INTERNATIONAL JOURNAL OF CLIMATOLOGY
RMetS Royal Meteorological Society

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| Journal: | *International Journal of Climatology* |
| Manuscript ID: | JOC-14-0250.R2 |
| Wiley - Manuscript type: | Research Article |
| Date Submitted by the Author: | n/a |
| Complete List of Authors: | Giovannini, Lorenzo; University of Trento, Department of Civil, Environmental and Mechanical Engineering<br>Laiti, Lavinia; University of Trento, Department of Civil, Environmentel and Mechanical Engineering<br>Zardi, Dino; University of Trento, Department of Civil, Environmentel and Mechanical Engineering<br>de Franceschi, Massimiliano; University of Trento, Department of Civil, Environmentel and Mechanical Engineering |
| Keywords: | lake breeze, valley winds, Ora del Garda, mountain meteorology, synoptic-scale flow |
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# Climatological characteristics of the Ora del Garda wind in the Alps

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Abstract

The Ora del Garda is a coupled lake and valley breeze regularly blowing from the northern shorelines of Lake Garda, in the Italian Alps, especially during warm-season clear-sky days. The climatological characteristics of this wind are investigated through the analysis of 10 years of observations collected at two representative surface weather stations – one on Lake Garda's shore and the other 30 km inland. Furthermore, the possible influences of the land-water temperature contrast and of the synoptic wind on the development and the propagation of the Ora del Garda are analysed. Lake breeze days are identified by means of a set of objective criteria based on observations of solar radiation, wind speed and direction at the two stations.

The analysis highlights that, on the lake's shoreline, the breeze develops on about 70% of the days in the warmest months, while it rarely occurs from October to February. Moreover, in the warmest months, the Ora del Garda reaches the inland weather station on about 80-90% of the days on which it blows on the lake's shore, after 3.5 h on average. It displays rather strong intensities, reaching average velocities of 5 m $s^{-1}$ and gusts of 10 m $s^{-1}$, respectively in summer on the lake's shore and in spring at the inland weather station.

No clear relationship is found between the land-water temperature contrast and the lake breeze strength. On the other hand, synoptic winds are observed to affect significantly the development of the breeze. In particular, onshore synoptic winds are associated with stronger intensities at the lake's shore. Moreover, in these situations the Ora del Garda propagates faster and is detected earlier at the inland weather station.

Keywords: mountain meteorology – lake breeze – valley winds – Ora del Garda – synoptic-scale flow.

# 1. Introduction

A variety of daily-periodic winds typically develop in the Alpine region under fair weather conditions, playing a central role in determining mountain climate and weather (Barry, 2008). These thermally-driven airflows develop as an organised and interacting system of air motions, including regional scale circulations, such as mountain-plain winds (Frei and Davies, 1993), mesoscale flows, such as valley winds (Rampanelli et al., 2004; Rotach and Zardi, 2007; Serafin and Zardi, 2011; Zardi and Whiteman, 2013), and local scale currents, such as slope winds (Serafin and Zardi 2010a,b). The fundamental mechanisms of mountain winds are well documented, as they have been extensively studied since the 1930s (Wagner, 1938; Defant, 1949, 1951). In particular, it has been clearly shown how the along-valley pressure gradients driving valley winds are induced by the higher amplitude of the daily temperature cycle occurring in the valley than over the adjacent plain, and leading to a distinct wind reversal between day and night (Vergeiner and Dreiseitl, 1987).

In a similar way, daily-periodic thermally-driven local circulations are also produced along coastal regions by the differential heating and cooling of neighbouring water and land surfaces and overlying air masses. In particular, during daytime the expansion of warmer air over land, vertically limited by a capping stable layer, results in a land-water pressure difference near the surface, originating an onshore flow and a weaker compensatory return current aloft (Simpson, 1994). However such breeze initially develops in a rather different way than an up-valley wind. Indeed the leading edge of the sea/lake breeze is essentially similar to a small-scale cold front, whose inland penetration is accompanied by a sharp decrease in temperature, increase in moisture content, and sudden shift in wind velocity and direction. However these features are less clearly observed as the front moves further inland, as marine/lake air properties are gradually modified. Sea and large-lake breezes have been widely observed and thoroughly investigated since the 1950s (see for example the climatological studies by Lyons, 1972; Laird et al., 2001; Furberg et al., 2002; Telišman Prtenjak and Grisogono, 2007; Zumpfe and Horel, 2007; Azorin-Molina and Chen, 2009; Papanastasiou and Melas, 2009; Azorin-Molina et al., 2011; Bajamgnigni Gbambie and Steyn, 2013, and the thorough reviews of theoretical, observational and numerical investigations offered in Atkinson, 1981; Simpson, 1994; Miller et al., 2003; Crosman and Horel, 2010, among others). On the contrary, to the authors' knowledge, less attention was paid to a systematic characterisation of breezes arising over small lakes (i.e. lakes of a few-kilometre size: cf. Segal et al. 1997). However, small lakes can produce their breeze systems and deeply influence the climatology of large regions, with important repercussions on pollutants' dispersion, human thermal comfort, tourism and outdoor activities. Moreover, even when a real lake-breeze system is not produced, small lakes can still significantly affect surface energy budgets, inducing strong modifications of the local airflow (Bischoff-Gauß et al., 2006).

Complex sea/lake breeze behaviours are generally found when these systems interact with topography-driven circulations, induced by complex coastal orography. In these cases, depending on the water body size, circulations may develop with different strengths. For example Kondo (1990), using idealised numerical simulations, provided evidences of an effective enhancement of the sea breeze in connection with a valley mouth in front of the ocean, leading to a so-called "Extended Sea Breeze" regional scale unified flow. Similarly, intensive observations of the airflow and the thermal structure of the atmosphere in the basin of Lake Tekapo (Sturman et al. 2003a,b) revealed a complex lake/valley-combined wind system, referred to as "Extended Lake Breeze" (McGowan et al., 1995; McGowan and Sturman, 1996; Kossmann et al., 2002). Indeed, Bergström and Juuso (2006) found that a continuous source of cold air at the valley bottom, such as a lake, leads in general to higher diurnal up-valley wind speeds. Recently, a lidar-based detailed picture of a sea breeze transitioning into an up-valley flow was provided by de Wekker et al. (2012), who also observed an acceleration of the breeze in the up-valley direction, as a result of the enhanced warming and the dynamic channelling produced by the valley.

The present work aims at investigating the climatology of the so-called "Ora del Garda" circulation, an unusually intense up-valley wind, regularly occurring in spring and summer in the south-eastern Italian Alps. This wind arises as a lake breeze over the northernmost part of Lake Garda, and extends northward by channelling in the valleys nearby, until, on most days, it breaks out into the Adige Valley, north of the city of Trento (Fig. 1). Here it interacts with the local up-valley wind, producing a strong and gusty flow in the area. The Ora del Garda is one of the most regular meteorological phenomena in the region, and consistently marks the local climate, influencing the city of Trento in the Adige Valley (Giovannini et al. 2011, 2013, 2014a). Moreover the Ora del Garda produces significant effects on local tourism and outdoor activities, as the northern part of Lake Garda is a well-known spot for sailing and windsurfing (~3 millions of tourists per year).

Early investigations on the Ora del Garda wind were carried out by A. Defant (1908, 1909), who analysed the pressure gradients associated with the development of valley winds between the Po Plain and the Adige and Sarca valleys (Fig. 1). Later on, the anomalous behaviour of diurnal winds in the Adige Valley north of Trento, due to the interaction with the Ora del Garda, was the subject of various investigations by German and Austrian meteorologists, as reported in Wagner's (1938) review on valley winds. The study of this wind has been recently resumed: a preliminary characterisation of the Ora del Garda from data collected at surface meteorological stations was performed by Daves et al. (1998) and Baldi et al. (1999). Furthermore various targeted measurement campaigns were carried out, including not only intensive surface observations (de Franceschi et al., 2002), but also airborne measurements by means of an instrumented motorglider (de Franceschi et al., 2003; Rampanelli and Zardi, 2004; Laiti et al., 2013a,b, 2014a), which explored the upper valley atmosphere and the boundary layer structure associated with the breeze development.

The main goal of the present paper is to determine the climatological features of the Ora del Garda and the main factors affecting its development. Accordingly, statistics are obtained on the basis of data over a 10-year period from two surface weather stations, one located at the Lake Garda shore and the other about 30 km inland, where the Ora del Garda overflows into the Adige Valley. These are the only stations in the area with a long and reliable dataset, suitable for such an analysis. Nevertheless, their data allow the investigation of the two key stages of the development of the Ora del Garda: its onset as a pure lake breeze at the lake's shore and its arrival in the Adige Valley, flowing down the western sidewall of the valley. Furthermore, lake's surface temperature observations and

700-hPa level wind speed and direction from model reanalysis were also analysed to investigate the role of land-water temperature contrasts ($\Delta T_{l\text{-}w}$) and of the synoptic wind in the development and propagation of the Ora del Garda.

Accordingly, the paper is organized as follows. In section 2 a concise introduction to the topography of the area where the Ora del Garda develops is provided, along with the description of the dataset adopted in the present study and the criteria used to objectively select lake-breeze days. The climatological characteristics of the Ora del Garda at the two weather stations and the dependence on $\Delta T_{l\text{-}w}$ are presented in section 3, while the influence of synoptic winds is analysed in section 4. Section 5 contains a discussion of the climatological features of the Ora del Garda in comparison with findings from similar studies. Finally, the principal results are summed up and conclusions are drawn in section 6.



## 2. Data and methods

*a) Study area*

The Ora del Garda develops at the northern shorelines of Lake Garda and then channels into the natural corridor formed by the Sarca Valley and the nearby Lakes Valley (Fig. 1). These valleys represent the northward extension of the Lake Garda basin, and run almost parallel to the nearby Adige Valley, from which they are separated by the Mount Bondone chain for approximately 30 km in SSW-NNE direction. The Sarca Valley consists of a rather wide and flat region, facing Lake Garda and displaying an altitude slightly higher than the lake's surface (65 m above sea level, ASL), with the only exception of the isolated relief of Mount Brione (376 m ASL). The Lakes Valley is geographically connected on its southern side to the Sarca Valley, while on the northern side it joins with the adjacent Adige Valley on its western sidewall, through the elevated saddle of Terlago (minimum height 580 m ASL), which is incumbent on the Adige Valley floor (200 m ASL) through a jump of about 400 m, immediately north of the city of Trento. Through this gap the Ora del Garda overflows into the Adige Valley, flowing down this steep sidewall. The altimetric profile of the valley is shown in Fig. 2. The average valley floor slope increases northward, from 1% (lower Sarca basin) to 4% (Lakes Valley). The surrounding crests height ranges between 1500 and 2200 m ASL, providing an average valley depth of about 1500 m.

*b) Dataset*

The climatological characteristics of the Ora del Garda were investigated using data from two surface weather stations, namely Riva del Garda (RIV), located on the shores of Lake Garda, and Gardolo (GAR), in the Adige Valley (Fig. 1), immediately below the Terlago saddle, where the Ora del Garda overflows into the valley. The dataset covers the years 2003-2012 and is composed of data from measurements of wind speed and direction and air temperature taken at both weather stations, and global solar radiation at RIV. For all the observed variables recorded data were available as hourly averages, with the exception of the additional information on hourly maximum wind gusts (based on gusts recorded every 10 s). Moreover, global solar radiation data from Arco weather station (ARC), located close to RIV (Fig. 1), were used to fill the gaps of RIV record (Laiti et al. 2014b). Wind speed and direction are measured at 5 m above ground level (AGL) at RIV, and at 3 m AGL at GAR, while temperature is measured at 2 m AGL at both stations. Both stations are equipped with an anemometer Davis Mod. 6410. Wind measurements were quality-controlled following the procedures reported in Jiménez et al. (2010) and Chávez-Arroyo and Probst (2013) (cf. Giovannini et al., 2014b for more details).

Hourly observations of lake water temperature at 10-m depth close to RIV station were used as a proxy for air temperature above the lake, following previous similar studies (e.g. Furberg et al., 2002), to evaluate the influence of $\Delta T_{l-w}$ on the development of the lake breeze. Water lake temperature is measured with a Yellow Spring (YSI) Mod. 6600 EDS probe. Unfortunately, water lake measurements began in 2010 and thus this dataset covers only the period 2010-2012.

Finally, in order to investigate the influence of the synoptic-scale flow on the development of the lake breeze, wind speed and direction evaluated at 700 hPa height from the National Center for Environmental Prediction (NCEP) Final Operational Global Analysis data on 1-degree grids were also used. In particular, daily values at 1300 LST at the grid point where RIV lies were analysed.

*c) Selection of lake breeze days*

Lake breeze days at the lake's shore were objectively identified by means of criteria applied to data from RIV station. These criteria were suggested by previous climatological investigations of sea breezes (e.g. Borne et al., 1998; Telišman Prtenjak and Grisogono, 2007; Azorin-Molina and Chen, 2009) and take into account both the physical mechanisms leading to the development of the lake breeze and its typical features, especially the wind shift from offshore to onshore in the morning and the opposite reversal in the evening. The above criteria are defined as follows:

(I) Global solar radiation until noon is > 30% of the maximum radiation measured in the same time period in that month. This criterion was selected on the basis of preliminary investigations of the relation between solar radiation and the strength of the lake breeze. It was found that the development of the lake breeze depends more on morning solar radiation than on daily radiation. In particular, it was found that the lake breeze very rarely develops when the morning solar radiation is < 30% of the maximum radiation in the same time period (not shown here).

(II) Wind direction (WD) reverses from offshore to onshore in the period between 2 hours after sunrise and 2 hours before sunset.

(III) WD becomes offshore or wind speed (WS) becomes < 1 m $s^{-1}$ after sunset.

(IV) WD is offshore or WS is < 1 m $s^{-1}$ for most of the hours between midnight and sunrise. This test aims at eliminating days with strong onshore synoptic wind, which might be wrongly interpreted as lake breeze.

(V) 135°N < WD < 255°N (i.e. valley axis ±60°, direction of the lake breeze) and at the same time WS is > 2 m $s^{-1}$ for at least 3 hours between 2 hours after sunrise and 2 hours after sunset.

As the available lake temperature measurements cover only the last 3 years of the analysed period, a criterion based on $\Delta T_{l\text{-}w}$ − which is the leading mechanism for the development of the lake breeze − could not be used (e.g. Borne et al., 1998; Telišman Prtenjak and Grisogono, 2007). Instead, global solar radiation (criterion I) is used here to identify days with a sufficient overheating of air temperature over land. However, an analysis of the influence of $\Delta T_{l\text{-}w}$ on the lake breeze strength is presented in section 4d.

Furthermore, to identify days when the lake breeze reaches GAR, an additional test was applied to wind speed and direction data measured at this weather station:

(VI) WD is in the range 240°N ± 30° and, at the same time, WS is > 2 m $s^{-1}$ for at least 1 hour in the period between the onset of the lake breeze at RIV and 2 hours after its cessation (240°N is the typical direction of the Ora del Garda at GAR).

The statistical analysis presented in section 3 includes onset and cessation times of the Ora del Garda at RIV and GAR. The onset time at the two stations is defined as the first hour in which criteria V and VI are satisfied respectively. On the other hand, the cessation time is defined as the first hour in which those criteria are no more met, and remain unsatisfied in the following hours too.

# 3. Ora del Garda climatology

In the following paragraphs the main climatological features of the Ora del Garda are discussed. Annual cycles of the characteristics of the breeze are presented using one month as averaging period. A preliminary analysis about the sensitivity of the results on the averaging period length was conducted, highlighting that averaging periods shorter than one month do not add relevant information, and instead display less robust statistics, due to the lower number of Ora del Garda days.

*a. Climatology at the lake's shore*

By applying the above criteria it turns out that, as expected, the lake breeze at RIV displays the highest frequencies of occurrence in the warmest months, reaching values around 70%. On the other hand, in wintertime the Ora del Garda rarely occurs at RIV. When the Ora del Garda develops, the average diurnal cycle of wind speed and direction displays alternating weak down-valley winds at night (land breeze), and stronger up-valley winds during the day (lake breeze, i.e. Ora del Garda), as shown in Fig. 3. Furthermore, the box and whisker plot in Fig. 5a highlights that the average velocity of the lake breeze tends to be higher in the warmest months, when median values around 5 m $s^{-1}$ occur. The same behaviour is found for the maximum daily gust speed, which displays median values slightly lower than 10 m $s^{-1}$ in June and July.

The annual cycle of the lake-breeze onset time retraces the cycle of the local sunrise (calculated considering the orography), shifted by 3-5 hours (Fig. 6). However it can be noted that, in the April-August period - when the lake breeze is best developed - the time lag between the local sunrise and the onset of the lake breeze becomes progressively longer. This may be attributed to the progressive warming of the lake surface during these months, and to the consequent later development of the land-water thermal contrast controlling the onset of the lake breeze. Furthermore the occurrence of the maximum intensity (maximum gust) of the lake breeze seems to follow a similar behaviour, with earlier occurrences in April and May than in the following months. However the annual variability is less marked than for the onset time, and the median value ranges from 1400 LST to 1500 LST in the whole year. The timing of the Ora del Garda cessation at RIV is strongly influenced by the local sunset time: it occurs on average around sunset, with the latest cessation times, around 1800 LST, in June and July (i.e. close to the summer solstice). As a consequence the annual cycle of the duration of the Ora del Garda follows that of the insolation time: in June the Ora del Garda lasts on average for 7 hours, while considerably shorter durations are found in winter and fall.

Figure 6 also highlights that cessation times of the lake breeze are characterised by a high variability, which is considerably higher than for the onset time. This may be explained observing that local weather conditions in the afternoon are strongly influenced, especially in the warm season, by the development of diurnal convective clouds, favoured by orographic factors, which can affect the duration of the lake breeze.

*b. Climatology in the Adige Valley*

Except for the coldest months, when the Ora del Garda is not well-developed, this local circulation reaches GAR on most days on which it blows at RIV, with rather constant frequencies in the March-October period, ranging between 76% in October and 93% in April (Fig. 7). Accordingly, it is also found that the lake breeze does not reach GAR mostly on the days when it is not well developed at RIV. Actually, on the days when the Ora del Garda does not reach GAR, it displays a weaker average velocity at RIV (with a deviation of -0.35 m $s^{-1}$ with respect to the mean, calculated on a monthly basis), and a shorter average duration, with a later onset (~30 min) and an earlier cessation (~55 min). Figure 3 shows the diurnal cycle of wind speed and direction at GAR on Ora del Garda days. It is characterised by a very weak down-valley wind at night and in the morning, while in the afternoon the wind direction is not aligned with the valley axis (N-S); instead, a rather strong cross-valley wind blows from WSW, marking the arrival of the

Ora del Garda into the Adige Valley. From the box and whisker plots in Fig. 8 it can be seen that, unlike RIV results, the intensity of the Ora del Garda at GAR (both average and gust speed) is considerably stronger in spring than in the following months. In March and April the median of the average velocity is about 4.5 m $s^{-1}$, while the maximum daily wind gusts reach median values of 12 m $s^{-1}$, higher than those registered at RIV. The higher velocities in these months are likely to be caused by the larger thermal contrasts between the colder Ora del Garda, which arrives into the Adige Valley after flowing down its western sidewall, and the warmer air inside the Adige Valley occurring in these period of the year with respect to the summertime, due to the progressive warming of the lake water.

The annual cycles of the time of the onset and of the maximum intensity (i.e. hour of the maximum gust) of the Ora del Garda at GAR display similar features to those found at RIV, though with a time shift of approximately 3.5 hours (Fig. 9). Indeed in the warm season the onset occurs at GAR between 1400 LST and 1500 LST, while the maximum intensity around 1700 LST. On the other hand, the annual cycle of the cessation time is different from RIV: in particular the latest cessation times occur in spring, with a progressive anticipation of the end of the Ora del Garda in the following months. Again, this behaviour is probably due to the stronger thermal contrasts occurring in spring between the colder air masses advected by the Ora del Garda and the warmer air inside the Adige Valley.. Therefore, above the Terlago saddle the air remains potentially colder than the air at the same level in the Adige Valley for a longer time in spring, continuing to flow down into the Adige Valley (cf. de Franceschi et al., 2002, Laiti et al., 2014a).

*c. Influence on the air temperature*

The onset of the Ora del Garda at RIV weather station is marked, on most days, by a sudden drop in the air temperature, following the onshore advection of the cooler air mass from above the lake. This behaviour affects significantly the climatology of the diurnal cycle of air temperature at RIV, as can be seen in the box and whisker plots in Fig 10a, which refers to the days when the Ora del Garda is developed. Air temperature drops around midday, and remains rather constant in the afternoon, with lower values than at other weather stations lying in the nearby valleys (see for example Laiti et al., 2014a). The magnitude of the temperature drop (calculated as the difference between the temperature in the hour after the onset of the Ora del Garda and the temperature in the hour before its onset) can be better appreciated from the box and whisker plots in Fig. 11: the median temperature drop is, in absolute value, more pronounced in April and May, with values close to -2.5°C, and becomes progressively smaller in the following months. Both in fall and in winter, when the lake surface temperature is comparable to the daytime air temperature at RIV, the temperature drop is not significant or even positive..

The arrival of the Ora del Garda is associated with a temperature decrease also at GAR, starting from 1400 LST (Fig. 10b). However, the strength of the temperature drop is smaller at GAR than at RIV, as the lake breeze gradually loses its characteristics while propagating along the Sarca and Lakes valleys. Moreover, on some days this drop is not clearly distinguishable from the "normal" afternoon cooling due to the decreasing solar radiation. For this reason it is not possible to estimate univocally the temperature drop induced by the arrival of the Ora del Garda at GAR. However, the effects of the breeze in the Adige Valley in the area north of Trento are still significant, as afternoon temperatures remain on average 1-2°C lower than in the area south of the city, which is not affected by this circulation (see also Giovannini et al., 2014a).

*d. Influence of the land-water temperature difference*

The analysis presented in this section aims at investigating the relationship between the lake breeze strength and $\Delta T_{l\text{-}w}$ on the lake's shore. Here $\Delta T_{l\text{-}w}$ is defined as the temperature difference between the air temperature at RIV and the lake water temperature measured close to this station. Following Telišman Prtenjak and Grisogono (2007), the relationship between $\Delta T_{l\text{-}w}$ and the lake breeze intensity is first investigated during all the hours when the Ora del Garda blows for both the mean and the maximum average hourly velocity, scanned for a $\Delta T_{l\text{-}w}$ interval of 0.1°C (Fig. 12). It is found that both the mean and the maximum wind speeds tend to slightly increase as $\Delta T_{l\text{-}w}$ increases until $\Delta T_{l\text{-}w} \simeq 3$°C, whereas wind velocity decreases for further increments of $\Delta T_{l\text{-}w}$. This behaviour is similar to what found by Telišman Prtenjak and Grisogono (2007) for the sea breeze on the Croatian coast. A similar relationship was found also for the maximum wind gusts (not shown here). This counterintuitive behaviour follows from to the nontrivial interaction between $\Delta T_{l\text{-}w}$ and the lake breeze intensity. Indeed $\Delta T_{l\text{-}w}$, which first drives the onset of the lake breeze, decreases at the breeze arrival, due to the advection of cooler air from the lake and the magnitude of this decrease depends in turn on the lake breeze strength. In order to screen this feedback effect, the relation between $\Delta T_{l\text{-}w}$ in the hour preceding the onset of the Ora del Garda, i.e. the temperature contrasts directly driving the development of the breeze, and the strength of the lake breeze in the hour following its onset was also explored. However, results highlighted again that the lake breeze strength is not significantly affected by $\Delta T_{l\text{-}w}$ (not shown here). In particular it was found that, on average, the Ora del Garda intensity in the hour following its onset is rather constant for $\Delta T_{l\text{-}w}$ in the hour before its onset ranging from 0 to 12°C.

# 4. Influence of the synoptic wind

As said above, in order to investigate the influence of the synoptic-scale flow on the lake breeze, wind speed and direction at the 700-hPa level from NCEP reanalysis over RIV station were used as representative of the geostrophic wind above the target area. Similarly to Azorin-Molina and Chen (2009), surface data were first aggregated in classes according to the synoptic wind direction with respect to the lake's shore. Then two supplementary subclasses were created, by selecting within the onshore and offshore wind direction classes only the data corresponding to synoptic wind speed > 8 m s$^{-1}$. The resulting classes are identified as follows (see also Fig. 1c):

- Onshore (On): 135°N ≤ WD ≤ 255°N
- Onshore Strong (OnStr): 135°N ≤ WD ≤ 255°N and WS > 8 m s$^{-1}$
- Offshore (Off): WD ≤ 75°N or WD ≥ 315°N
- Offshore Strong (OffStr): WD ≤ 75°N or WD ≥ 315°N and WS > 8 m s$^{-1}$
- Parallel East (E): 75°N < WD < 135°N
- Parallel West (W): 255°N < WD < 315°N

This analysis was performed for the April-September period only, to evaluate the effects of the synoptic wind when the Ora del Garda is best developed.

*a. Influence of the synoptic wind at the lake's shore*

Figure 13 shows that the synoptic wind influences significantly the Ora del Garda intensity at RIV. Both average velocity and maximum daily gusts tend to be stronger when an onshore synoptic wind blows. Differences of the order of 0.3-0.5 m $s^{-1}$ and 1.0-1.2 m $s^{-1}$ between OnStr class and Off, OffStr and W classes are found for the average velocity and the gusts respectively. The differences between OnStr and E classes are even larger, resulting in 1.0 m $s^{-1}$ and 2.4 m $s^{-1}$ for the average velocity and the gusts respectively. In fact, the weakest intensity of the lake breeze occurs with the 700-hPa wind blowing from East. This is likely due to the fact that, in most cases, easterly winds channelling in the valley are deflected and appear at the lowest levels as northerly winds (offshore), which contrast the development of the lake breeze (cf. Gross and Wippermann, 1987; Whiteman and Doran, 1993). The E class is also associated with shorter durations of the Ora del Garda, with a later onset (30 min later than OnStr) and an earlier cessation (30-50 min earlier than the other classes).

*b. Influence of the synoptic wind in the Adige Valley*

Results presented in section 3b highlighted that the Ora del Garda does not develop enough to reach the Adige Valley only on average on 14% of the days in which it is observed to blow at RIV in the April-September period. However, from the analysis of wind at the 700-hPa level, it is found that this percentage is not constant within the four wind direction classes considered: higher frequencies are found for easterly (25%) and offshore winds (16%), than for onshore (11%) and westerly winds (9%). These results are coherent with the above findings that the Ora del Garda at RIV has on average a weaker intensity and a shorter duration on the days in which it does not arrive at GAR (see section 3b).

Differently from what was found at RIV, Fig. 14 shows that at GAR the Ora del Garda is stronger with offshore (especially with OffStr) than with onshore 700-hPa winds. The differences reach ~0.3 m $s^{-1}$ and ~1 m $s^{-1}$ for the average velocity and the maximum daily gusts respectively. This is probably connected to the fact that the up-valley wind south of Trento is stronger with onshore (southerly) synoptic winds and, as a consequence, it contrasts more effectively the arrival of the Ora del Garda into the Adige Valley (see below), as highlighted by the numerical simulations presented in Giovannini et al. (2014a) for a typical sunny summer day.

Figure 14 shows that the synoptic wind has a significant influence also on the timing of the lake breeze arrival at GAR. The onset time occurs on average 50-60 min earlier for OnStr than for Off and OffStr, and differences are even greater (~1 h 10 min) when compared with easterly synoptic winds. This is probably due to the stronger intensity of the lake breeze at RIV under OnStr conditions in comparison with the other classes, (in particular with the E class), as well as to the slower propagation of the lake breeze along the Sarca and Lakes valleys when a contrasting synoptic wind occurs. In fact, it is found that the propagation of the Ora del Garda from RIV to GAR is slower with easterly and offshore synoptic winds, than with onshore and westerly ones (not shown). It is likely that easterly winds are particularly effective at slowing down the lake breeze propagation in the northernmost Lakes Valley, which is roughly west-east oriented (Fig.1).

Figure 14d shows that the Ora del Garda at GAR ceases considerably earlier with onshore winds (especially with OnStr) than with the other classes. This behaviour is probably associated with the stronger up-valley wind blowing along the Adige Valley in connection with southerly synoptic winds: when this enhanced up-valley wind is strong enough, it may block or limit the penetration of the Ora del Garda into the Adige Valley. In favour of this hypothesis it may be worth remarking that on most days (~55%) the Ora del Garda at GAR is not immediately replaced by a regular down-valley wind in the late afternoon or early evening, but rather by a wind still blowing up-valley.

# 5. Discussion

From the analysis presented above it appears that the Ora del Garda is characterised by high frequencies of occurrence in spring and in summer, strongly determining the climatology of the valleys where it develops: at the lake's shoreline it blows on ~70% of the days during these seasons, and on 80-90% of these days it also propagates considerably inland, reaching the Adige Valley. These values are in the upper part of the range of frequencies found in similar studies on sea or lake breezes. For example Furberg et al. (2002) reported an average frequency for the sea breeze in Sardinia of 40% in the summer months, while frequencies of 20-30% were found for the lake Michigan by Lyons (1972) and Laird et al. (2001). On the other hand, for the sea breeze in Athens, Papanastasiou and Melas (2009) found an annual cycle of frequency similar to that found in the present work, while Sills et al. (2011) reported frequencies higher than 80% for the southern Great Lakes region. The high frequency of occurrence of the Ora del Garda is probably to be attributed to the combination of the lake and valley effects, both contributing to the development of an up-valley wind during the day. A similar conclusion was suggested by Telišman Prtenjak and Grisogono (2007), who found higher frequencies of occurrence of the sea breeze on the Croatian coast where the sea breeze interacts with local circulations generated by the presence of complex terrain close to the coast. The coupling between these two different mechanisms probably explains also the rather strong intensity of this local circulation, as observed in similar geographic situations, where lake or sea breezes couple with valley winds (Bastin et al., 2005; Bergström and Juuso, 2006). In particular the observed strength is unusual for such a small lake (cf. Crosman and Horel 2012), considering that Segal et al. (1997) found that lake breeze strength approaches sea breeze strength only when the lake size is greater than 80 km.

The timing of the Ora del Garda, which, on most days, starts blowing 3-5 hours after sunrise and lasts on average 6 hours, until sunset, is in good agreement with the results found in similar investigations on sea breezes. For example, a sea breeze onset around 4 hours after sunrise is reported in Furberg et al. (2002), Papanastasiou and Melas (2009) and Bajamgnigni Gbambie and Steyn (2013), for Sardinia, Greece and Benin respectively. Moreover Furberg et al. (2002) showed that in summertime the cessation of the sea breeze in Sardinia occurs on average shortly before sunset. In the present work it is also found that the onset time progressively shifts forward in time from April to September, due to the gradual warming of the lake water during the warm season and to the resulting later onset of the land-water thermal contrast required for the development of the lake breeze. However, the analysis of the dependence of the lake breeze strength on land-water temperature differences did not show a clear relationship. As pointed out also by Telišman Prtenjak and Grisogono (2007), this is probably attributable to the complex feedback between land-water temperature contrasts and the lake breeze: on one hand the latter is produced by these contrasts, but on the other hand it tends to damp them, through the advection of colder air from above the lake surface, as soon as it starts blowing over the land. Furthermore, it is also found that thermal contrasts occurring in the hour preceding the onset of the lake breeze – and thus not affected by these feedback effects – do not influence the strength of the lake breeze. Concordant results were presented by Arritt (1987), who, on the basis of numerical simulations, found little sensitivity of the lake breeze to the temperature of the water surface. Similarly, Sun et al. (1997) highlighted that the development of the lake breeze over the Candle Lake (Canada), was not influenced by lake/land temperature contrasts. They suggested that the strength of the lake breeze rather depends on the horizontal contrasts between the different thermal structures characterising the diurnal boundary layers over the land and over the lake. Furthermore, in the present case study, it has to be considered that a "standard" up-valley wind is likely to develop independently from land-water temperature differences, due to the pressure gradients induced by the differential heating between the lower Sarca Valley and the upper Lakes Valley.

On the other hand, the development of the lake breeze appears to be deeply influenced by the synoptic flow, both on the lake's shoreline and in the Adige Valley, but with different effects. On the lake's shoreline the lake breeze is on average stronger when onshore synoptic winds blow, while considerably lower velocities occur with easterly winds, probably because the latter channel as northerly winds in the low levels in the Sarca Valley. In contrast, in the Adige Valley the Ora del Garda is on average weaker with onshore (southerly) synoptic winds, for the up-valley wind of the Adige Valley is stronger in these situations, contrasting more effectively the arrival of the Ora del Garda. Moreover, onshore winds accelerate the propagation of the Ora del Garda and favour its arrival at the inland weather station. The dependence on the synoptic wind illustrated in this work is even more evident than what reported by Azorin-Molina and Chen (2009) for the sea breeze in the bay of Alicante (Spain). This may be due to the fact that the synoptic flow, when able to reach the low levels, channels inside the valley and thus it contrasts or strengthens more effectively the development of the Ora del Garda (cf. Whiteman and Doran 1993).

## 6. Summary and conclusions

The main climatological characteristics of the Ora del Garda wind – a coupled lake and valley breeze blowing typically in the warm-season months in the valleys north of Lake Garda, in the Italian Alps – were investigated in detail. In particular, the analysis concentrated on wind and air temperature data from two surface stations, as well as on lake water temperature measurements, and wind speed and direction at the 700-hPa level from model reanalysis.

The main findings of this work may be summarised as follows:

- the Ora del Garda appears characterised by high frequencies of occurrence, reaching 70% on the lake's shore in the warmest months;
- it displays rather high average speeds and gustiness, reaching frequently values larger than 10 m $s^{-1}$; gusts are particularly strong in the Adige Valley in the spring months, due to the thermal contrast between the cooler lake breeze air, which flows down into the valley through an elevated saddle on its western sidewall, and the air inside the valley;
- the onset and the cessation times of the Ora del Garda on the lake's shore strongly depend on the local sunrise and sunset times respectively: in particular, the onset occurs 3-5 hours after sunrise on average, while the cessation occurs around sunset;
- it takes ~3.5 hours for the breeze to reach GAR in the Adige Valley: the annual cycle of the onset time of the Ora del Garda inside the Adige Valley is similar to that found on the lake's shore, with a time shift of 3-4 hours, while the annual cycle of the cessation time is different, with later cessation times in spring;
- no significant relations between the land/water temperature contrasts and the intensity of the lake breeze are found;
- the synoptic flow significantly affects the development of the Ora del Garda: southerly synoptic winds favour stronger intensities of the breeze on the lake's shore, with respect to northerly and especially easterly winds. On the other hand, an opposite behaviour is found in the Adige Valley, due to the

interaction between the Ora del Garda and the normal up-valley wind blowing in the Adige Valley.

This work provides a basis for a comprehensive understanding of the processes affecting the development and the main features of the Ora del Garda wind, whose occurrence deeply influences local climatic conditions, pollutants' dispersion (de Franceschi and Zardi, 2009, Rada et al., 2011; Ragazzi et al., 2013) and outdoor activities. In particular, on the northern shorelines of Lake Garda, tourism and water sport practice are tightly connected with the regular development and the unusual strength of this local circulation. Although these results are, of course, site-specific, yet they might be extended to similar geographic configurations, e.g. to other mountain valleys with a lake at their bottom. However, findings presented here are not conclusive, as they are limited to the effects of the Ora del Garda on near-surface climatic conditions. As a next step, atmospheric boundary layers structures typically associated with the development of this local circulation will be investigated by means of high-resolution numerical simulations, which will be validated against data from airborne measurements (Laiti et al. 2013a,b, 2014a). Also the characteristics of surface layer turbulence associated with the development of the Ora del Garda and its effects on surface-atmosphere exchanges will be a relevant subject for future investigations. Providing a remarkable example of highly non-stationary situations over complex topography, turbulence measurements taken on such a situation will be an appreciable benchmark for the adoptation of suitable criteria and tools for the analysis of turbulence properties in highly non-uniform situations (de Franceschi and Zardi, 2003, de Franceschi et al. 2009).

*Acknowledgments.*

The Geographic Information System Unit of the Edmund Mach Foundation and the Environmental Agency of the Province of Trento are kindly acknowledged for providing data from their stations.

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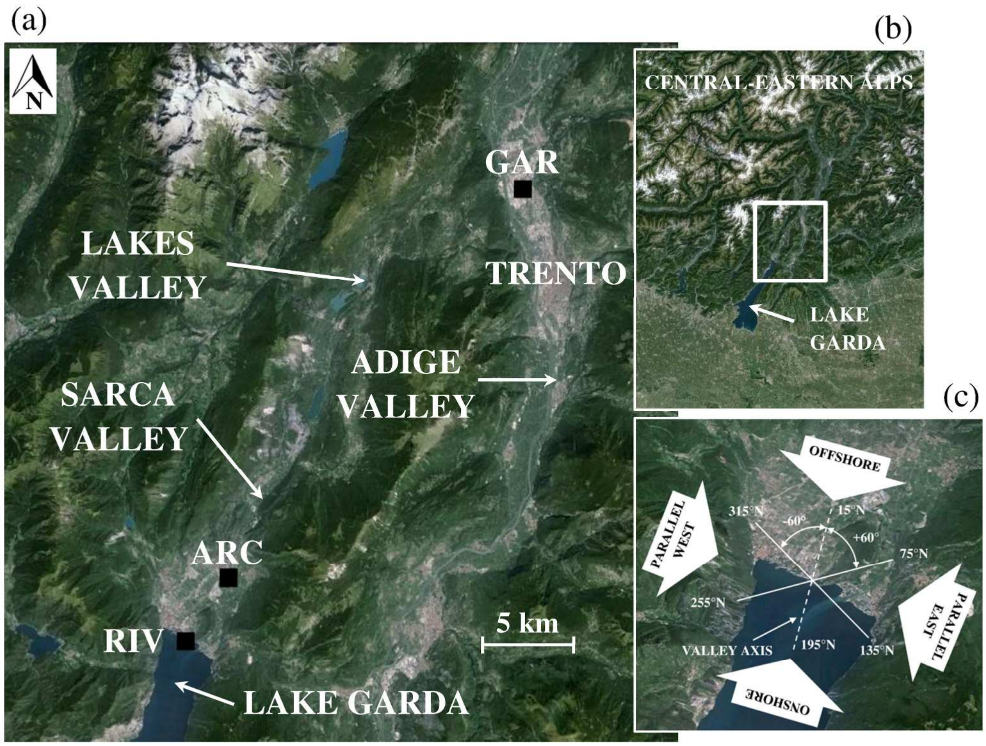


FIG. 1. (a) Study area and weather stations considered in this work: Riva del Garda (RIV), Arco (ARC), and Gardolo (GAR); (b) position of the study area in the central-eastern Italian Alps; (c) schematic representation of the wind direction classes for the synoptic wind. Background maps from Google Earth.
123x93mm (600 x 600 DPI)

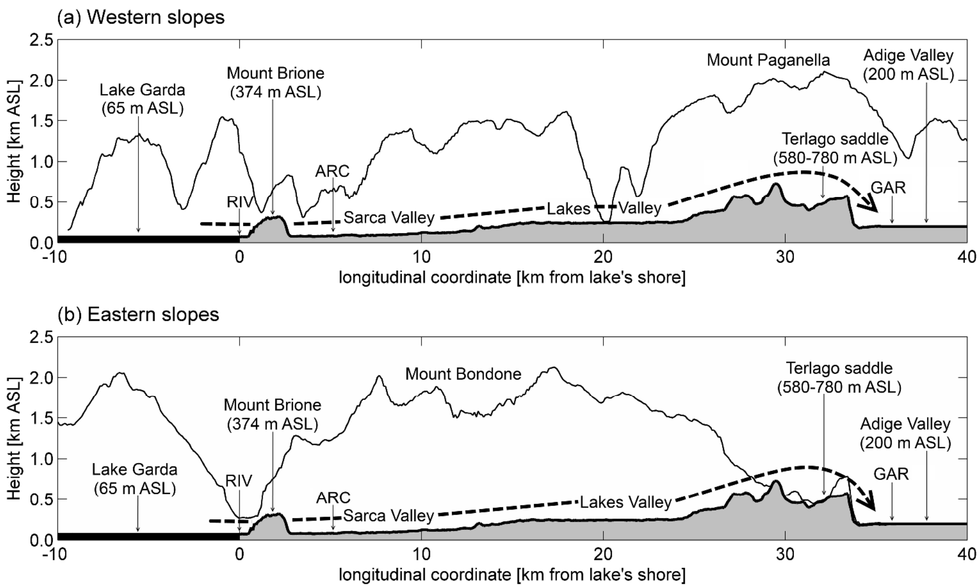


FIG. 2. Elevation profile of the valleys where the Ora del Garda wind (dotted arrow) flows, from Lake Garda's shoreline to the final overflow into the Adige Valley. Surrounding crests' elevation is shown for both the valley sides.
1027x613mm (144 x 144 DPI)

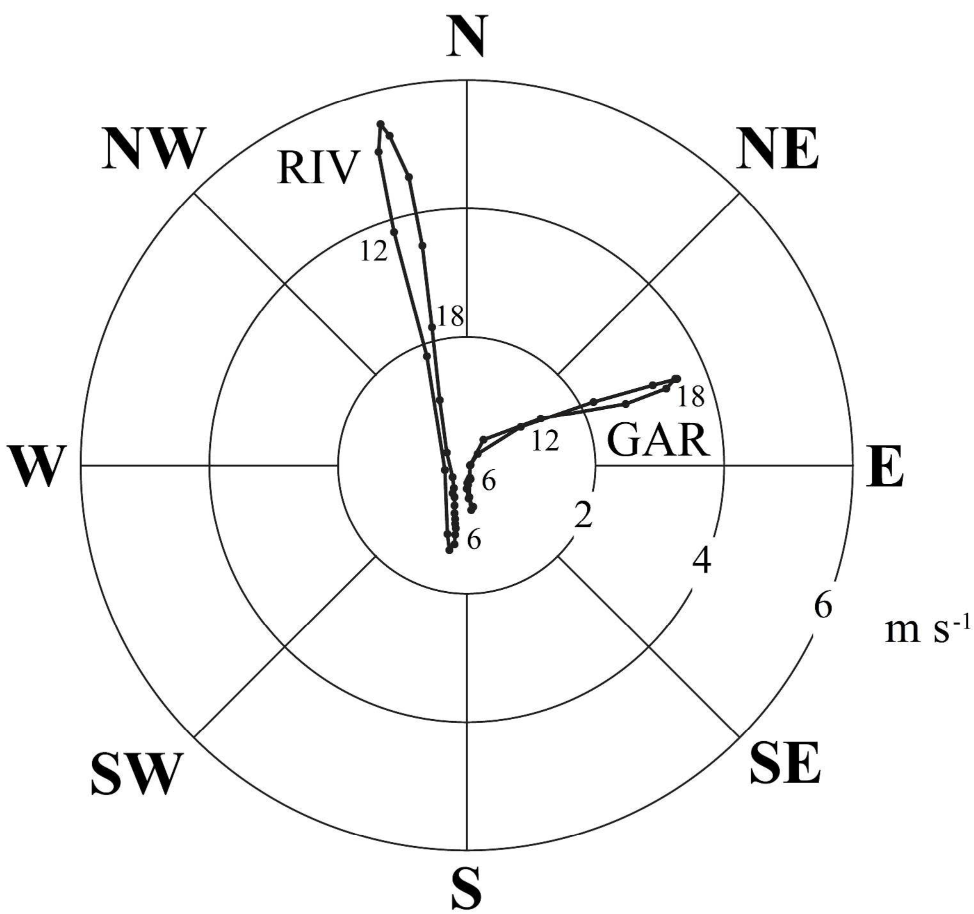


FIG. 3. Mean hourly hodographs averaged over all the Ora del Garda days for RIV and GAR stations.
194x183mm (600 x 600 DPI)

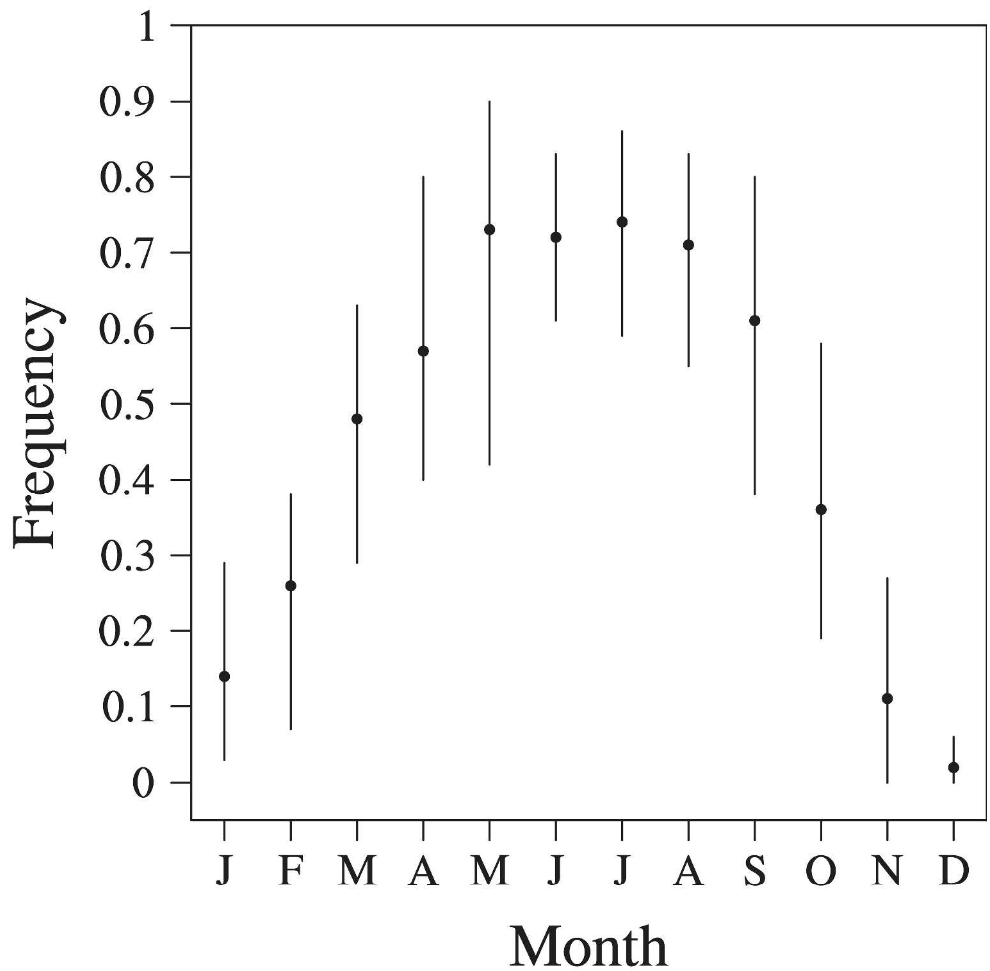


FIG. 4. Mean (dots) and range of the monthly frequency of the Ora del Garda at RIV.
181x176mm (600 x 600 DPI)

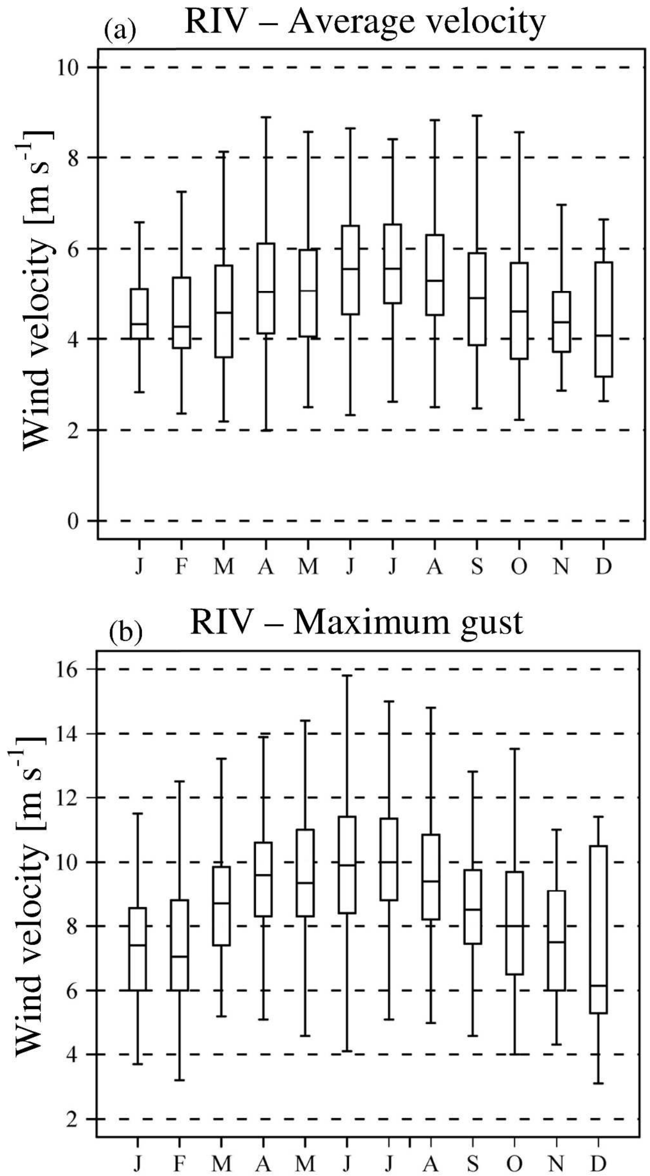


FIG. 5. Monthly box and whisker plots of (a) the average daily intensity and (b) the maximum daily gust of the Ora del Garda at RIV. The bottom and the top of the boxes represent respectively the first and the third quartile (Q1 and Q3), while the line in the middle is the median (Q2). The whiskers include respectively the lowest datum still within Q1-1.5•(Q3-Q1) and the highest datum still within Q3+1.5•(Q3-Q1). This description applies to all the box and whisker plots in this paper.
217x395mm (600 x 600 DPI)

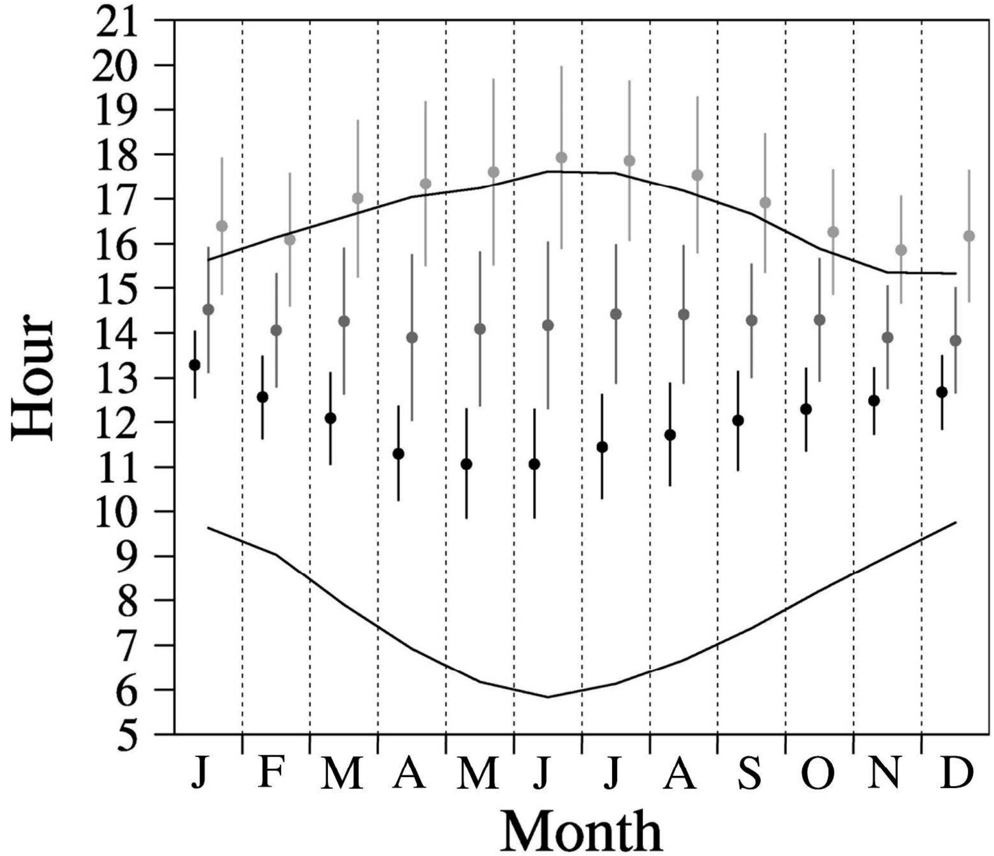


FIG. 6. Monthly distribution of the mean (dots) and standard deviation of the onset (black), maximum gust (dark grey) and cessation (light grey) of the Ora del Garda at RIV. This figure shows also the local sunrise and the sunset times at RIV (solid lines).
132x115mm (600 x 600 DPI)

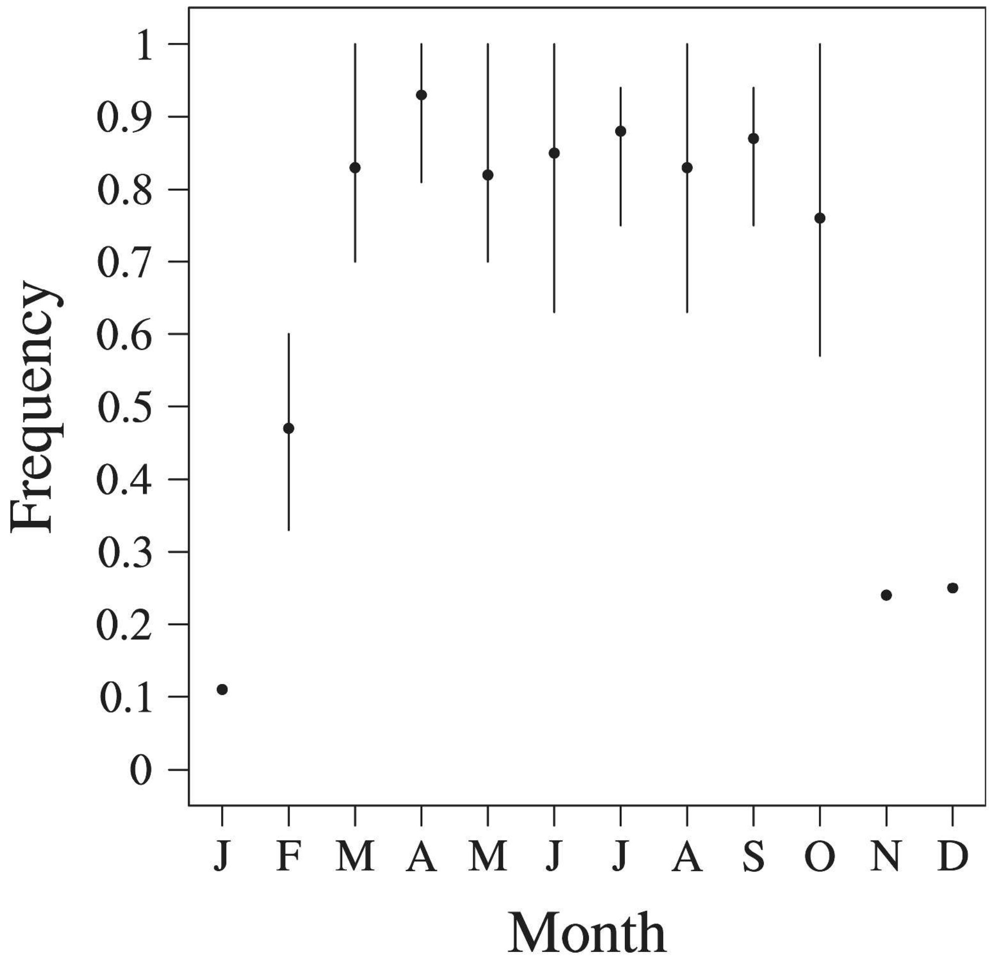


FIG. 7. Mean (dots) and range of the monthly frequency of the Ora del Garda at GAR on the days when the lake breeze is developed at RIV. The range is not calculated for January, November and December, as the Ora del Garda days at RIV in these months are too sparse to obtain robust values of the monthly frequency for every single year.
181x177mm (600 x 600 DPI)

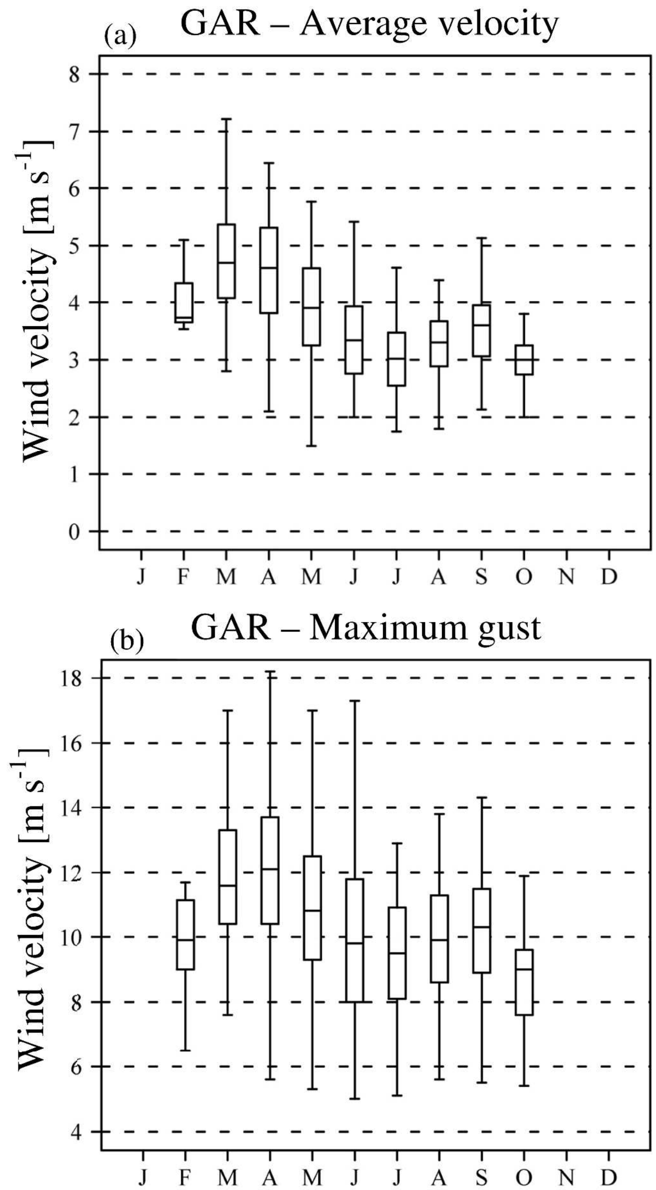


FIG. 8. Monthly box and whisker plots of (a) the average daily intensity, and (b) the maximum daily gust of the Ora del Garda at GAR. See Fig. 4 for the explanation of the statistics represented in this graphic. Statistics are not calculated for January, November and December, as the Ora del Garda days at GAR in these months are too sparse (2, 5 and 1 days respectively) to obtain robust statistics.
216x393mm (600 x 600 DPI)

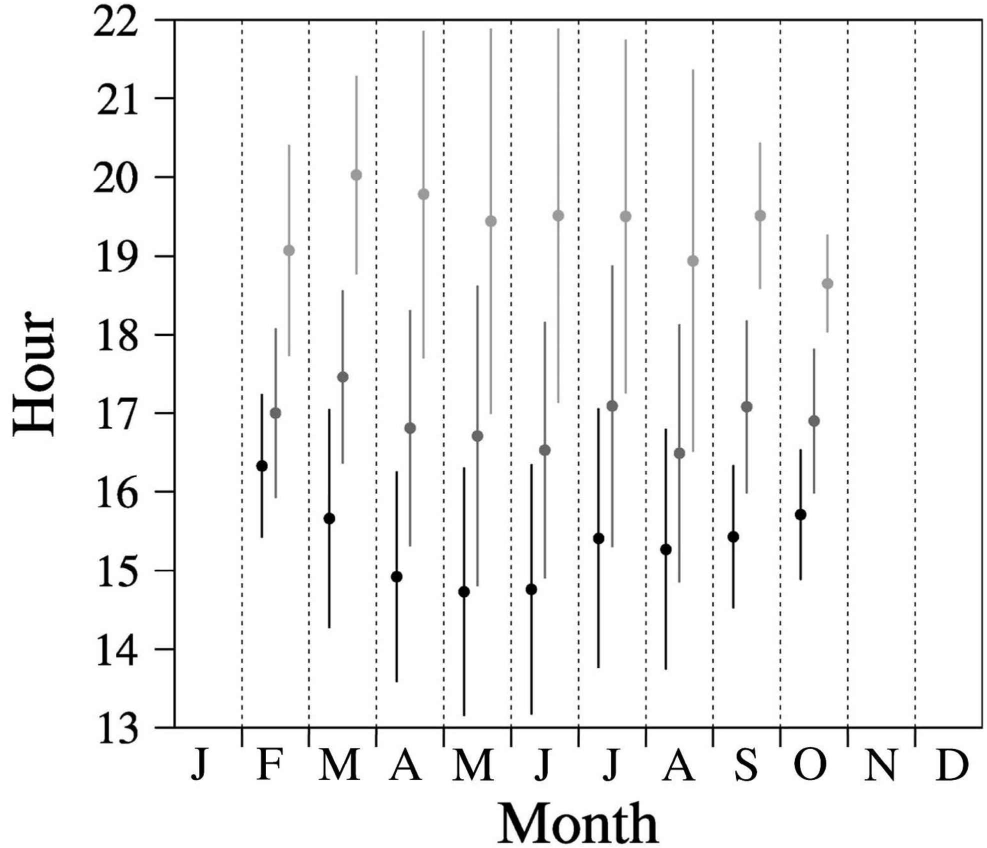


FIG. 9. Monthly distribution of the mean (dots) and standard deviation of the onset (black), maximum gust (dark grey) and cessation (light grey) of the Ora del Garda at GAR. Statistics are not calculated for January, November and December, as the Ora del Garda days at GAR in these months are too sparse (2, 5 and 1 days respectively) to obtain robust statistics.
134x116mm (600 x 600 DPI)

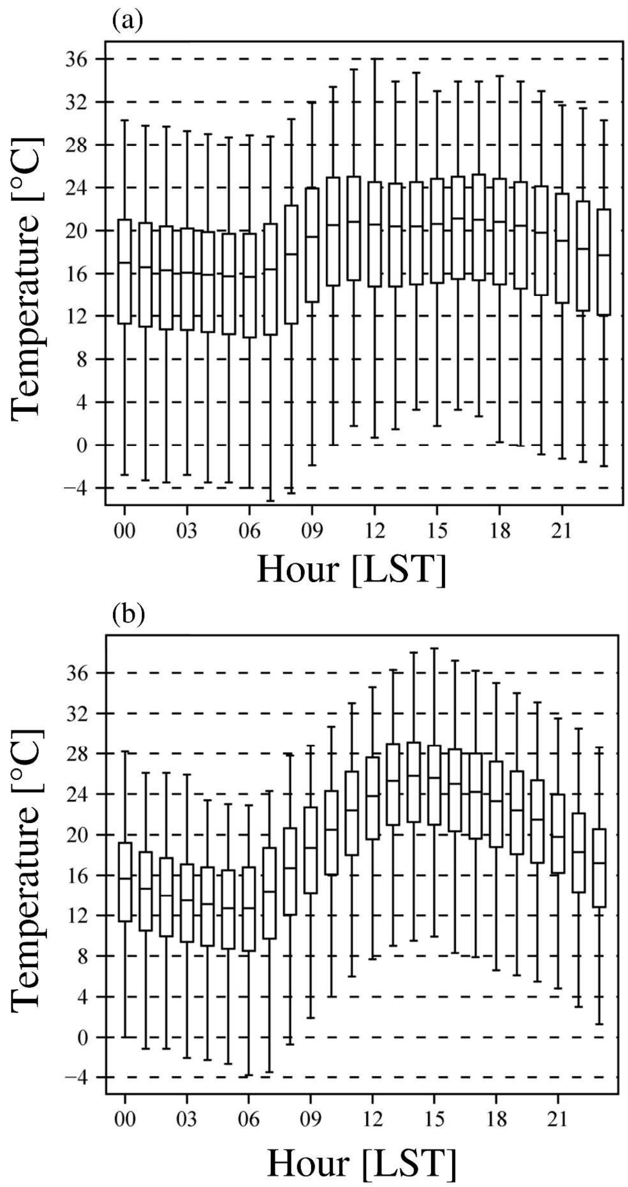


FIG. 10. Box and whisker plots of the diurnal cycle of temperature at (a) RIV and (b) GAR on the days when the Ora del Garda blows. See Fig. 4 for the explanation of the statistics represented in this figure.
223x414mm (600 x 600 DPI)

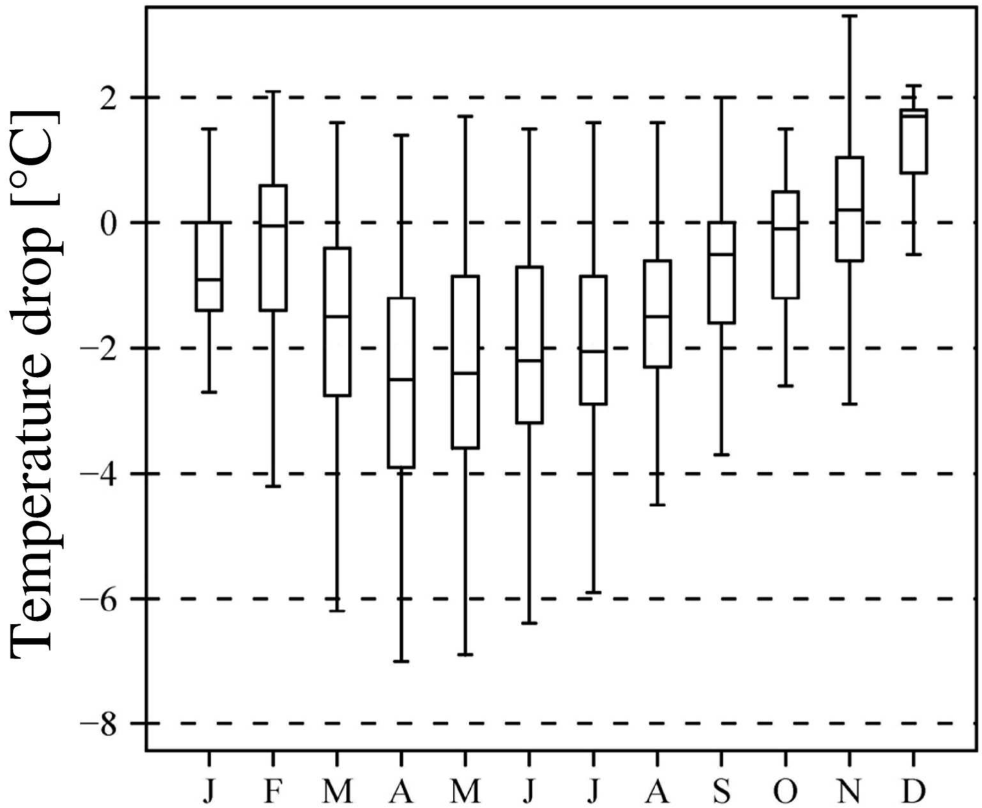


FIG. 11. Box and whisker plot of the temperature drop (°C) produced by the arrival of the Ora del Garda at RIV on a monthly basis. The temperature drop is calculated as the difference between the temperature in the hour after the onset of the Ora del Garda and the temperature in the hour before its onset. See Fig. 4 for the explanation of the statistics represented in this figure.
94x78mm (600 x 600 DPI)

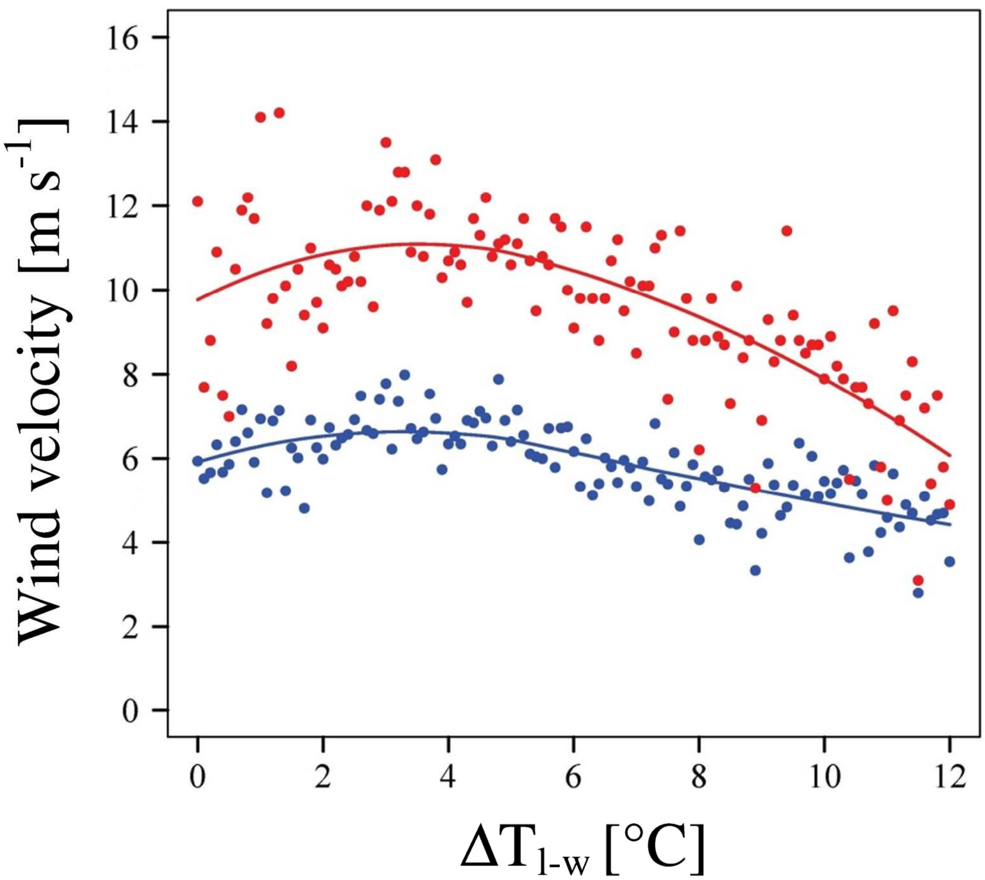


FIG. 12. Mean (blue dots) and maxima (red dots) of lake breeze intensity (hourly average data) evaluated for every 0.1°C interval of water-air temperature difference ($\Delta T_{l-w}$), over all the lake breeze hours. Fitting LOESS smooth curves with a span value of 1°C are also shown.
98x88mm (600 x 600 DPI)

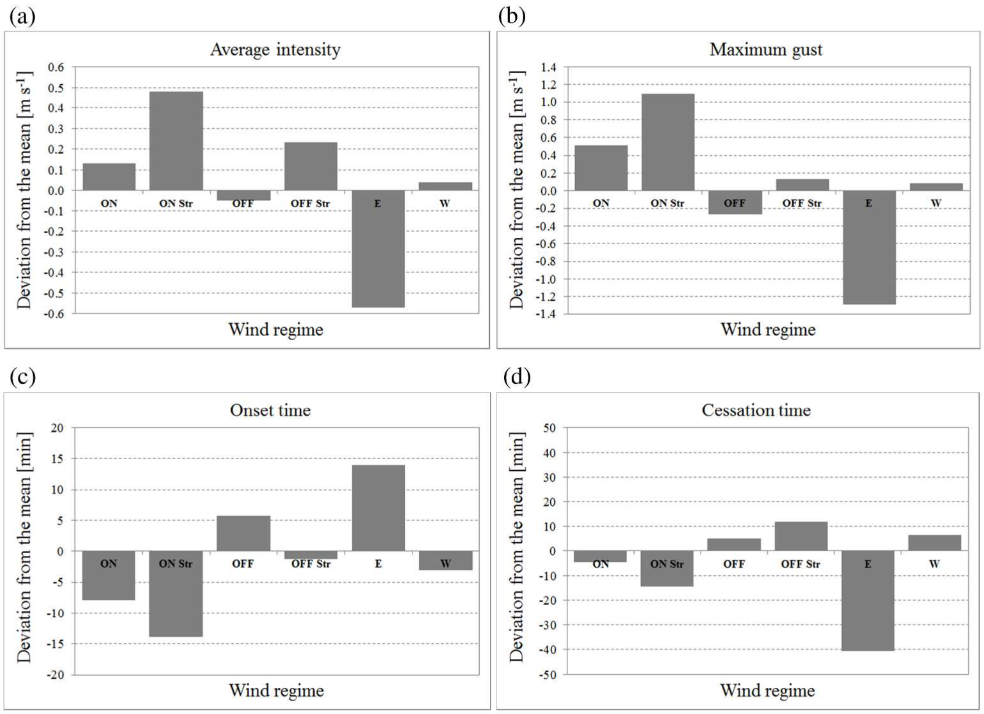


FIG. 13. Deviation from the mean of the (a) average daily intensity, (b) maximum daily gust, (c) onset time, and (d) cessation time of the Ora del Garda at RIV for the six synoptic wind classes (see text for explanation).
122x88mm (600 x 600 DPI)

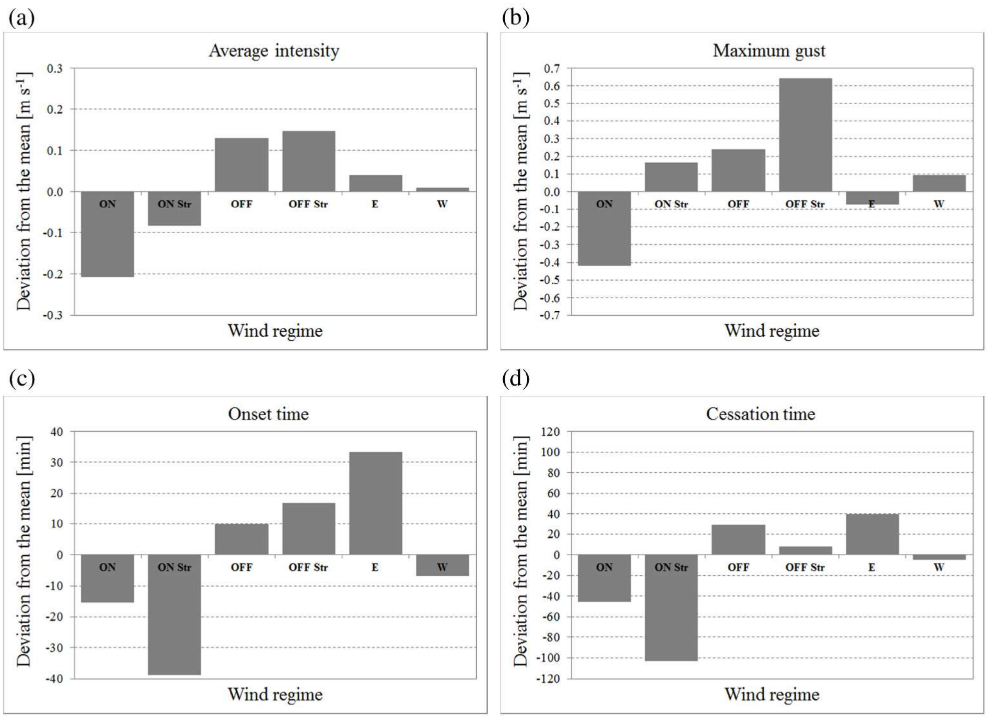


FIG. 14. As in Fig. 13, but for GAR weather station.
122x89mm (600 x 600 DPI)