions between the heat island circulation and the lake-breeze circulations were expected to lead to more intense lake breezes along the eastern and northern shores compared with those along the southern shore.

6. Discussion

Observational data collected over a year were utilized to describe the temporal and spatial variations of the lake breezes at Lake Taihu. The results demonstrated several unique features of the lake breezes at Lake Taihu in comparison with deep lakes elsewhere. However, our analysis has several limitations. First, one year of observational data is not sufficient to quantify the general characteristics of lake breezes. As discussed above, two landing typhoons occurred in July 2012, contributing a lower occurrence frequency of lake breezes in July than in June and August. Without the interference of these typhoons, the frequency of lake-breeze occurrences in July should have been similar to the frequency in June and August. Thus, multiyear observational data are needed in order to obtain statistics describing lake breezes. Second, the AWOS monitoring network had large gaps. As shown in Fig. 1, only a few observational sites were available on the western lakeshore. Furthermore, the current site arrangement was not able to provide enough information for quantifying the maximum penetration distance of the lake breezes. Third, the three-dimensional structure of the lake-breeze circulation was not well quantified from the available observational data. High-resolution numerical simulations with regional numerical weather predictions or LES models are needed to generate a better understanding of lake-breeze circulation and its driving factors.

The UHI effect could enhance the lake–land temperature gradient and strengthen the lake-breeze local circulation. A greater UHI may cause stronger lake breezes on the northern lakeshores because of a larger urban land area than on the other lakeshores. However, more observational and modeling studies are needed to refine our understanding of the UHI interactions with the lake-breeze circulations at Lake Taihu.

7. Summary and conclusions

Lake Taihu is the third largest lake in China and has an average depth of approximately 2.0 m. Observational data collected in one full year (2012) were used to characterize the temporal and spatial variations of lake breezes and assess the impacts of different geophysical factors on lake breezes.

The identification criteria of Laird et al. (2001) with appropriate modifications were used to identify the occurrence of lake breezes: 1) perpendicular onshore winds were observed on three or four shores in any hour from 1100 to 1300 LST; 2) the 1.5-m air temperature difference between the moored buoy station Meiliangwan (MLW) and the inland site M3850 was larger than 0.5°C during the period of 0700–0900 LST; 3) an average wind speed in the morning (0700–0900 LST) was less than $3.0\,\mathrm{m\,s^{-1}}$; 4) the geostrophic wind at the height of 1500 m was lower than $4.5\,\mathrm{m\,s^{-1}}$ during the period of 0700–0900 LST.

The lake breezes at Lake Taihu exhibited several unique features, including a low lake-breeze frequency of occurrence (monthly frequency ranging from 12% to 17%), a weak lake-breeze speed (monthly mean speed ranging from 1.5 to $3.3\,\mathrm{m\,s^{-1}}$), late onset (average onset at around 1100 LST, with a range from 0900 to 1300 LST), short duration (annual mean duration of 3.5 h), and a low lake-breeze circulation depth (average depth of 400 m from 1200 to 1400 LST). These characteristic qualities indicated that the lake-breeze circulation at Lake Taihu were much weaker than that at the Great Lakes and other deep lakes.

The geostrophic wind and the land–lake temperature differences were the two critical factors for the development of lake breezes at Lake Taihu. Lake breezes were greatly suppressed when geostrophic winds were higher than $4.1\,\mathrm{m\,s^{-1}}$ in the summer. From late fall to early spring, lake breezes were not able to develop when the morning background winds were higher than $1.5\,\mathrm{m\,s^{-1}}$. The monthly mean of the maximum temperature difference between the land and the lake was approximately 2.8°C in the summer months, which was much lower than that at Lake Michigan (5.5°–16.0°C; Laird et al. 2001). These differences may account for the low frequency of lake-breeze occurrence at Lake Taihu.

This study was based on an analysis of observational data collected over one year. Multiyear observational data are needed to confirm the results obtained in this study. Furthermore, high-resolution numerical simulations with regional numerical weather prediction or large-eddy simulation models are needed to better understand the complex structure of the lake-breeze circulation and to accurately quantify the impacts of different geostrophic factors.

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