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Original scientific paper

Lake-land breezes over a small elongated lake (Kozjak, Plitvice Lakes, Croatia)

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The temperature of a small elongated lake (2.3 km by 0.1–0.6 km; maximum depth of 46 m) located in a mountaneous area was measured during July-September period over three years (2018–2020) at the depth close to the lake surface (0.2 m). Concurrent standard meteorological variables were measured in the vicinity of the lake. Criteria based on atmospheric and lake conditions were defined to detect the days with persistent lake-land breeze (LLB) events. The results showed that 17.7% of the investigated days were associated with LLB events. These days were accompanied by elevated energy in the normalized wavelet spectra for the wind speed at period of 24 hours. Daytime onshore lake breezes were mainly channeled in the along-lake direction due to the surrounding topography. Accordingly, during the daytime, diurnal wind veering was distorted. However, during the nighttime, a clear clockwise wind rotation was present. In addition, the results exhibited a clear relationship between the lake-land temperature difference and the strength of the LLBs.

Keywords: coherence, diurnal periodicity, thermal circulation, wavelet analysis, wind rose

1. Introduction

As lakes interact with the atmosphere through fluxes in heat, momentum, moisture and mass at lake surfaces, they generally modify the weather and climate of their surrounding areas (*e.g.*, Passarelli and Braham, 1981; Laird et al., 2009; Klaić and Kvakić, 2014; Potes et al., 2017). One such modification of weather/climate imposed by the presence of a lake is the establishment of a lake-land breeze (LLB) circulation. Similar to a sea-land breeze (SLB), the LLB is also a local thermal circulation system that is driven by surface heterogeneity, that is, by differential heating between the land and water. Thus, the basic dynamics and properties of a SLB and LLB are the same. As a weakly stratified atmosphere is more favorable for SLB/LLB establishment than a strongly stratified atmosphere (which suppresses circulation), nighttime offshore breezes are weaker than daytime onshore breezes (*e.g.*, Crosman and Horel, 2010).

While numerous studies address SLBs (*e.g.*, Simpson, 1996; Miller et al., 2003 and references therein; Nitis et al., 2005; Klaić et al., 2009; Babić et al., 2012; Jiménez et al., 2016; Grau et al., 2020) or LLBs over large lakes (*e.g.*, Keen and Lyons, 1978; Arritt, 1987; Comer and McKendry, 1993; Laird et al., 2001; Sills et al., 2011; Gu et al., 2016), only a few authors have reported on LLBs produced by small lakes or reservoirs (Asefi-Najafabady et al., 2012; Giovannini et al., 2015). In terms of morphometry, small, medium, and large lakes correspond to maximum lake fetches (d) of $d < 50$ km, $d \approx 50$–100 km, and $d > 100$ km, respectively (*e.g.*, Crossman and Horel, 2010).

Segal et al. (1997) proposed a conceptual model of a daytime lake breeze and analyzed observational data. The authors concluded that for a small midlatitude lake under clear sky conditions, the magnitude of the surface sensible heat flux over the surrounding land was the key factor governing the lake breeze. On the other hand, the effective surface thermal flux over a lake (which is the result of a downward surface sensible heat flux and cooling of the lower atmosphere forced by radiative longwave flux divergence; both increase with a decrease in the lake water temperature) was of lesser importance for the lake breeze intensity. However, the importance of cooling increased with lake depth and geographical latitude. Furthermore, based on conceptual evaluation, Segal et al. concluded that for lakes less than 2 km wide, the direct lake breeze would likely be undetectable even in the absence of background flow.

Background mesoscale or synoptic-scale flows can obscure or even suppress the establishment of LLBs, as the pressure gradient at a larger scale can overtake over the local pressure gradient. According to Crossman and Horel (2010), an ambient geostrophic wind above 3–5 ms^{-1} prevents the formation of LLBs over small and medium-sized lakes (d less than ≈ 100 km). Asefi-Najafabady et al. (2012) reached a similar conclusion while investigating lake breezes produced by a small reservoir with a mean width of ≈ 2 km. They found that despite the small size of the reservoir and relatively small lake-land temperature difference (a few degrees Celsius), lake breezes were formed, and they persisted over a range of ambient winds as long as the wind speeds of the ambient winds were below ≈ 5 ms^{-1}.

In mountainous areas, LLBs can interact with another type of thermally induced circulation, that is, with up- and down-slope winds (which are established at south-facing mountain slopes), as both circulations are favored by the same atmospheric conditions (*i.e.*, clear-sky and weak synoptic-scale pressure gradients). Anyah et al. (2006) performed modeling tests with realistic and smoothed topography for a large lake (Lake Victoria, East Africa). They showed that steep topography contributed to enhancement of both daytime and nighttime thermal gradients between the lake and land, and thus, resulted in strengthening of LLBs. Likewise, a stronger lake-land thermal contrast, and consequent, stronger land breezes were found for a large Qinghai Lake, China, Su et al. (2020) for regions of steeper topography. Similarly, due to the influence of the local topography, SLBs are also found to be stronger along the eastern in comparison to the western Adriatic coast (Klaić et al., 2009).

Recently, Xu et al. (2021) investigated 'extended' LLBs, that is, the flows that are a result of interactions between LLBs and mountain-valley winds for a small lake (42 km × 9 km). Based on observational data and the results of the atmospheric numerical model, they concluded that daytime and nighttime breezes usually formed 1–2 hours after sunrise and 1.5 hours before sunset, respectively. Additionally, Xu et al. found that daytime breezes resulted in a decrease in sensible heat flux and an increase in latent heat flux, while during the nighttime, the influence of the breeze on fluxes depended on the wind direction of the breeze.

Channeling effects of the surrounding topography on LLBs have also been considered. Lemmin and D'Adamo (1996) showed that LLBs over medium lake (Lake Geneva, Switzerland and France), were strongly modified both temporally and spatially. Namely, due to the adjoing topography, short episodes of strong winds were regularly observed over parts of the lake when channeled flows were superimposed to the cyclic pattern of SLBs.

In the present study, we investigated whether a very small elongated lake (d < 3 km) can produce LLBs. Before that, to identify days with an LLB, we defined the criteria that atmospheric variables and lake temperatures must meet during an LLB event. We focused on a lake placed in the mountainous area of Croatia (Lake Kozjak, Plitvice Lakes). The lake is approximately 2.3 km long and 0.1–0.6 km wide. The maximum and average lake depths, lake area, and volume are 46 m, 17.3 m, 0.82 km^2, and 0.01271 km^3, respectively (*e.g.*, Klaić et al., 2018). The lake belongs to Plitvice Lakes National Park (PLNP), and within the PLNP monitoring system, the lake temperatures are measured once a month. However, during a recent project dealing with lake dynamics, fine-resolution lake-temperature experiments were performed. Data collected within these experiments enabled us to detect LLB events and to describe their main features. Additionally, the present results contribute to our knowledge of the otherwise poorly documented characteristics of the recent climate of the PLNP area (Klaić et al., 2018).

As the lake is surrounded by a complex topography, at slopes which are during the daytime heated through inslolation, up- and down-slope winds should establish along with LLBs (both with generally similar wind directions throughout the day). Thus, at these regions, the two thermal circulations interact, and instead of a "pure" LLB, a resultant, somewhat stronger winds are expected. Nevertheless, this interaction would not generally affect the occurrence of an LLB event, only the intensity and timing.

2. Measurements

Lake temperatures were measured in the northern, deepest part of Kozjak Lake (φ = 44.8902° N, λ = 15.6038° E, 535 m a.s.l., red bubble in Fig. 1, right) as described in detail in Klaić et al. (2020). Lake temperatures were available at multiple lake depths at a temporal resolution of 2 min for the period from 7 July 2018 to 1 November 2020 (with occasional interruptions due to data acquisition). However, in the present study, we used only the hourly mean summertime temperatures observed at the depth closest to the lake surface (that is, a depth of 0.2 m). Specifically, we investigated the period from 8 July to 30 September each year, as all data were available for these three periods. The observed hourly mean lake temperatures at a depth of 0.2 m for the three selected summertime periods are shown in Fig. 2.

Concurrent hourly mean meteorological data (specifically, air temperature, air pressure, wind speed and direction, relative humidity and precipitation; Fig.

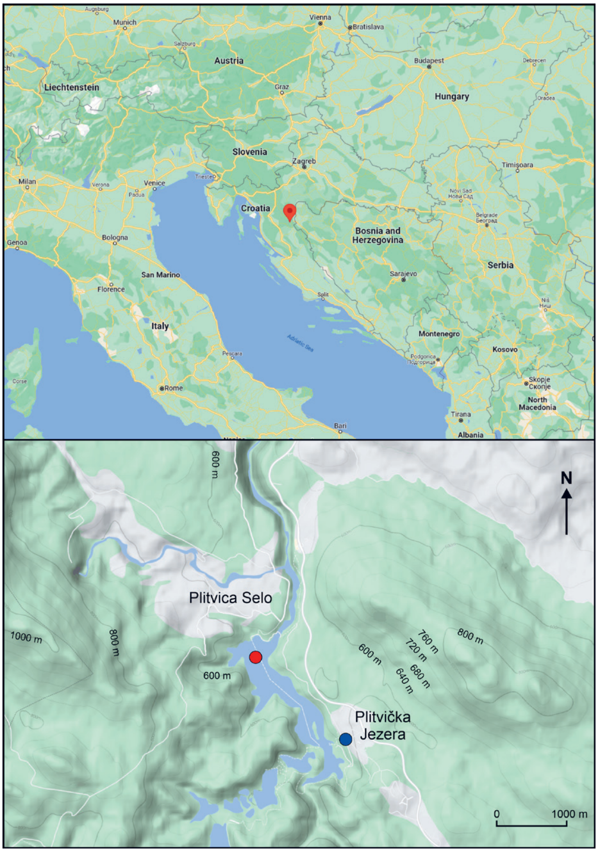

Figure 1. Position of Kozjak Lake (red bubble, *top*). A closer look at the measuring points (*bottom*). Red and blue circles correspond to the positions of the lake temperature measuring point (φ = 44.8902° N, λ = 15.6038° E, 535 m a.s.l.) and the meteorological measuring site Plitvička Jezera (φ = 44.8811° N, λ = 15.6197° E, 579 m a.s.l.) that is approximately 2 km away. (Source: © Google Maps).

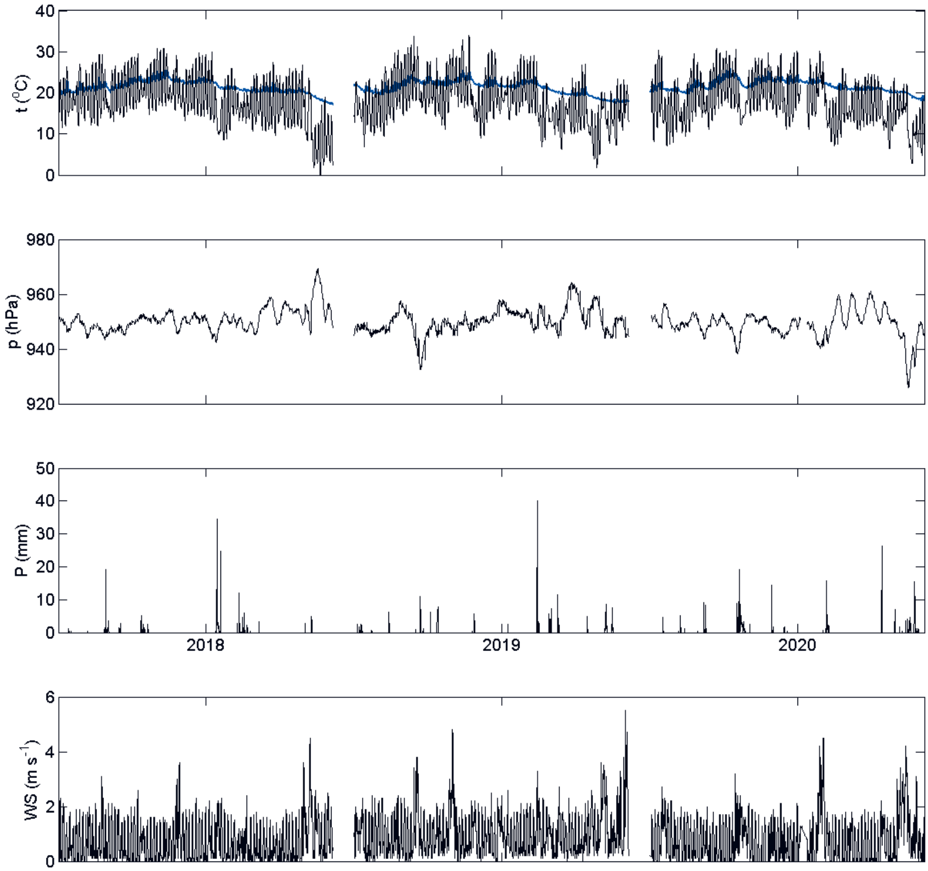

Figure 2. Observed hourly values of the air and lake temperature at a depth of 0.2 m (*t*, black and blue lines, respectively), air pressure (*p*), precipitation amount (*P*), and wind speed (*WS*) for 8 July–30 September of 2018–2020.

2) were automatically measured at the Plitvička Jezera meteorological station (φ = 44.8811° N, λ = 15.6197° E, 579 m a.s.l., yellow bubble in Fig. 1, right). Meteorological measurements are maintained by the Croatian Meteorological and Hydrological Service (MHS). MHS also performs quality control of the measured data. The meteorological site is approximately 2 km southeast of the lake temperature measuring point and approximately 200 m northeast of the southeastern lakeshore. The site is on the southwest-facing slope of Medveđak Mountain (884 m; it stretches approximately parallel to the main axis of the lake), and it is surrounded on almost all sides by nearby topographical obstacles. The lake fetch in the direction perpendicular to the lakeshore closest to the meteorological site (that is, the lake width in the vicinity of the meteorological site) is approximately 150 m long.

3. Methods

To identify days with LLB circulation, we designated several criteria based on the studies of Laird et al. (2001) and Prtenjak and Grisogono (2007). Specifically, the days with LLB should satisfy the following conditions:

1. Between 09:00 and 18:00 LST (local standard time; without summertime advancement by 1 h), winds should blow onshore for at least three consecutive hours.

2. Between 00:00 and 05:00 LST, onshore winds should not blow for more than two hours. In addition, the speeds of these onshore winds should be lower than 0.2 ms^{-1}.

3. The diurnal amplitude of the air pressure should be below 5 hPa.

4. The difference between the maximum air temperature (observed routinely at 2 m above the ground) and the maximum lake temperature measured at a depth of 0.2 m should be positive.

5. The mean air temperature between 05:00 and 07:00 LST should be lower than the mean air temperature between 16:00 and 18:00 LST.

6. The mean wind speed from 05:00 to 07:00 LST should be lower than the mean wind speed for the investigated period (8 July–30 September) of the corresponding year.

7. No precipitation occurred throughout the entire day (from 00:00 to 24:00 LST).

Conditions 2–3 and 5–7 were chosen to eliminate winds with directions that correspond to those of LLBs but are produced by stronger synoptic forcings. While Conditions 2–5 were simply adopted from Laird et al. (2001) and Prtenjak and Grisogono (2007), Conditions 1 and 6–7 were defined to take into account the small lake size and sheltering effects of the surrounding topography. Namely, instead of the wind speed limit of 5.5 ms^{-1} proposed by Laird et al. (2001) for the very large and less sheltered Lake Michigan, where stronger LLBs can be expected due to the lake size, in Condition 6, we eliminate winds stronger than the summertime means. Similarly, the condition of at least four consecutive hours of daytime onshore winds (Prtenjak and Grisogono, 2007) was defined for substantially larger water bodies (Northern Adriatic), above which more persistent breezes can be expected. Here, we employ a less rigid condition (1), that is, at least three consecutive hours with daytime lake breezes. Finally, although LLBs can favor cloud formation and eventual precipitation (*e.g.*, Laird et al., 2009, 2010; Asefi-Najafabady, 2012), a detailed inspection of the observed summertime data showed that precipitation events observed near the investigated small lake always coincided with a notable pressure and/or air temperature drop (Fig. 2); that is, they were associated with synoptic disturbances. Therefore, an additional condition (7) was introduced.

It should be noted that on days that satisfy all 7 conditions both daytime and nighttime breezes occur. In other words, days selected based on these conditions contain only persistent LLB events that last throughout the entire 24 hours, while shorter periods (that is, days for which existing lake- or land-breeze circulation is interrupted due to any reason at some point) are not taken into account.

To verify how well the above conditions define LLB events, wavelet analysis (Torrence and Compo, 1998 and Grinsted et al., 2004, with wavelet bias corrections from Liu et al., 2007 and Veleda et al., 2012) was applied. Wavelet analysis is widely used for analyzing nonstationary time series (*e.g.*, Flinchem and Jay, 2000; Mihanović et al., 2009; de Alcântara et al., 2011; Šepić et al., 2012; Vilibić et al., 2014; Potočki et al., 2017; Schmidt et al., 2018; Chang et al., 2019; Valerio et al., 2019), as it detects frequency and time signals. In other words, it points to time intervals that are characterized by an elevated energy content for a particular frequency where energy content evolves over time. Namely, the wavelet transform employs an adaptive window where low- and high-frequency events are analyzed with long and short time-intervals, respectively. Thus, a signal is analyzed over multiple time-frequency slots whose dimensions are adjusted to the local signal characteristics. As Morlet or Meyer wavelets are considered the most appropriate for environmental time series analyses (*e.g.*, Marsili-Libelli, 2016), in the present study, we employed the commonly used (*e.g.*, Mihanović et al., 2009; de Alcântara et al., 2011; Valerio et al., 2019) Morlet transform. The frequency parameter (non-dimensional frequency) was set according to Torrence and Compo (1998) to $\omega_0 = 6$, while the maximum level of decomposition (number of scales) was set to 64. All wavelet calculations were performed with MATLAB software (Version R2014a).

To estimate the relationship between the time series of the lake-land temperature difference $x(t)$ and wind speed $y(t)$ in the frequency domain, magnitude squared coherence (γ^2) was calculated as follows (*e.g.*, Holm, 2014):

$$\gamma^2 = |Pxy(f)|2/(Pxx(f) \cdot Pyy(f)),$$

where $Pxx(f)$ and $Pyy(f)$ are the power spectra of the two time series, $Pxy(f)$ is the cross spectrum, and f is the frequency. The coherence ranges between 0 and 1, where $\gamma^2 = 0$ for a particular frequency f indicates no coherence between two time series at this frequency, while $\gamma^2 = 1$ indicates a strong coherence between the two time series at frequency f. Values of the magnitude squared coherence γ^2 between the wind speed and the land-lake temperature difference were calculated using a Hamming window (*e.g.*, Solomon, 1991) with a 50% overlap. The window length was set to 256 datapoints. In the calculation, the MATLAB built-in function mscohere was used.

4. Results and discussion

Table 1 shows the basic statistics for all analyzed days and for those identified as days with an LLB (*i.e.*, those satisfying Conditions 1–7 listed in Section

3). It is worth mentioning that a day with an LLB can also be accompanied with up- and down-slope winds (which depends on particular location with respect to surrounding topography). Relative contribution of these two circulations to resultant wind speed could not be distinguished based on employed Conditions. However, these Conditions should point to presence of an LLB. Out of the 255 investigated days, 45 (*i.e.*, 17.7%) were days with an LLB. We note that due to strict conditions, the LLB events were assigned only to days with a persistent, 24-h lasting thermal circulation (that is, the days satisfying both daytime and nighttime conditions), while days in which any of the two LLB components (daytime or nighttime) was interrupted due to stronger synoptic forcing were eliminated. As expected, both the average wind speed and the standard deviation were lower for days with an LLB than for all analyzed days. This is also shown in Fig. 3, which demonstrates that the highest wind speeds for all days were approximately twice as high as the highest wind speeds for the days with an LLB.

The relative frequencies of winds from the SW quadrant, as well as for NNE and WNW winds, were similar for both all days and the days with LLB (Fig. 3). Conversely, winds from the SE quadrant, as well as NE and NW winds, exhibited different patterns for all days in comparison with only the days with an LLB. Nevertheless, for both groups of days, generally, the most frequent wind directions were NW (the most frequent for all days) or NNE and NE (the most frequent for LLB days), while winds from the SW quadrant were the rarest. While frequent NW winds point to the channeling of the flow as they are parallel to the main lake axis (Fig. 1., right), frequent NNE and NE winds are most likely associated with the two thermally induced circulations, specifically, the nocturnal (offshore) component of the LLB (*e.g.*, Keen and Lyons, 1978) and the nocturnal downslope surface winds established at south-facing slopes (*e.g.*, Klaić et al., 2003) of the Medveđak Mountain. Moreover, NNE and NE winds were accom-

Table 1. Basic statistics for all days and days with an LLB (i.e., days satisfying all seven conditions listed in Section 3) for the period from 8 July to 30 September. NALL, NLLB, and PLLB correspond to the total number of analyzed days, number of days with an LLB, and percentage of days with an LLB, respectively. The mean wind speed for all days is denoted by $v_{meanALL}$ *while the mean wind speed for the days with LLB is denoted by* $v_{meanLLB}$*. The corresponding standard deviations are* $stdv_{ALL}$ *and* $stdv_{LLB}$*.*

year	2018	2019	2020	2018–2020
N_{ALL}	85	85	85	255
N_{LLB}	21	10	14	45
P_{LLB} (%)	24.7	11.8	16.5	17.7
$v_{meanALL}$ (m s^{-1})	0.710	1.061	0.792	0.854
$stdv_{ALL}$ (m s^{-1})	0.720	0.795	0.800	0.787
$v_{meanLLB}$ (m s^{-1})	0.586	0.790	0.558	0.623
$stdv_{LLB}$ (m s^{-1})	0.639	0.617	0.664	0.648

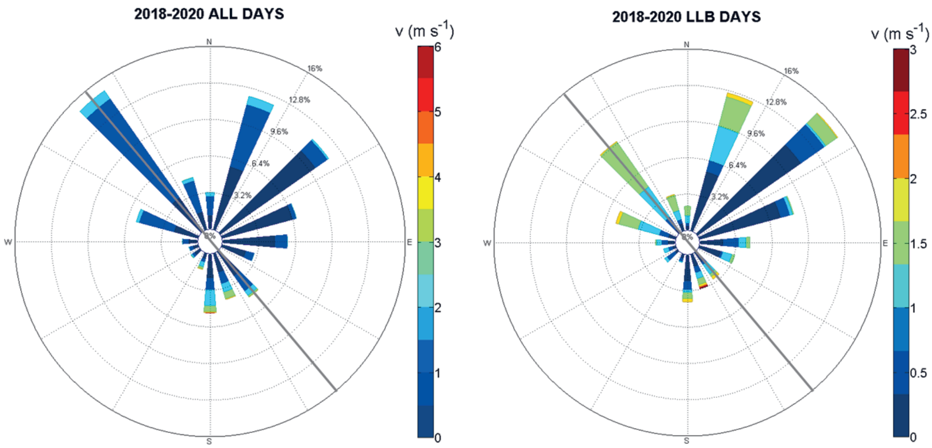

Figure 3. Wind roses for all analyzed days (*left*) and for days with an LLB (*right*). Grey solid line shows direction of the main lake axis. Note that the range of wind speed values for all days is twice as large as that for LLB days.

panied by relatively low wind speeds for both groups of days (up to 2.5 and 2 ms^{-1} for all days and LLB days, respectively).

The average diurnal variation in the wind rose for days with an LLB (Fig. 4) suggests a tendency toward wind veering, that is, anticyclonic (clockwise in the Northern Hemisphere) diurnal wind rotation, although in a mean hodograph (not shown here), the veering was not persistent throughout entire day. Based on simple theoretical considerations, wind veering is generally expected in the SLB due to the effects of the Coriolis force (Haurwitz, 1947), and it was also observed in a number of coastal sites, as described in experimental studies on the SLB (*e.g.*, Orlić et al., 1988; Prtenjak and Grisogono, 2007;) and LLB (*e.g.*, Keen and Lyons, 1978). However, for some places, an opposite (cyclonic) wind rotation was observed. This was attributed to the influence of topography/flow channeling or to strong mesoscale pressure gradients (*e.g.*, Orlić et al., 1988; Simpson, 1996; Prtenjak and Grisogono, 2007; Prtenjak et al., 2008).

As depicted in Fig. 4, as of midnight until the early morning hours (06:00 LST), weak winds, with speeds up to at most 2.3 ms^{-1} from the northeastern quadrant, prevailed. We note that the directions of these flows coincide with both the nighttime land breezes produced by the lake, and the nighttime downslope winds that are expected at the southwestern slope of the Medveđak Mountain under the same fair weather (synoptically undisturbed) conditions. Thus, the observed nighttime winds are very likely a superposition of flows produced by the two thermal circulations. Over time, winds turned clockwise, and thus, at 09:00 LST, the most frequently observed flows were southern winds. These winds were followed by northwestern flows, which were on average stronger than southern flows. In addition, although rare, the strongest winds were associated with southeastern direction on average. As both NW and SE winds roughly coincide with the main axis of the lake (Fig. 1), these winds point to channeling effects of the surrounding topography. Thus, the pattern of the wind rose at 09:00 LST reflects two influences. One is clockwise wind rotation with respect to previous times, and the other is topographically induced wind channeling. Throughout the daytime, from 12:00 to 18:00 LST, west-northwestern and later northwestern flows dominated, although north-northeastern (at 12:00, 15:00, and 18:00 LST) and southern winds (at 18:00 LST) were also prominent, which again points to a departure from straightforward clockwise wind rotation. In addition, it is notable that during the daytime, onshore winds perpendicular to the shoreline were rather scarce. This is most likely due to small lake dimensions in that direction. Thus, there is not enough water to produce a significant lake-land temperature gradient, and consequently, the lake breezes in that direction. Finally, in the evening hours (21:00 LST), the land breeze was established again, most likely accompanied by the downslope wind. Accordingly, east-northeastern and northeastern winds were the most frequent.

Figures 5–7 show the results of wavelet analysis for individual summer periods. The days with an LLB, that is, the days satisfying Conditions 1–7, which are listed in Section 3 (periods depicted in red above the top panels), coincided with elevated energies in normalized wavelet spectra associated with a 24 h period. Conversely, time intervals that had high energies associated with periods of several days (*e.g.*, the time interval from 13 to 17 August 2018 with high energy for periods of approximately 3 or more days, Fig. 5) were without LLB events. Therefore, we conclude that LLB events were well defined by Conditions

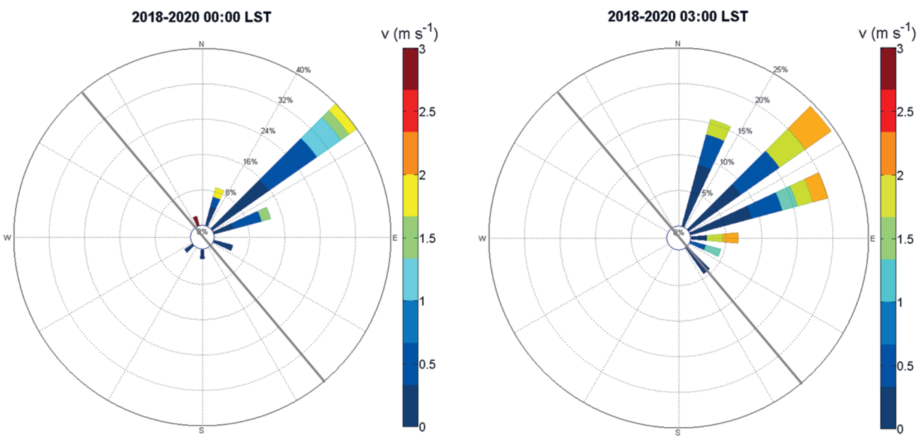

Figure 4. Diurnal variation of wind rose for days with an LLB. Corresponding times are given in local standard time (LST, without summertime advancement by 1 h). Grey solid line shows direction of the main lake axis.

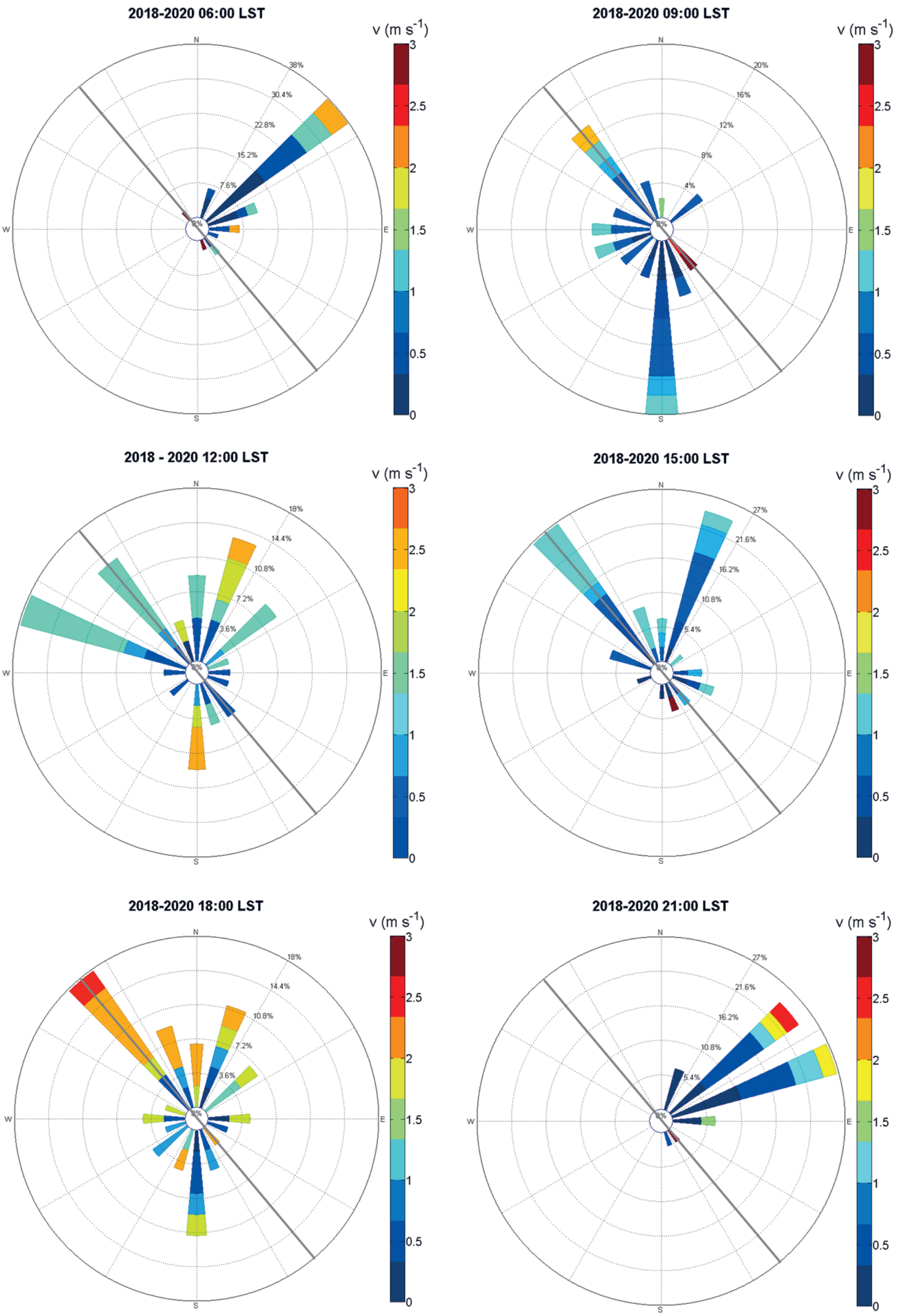

Figure 4. Continued.

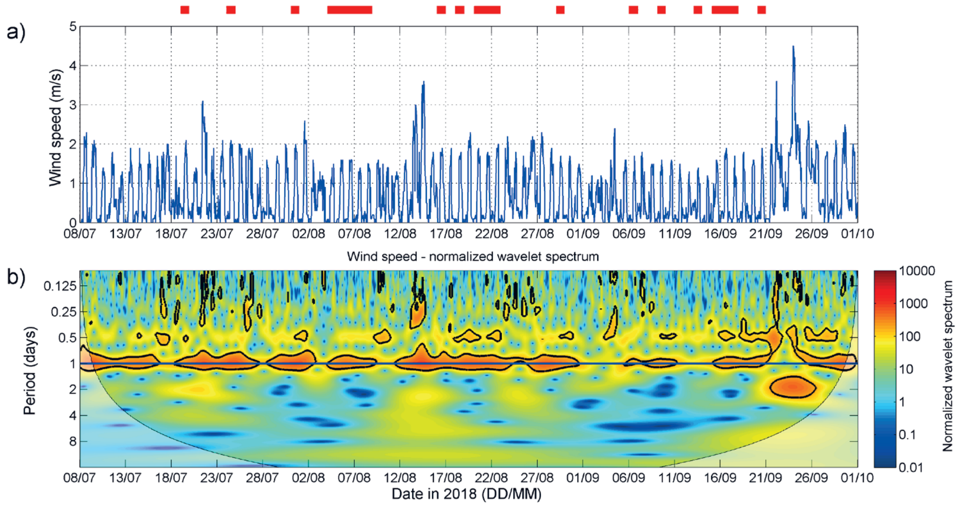

Figure 5. Wind speed (Panel *a*) and the corresponding normalized wavelet spectrum (Panel *b*) for summer 2018. Time intervals that satisfy LLB Conditions 1–7 listed in Section 3 are indicated in red above the Panel *a*. The horizontal blue line in Panel *b* corresponds to a period of 24 h. The thick black line indicates the 95% confidence level, with red noise as the background spectrum. Lighter shadings on both ends in Panel b denote regions where edge effects become important.

1–7. Additionally, we note that diurnal periodicity was present in the wavelet spectra even more frequently than suggested by Conditions 1–7. This is not surprising since due to these strict conditions, only days with persistent thermal circulation (which lasted throughout the entire 24 hours of a particular day) were categorized as days with an LLB, while days in which the LLB was interrupted at some point, as well as the days with wind speeds above the average speed during a particular summer, were omitted.

In addition, the normalized wavelet spectra of a cross-shore wind component suggested a smaller number of days with diurnal periodicity in comparison with spectra obtained for wind speed magnitude, while for the alongshore wind component the difference between the results for the wind component and the wind speed magnitude was smaller (not shown here). This points to both the channeling effects of the nearby topography and the influence of small lake dimensions in the cross-shore direction. Namely, due to the small lake dimension in the cross-shore direction (≈ 150 m), daytime breezes approximately perpendicular to the shoreline could not be fully developed, while daytime winds in directions other than perpendicular to the shoreline were channeled in along-lake directions. This is also confirmed by the results shown in Fig. 4.

Figure 8 shows the dependence of the wind speed on the difference between the air temperature at 2 m above the ground (Tair) and the lake temperature at a depth of 0.2 m (Tlake). For all days (Fig. 8 top), the wind speed increased with

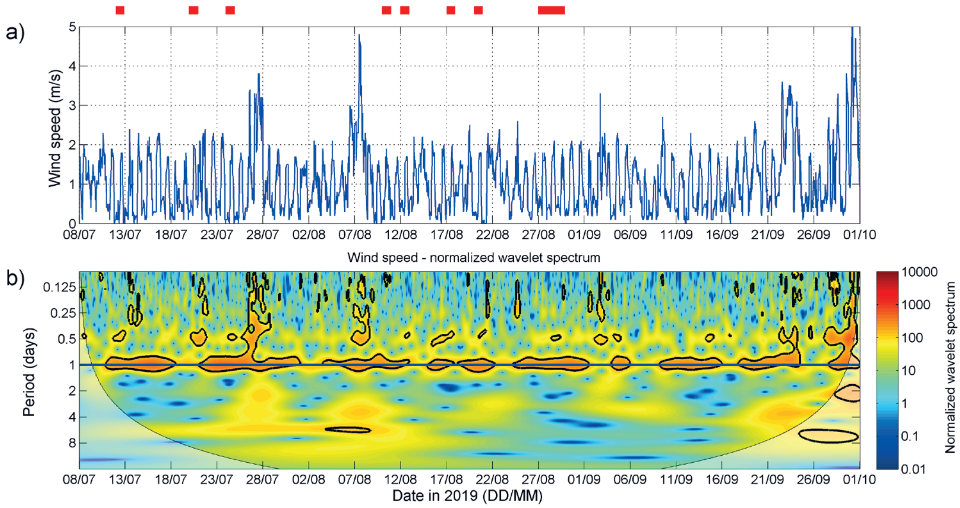

Figure 6. Same as Fig. 5, but for summer 2019.

an increase in the temperature difference for difference values above –6 °C, while for negative differences with values below –6 °C (which correspond to the nighttime), the relationship was unclear. On the other hand, for days with an LLB, for difference values below –2°C (again, nighttime), weak winds with approximately constant median values for all classes of negative temperature

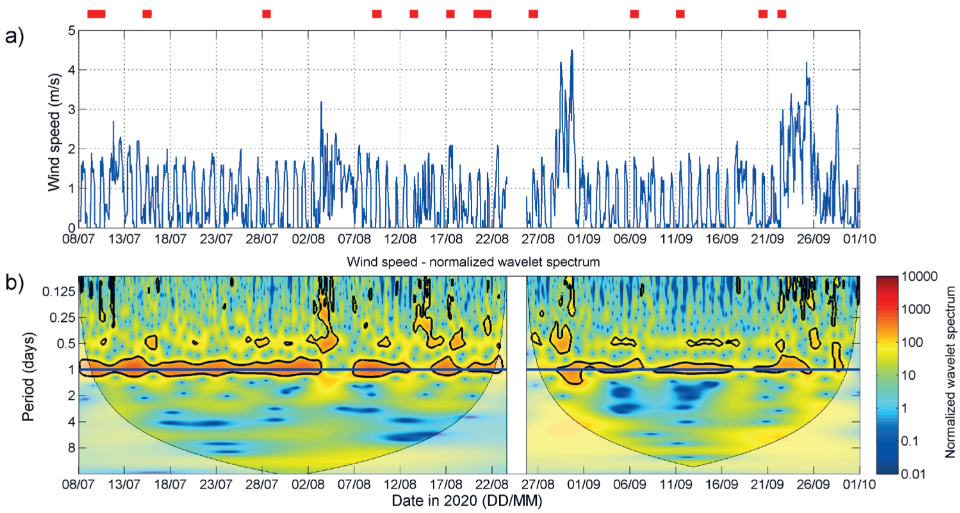

Figure 7. Same as Fig. 5, but for summer 2020. Due to missing wind data two separated wavelet spectrums were calculated.

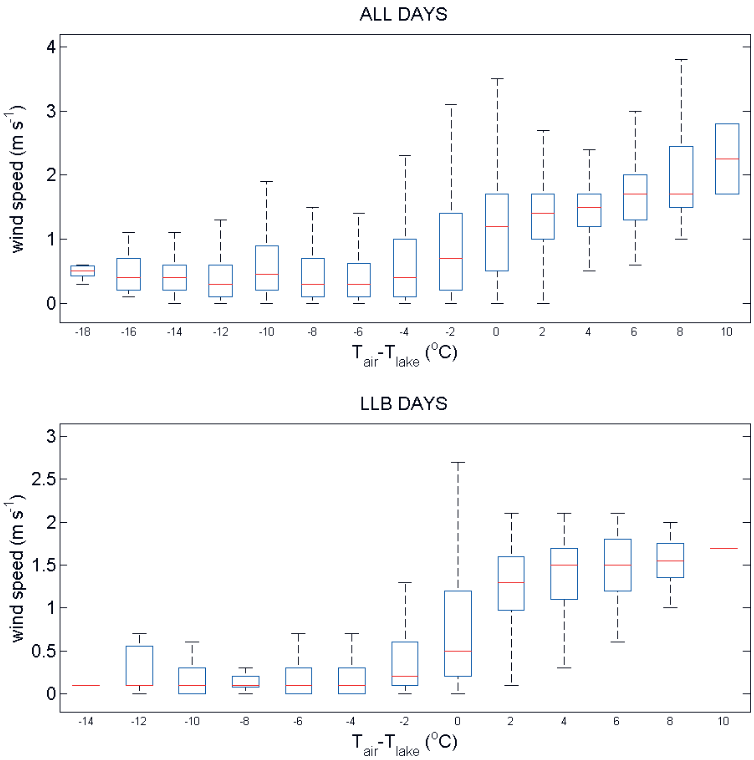

Figure 8. Wind speed *vs*. land-water temperature difference.

differences were found, while for the small negative and positive (daytime) differences, wind speeds clearly increased with an increase in the temperature difference (Fig. 8, bottom). This result differs from the findings of Giovannini et al. (2015), who did not find any relationship between the land-water temperature difference and the lake-breeze strength for northern shorelines of Lake Garda, which are surrounded by the complex topography of the Italian Alps. (Lake Garda is notably larger than Lake Kozjak. It is also elongated, and the along-lake axis is close to 50 km, while the lake width in its northern part is between 2 and 4 km.) Finally, as expected, the daytime onshore winds (winds associated with positive temperature difference in Fig. 8, bottom) were stronger than the night-time offshore winds (winds associated with negative temperature difference).

The relationship between the wind speed and the land-lake tempera-ture difference is further corroborated by the magnitude squared coherence values γ^2. As seen from Fig. 9, high coherence values between these two time series were associated with diurnal periodicity, where $\gamma^2 \approx 0.9$ and $\gamma^2 \approx 0.95$ were obtained for 2018 and 2019, respectively. As some air temperature data for 2020 were missing, γ^2 values for this year could not be calculated.

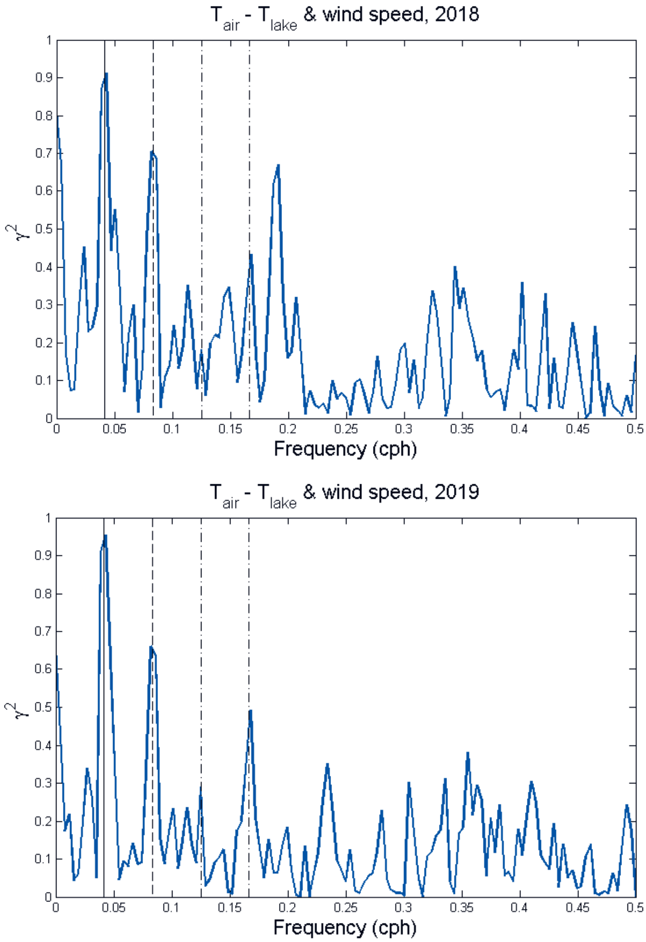

Figure 9. The magnitude-squared cohrerence (γ^2) between the hourly mean wind speed and the hourly mean land-water temperature difference. The vertical solid, dashed, dashed-dotted, and dotted lines correspond to periods of 24, 12, 8, and 6 h, respectively. Values for 2020 could not be determined since some of the air temperature data for this year were missing.

5. Conclusions

The aim of the present study was to inspect whether a small elongated lake (surface area of 0.82 km^2, along-lake axis of ≈ 2300 m, and lake width from 100 to 600 m) can produce LLBs. Days with an LLB were identified using 7 criteria that correspond to both daytime and nighttime atmospheric conditions. Thus, only days with a persistent LLB (that is, the days satisfying both daytime and nighttime meteorological criteria) were classified as days with an LLB. The days with an LLB that were identified based on prescribed criteria were characterized by elevated energy in the normalized wavelet spectra for the wind speed at a frequency corresponding to the period of 24 hours. Thus, we conclude that the defined criteria can be used to distinguish the days with persistent LLBs that were produced by small lakes from the days without or with intermittent LLBs.

Based on the obtained results, we conclude that despite of the small lake size, the produced lake-land temperature differences were large enough to produce these thermal circulation systems. Thus, 17.7% of the 255 investigated summer days were accompanied by persistent LLBs. However, we note that the observed LLBs were most likely superposed with the thermally induced up- and downslope winds, as the investigated small lake is confined by nearby mountains. Namely, both thermal circulations (up- and downslope winds and LLBs) are generally established under the same synoptically unperturbed conditions, and they both generally have similar directions throughout a day. Specifically, the directions of daytime onshore winds concur with the directions of upslope flows, while during the nighttime, the directions of offshore and downslope winds coincide. Therefore, wind speeds of "pure" LLBs produced by Lake Kozjak are most likely slightly weaker. Furthermore, as expected, daytime lake breezes were stronger than nighttime land breezes.

Due to the small lake fetch (≈ 150 m), the daytime (onshore) lake breezes approximately perpendicular to the shoreline were rather weak and less frequent. Instead, daytime winds were frequently channeled in the along-lake direction due to the surrounding topography. Thus, during the daytime, wind rotation departed from a straightforward clockwise direction, although diurnal variation in the wind rose exhibited a tendency toward such wind rotation. Conversely, during the nighttime, a clear clockwise wind rotation was present.

In contrast to findings for the narrow part of an approximately 20 times longer elongated alpine lake (Lake Garda, Giovannini et al., 2015), the present results suggested a clear relationship between the lake-land temperature difference and the strength of LLBs.

Finally, to obtain a more complete picture of the LLB characteristics (such as, the height of a circulation cell and inland penetration) for Lake Kozjak, an atmospheric numerical model should be applied. Due to the small lake size and the complex surrounding topography, a fine resolution should be employed in the model application. Furthermore, a fine resolution modeling study could also serve to investigate impacts of surrounding topography on resultant breezes (including both, relative contributions of LLBs and up- and down-slope winds, and channeling effects). In that case, results of numerical simulations with realistic topography (*i.e.*, control simulations) should be compared to results of sensitivity experiments in which the surrounding mountains are replaced with flat areas.

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SAŽETAK

Povjetarac nad malim duguljastim jezerom (Kozjak, Plitvička jezera, Hrvatska)

Darko Staver, Hrvoje Mihanović i Zvjezdana B. Klaić

Temperatura malog duguljastog jezera (2,3 km × 0,1–0,6 km; maksimalna dubina od 46 m) smještenog u brdsko-planinskom području mjerena je tijekom tri razdoblja od srpnja do rujna u blizini jezerske površine (dubina od 0,2 m). Istovremeno su u blizini jezera mjerene standardne meteorološke varijable. Na temelju atmosferskih i jezerskih uvjeta definirani su kriteriji za detekciju dana s perzistentnim povjetarcem (LLB). Rezultati su pokazali da se u 17,7% ispitanih dana nad jezerom uspostavljao povjetarac. Svi ti dani bili su popraćeni s povišenom energijom u normaliziranom valićnom spektru brzine vjetra pri periodu od 24 sata. Dnevni povjetarac s jezera najčešće je zbog okolne topografije bio kanaliziran u smjeru glavne osi jezera. Sukladno tome, dnevno anticiklonalno zakretanje vjetra bilo je poremećeno. Međutim, noću je bila izražena rotacija vjetra u smjeru kazaljke na satu. Nadalje, rezultati su pokazali jasnu vezu između jačine povjetarca i razlike temperature zraka nad tlom i nad jezerom.

Ključne riječi: dnevna periodičnost, koherencija, ruža vjetra, termička cirkulacija, valićna analiza.

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