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Andrija Mohorovičić Geophysical Institute, Department of Geophysics, Faculty of Science,
University of Zagreb, Zagreb, Croatia

Sea/land breeze climatological characteristics along the northern Croatian Adriatic coast

M. Telišman Prtenjak and **B. Grisogono**

With 10 Figures

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Summary

Climatological characteristics along the northern Croatian Adriatic coast have been examined for nine meteorological stations for the summertime sea/land breeze circulation. The stations considered are Pula-airport, Opatija, Rijeka, Senj, Malinska, Rijeka-airport, Mali Lošinj, Rab and Zadar. The hourly surface measurements at each station from June to September for the period 1991–2004 as well as the radiosoundings in Zadar (from 2002 to 2004) were used for the analysis. A dataset with the sea/land breeze days was formed according to the several criteria.

The mean daily maxima of both air and sea surface temperatures were more influenced by the large scale disturbances toward north (e.g. in Rijeka or Opatija) compared to the values for e.g. Zadar. Furthermore, the influence of the large scale disturbances diminished toward the south concerning the sea–land temperature difference only at the stations placed at Rijeka Bay and Velebit channel. The strongest sea breeze was found at Pula-airport and the most frequent ones at Opatija and Zadar. At Senj the rarest, the weakest and the shortest sea breeze was observed. The climatological records of wind speed and air-sea temperature difference (ΔT) showed for Opatija, Malinska and Zadar that the maximum measured wind speed is around 4.5 °C confirming the nonlinear relationship between the sea breeze speeds and the ΔT during the day.

At most stations, the clockwise rotation of the hodographs prevails which is typical for the Northern hemisphere due to Coriolis force, with the exception at Senj and Malinska. While the hodographs for Pula, Rijeka-airport and Mali Lošinj display a later onset of the prevailing sea breeze because of the interaction among several sea breeze circulations, the results for Opatija, Zadar and Senj show considerably distorted hodographs because of the nearby channeling of the air flow.

1. Introduction

Along the northern Croatian Adriatic coast (hereafter northern Adriatic), the Istria and a large number of islands in the Kvarner Bay often generate the sea/land breezes (SLB) that play an important role in local weather and climate dynamics (Fig. 1). In this area, many polluted cities lie in relatively narrow zones between the sea and mountainous hinterland and the development of the sea breeze (SB) usually makes coastal areas more comfortable and healthy for human habitation than the inland region. Despite its high importance for human activities in the northern Adriatic, the SLB is still the phenomenon that is not fully revealed and analyzed satisfactory, especially on the quantitative climatological basis of the 24-hourly measurements.

Studies which analyzed the observations (Orlić et al., 1988; Prtenjak, 2003; Pandžić and Likso, 2005) have established both the importance and the frequency of the SLB in this area. Orlić et al. (1988) analyzed the average 24-hourly cycle of the surface wind vectors by rotary spectra analysis

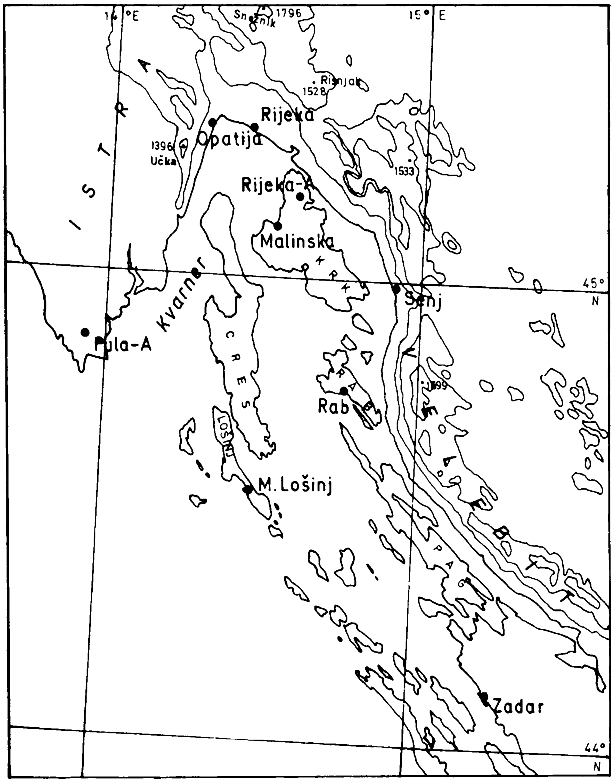

Fig. 1. Map of Istria, Kvarner Bay and the mid-Adriatic showing the measuring sites (M. Lošinj = Mali Lošinj, Pula-A = Pula-airport, Rijeka-A = Rijeka-airport). The topography contours are given every 500 m, starting from 0 to 1500 m

for some meteorological stations (six stations along east Adriatic) using measurements of the years 1978 and 1979. Diurnal peaks in the rotary spectra were matched to the SLB. Along the east Adriatic coast, Orlić et al. (1988) obtained that the energy of the SLB decreases with the higher latitudes. They hypothesized that this energy decrease at the northern Adriatic was due to smaller sea–land temperature differences (ΔT) compared to the south Adriatic. They argued that an increase of the synoptic scale disturbances could be one of reasons for the reduction of the ΔT. Although using very short selected dataset, Lukšić (1989) described the main characteristics of the diurnal winds at Senj station. Prtenjak (2003) showed some preliminary characteristics of the average SLB at ten chosen stations in the Istria and Kvarner Bay for the period 1999–2002. There the shortness of the data sequences did not allow statistically representative results in the climatological sense. Pandžić and Likso (2005) applied a complex principal component analysis as an objective procedure for the classification of all wind patterns there. For that purpose, they used the time series of instantaneous (at 7, 14 and 21 h local time) wind data, the reanalysis of the constant-pressure levels of 1000 and 850 hPa, as well as the thickness of 850–1000 hPa. The results indicate 11 typical wind patterns over the Adriatic area which include, among others, the etesians, SLB and a combination of these that is called maestral.

Recently, Nitis et al. (2005) and Prtenjak et al. (2006) paid more attention to the SLB numerical modeling revealing the dynamics of the SLB three-dimensional structure, while Trošić et al. (2006) analyzed the local observations and SB energetics in Zadar. In Nitis et al. (2005), a numerical model was applied for simulating and examining the main characteristics of the SLB circulation for three similar meteorological periods favoring the development of the local circulations. Prtenjak et al. (2006) using the same numerical model, studied the small scale variability in the wind field during a summertime anticyclonic situation. The results revealed the mesoscale eddies inside the Kvarner Bay and convergence zones (CZs) above Istria and Krk in the thermally driven mesoscale circulations. The nighttime deeper eddy exhibited anti-clockwise rotation, while the late afternoon shallow one showed the opposite rotation. During the afternoon, both the anabatic flow and the mature SB, due to the coastal geometry and terrain height caused the appearance of the afternoon eddy inside the shallow stable marine boundary layer. The channeling effect between Istria and Cres island was very important in the formation of the afternoon eddy. The Istrian CZ formed around the noon as a result of the merged SBs from the different parts of the peninsula. During the afternoon, the Istrian CZ moved toward the east. The CZ over the NE part of Krk was influenced by the topography as was the baroclinic channeled flow between the mainland and Krk.

The aim here is to investigate climatological characteristics of the SLB at the northern Adriatic and to obtain climatological hodographs that have not been analyzed before. This work continues on Prtenjak et al. (2006) now in a "micro-climatological" sense, while in a broader sense it also proceeds after Orlić et al. (1988) and Pandžić and Likso (2005). The hourly measurements of the wind and the sea and land temperature from the nine meteorological stations are examined from June to September for the period 1991–2004. The climatological diurnal variation of the temperature and wind characteristics for the selected SLB days is obtained for every station. Besides the maximum air and sea surface temperature, their difference and the planetary boundary layer (PBL) height are estimated from the temperature data. From the selected wind dataset the following characteristics are analyzed: the SLB frequency, the SLB onset and cessation, the SLB strength, the SLB duration as well as the rotation of the wind hodographs (clockwise versus anticlockwise). Furthermore, by the available radiosounding in Zadar from 2002 to 2004, the overall vertical SLB characteristics were also evaluated. According to the hypothesis made by Orlić et al. (1988) we examine the large scale disturbance influence on the SLB evolution depending on latitude.

2. Data and methods

2.1. Data set

Pandžić and Likso (2005) showed the favorable large scale conditions for the SLB development (see types 1 and 5 in their fig. 10). Such conditions are set when a ridge from the Azores anticyclone reaches the Adriatic area and the weakest gradients in the surface pressure level form over the northern Adriatic. Then the persistent northwesterly (NW) wind flow, known as the etesians, blows over the eastern Mediterranean giving bright and dry weather. During such weather conditions, the large-scale wind is weak allowing the formation of the local thermal circulations. Therefore, the observations used are from June to September for the observed periods 1991–2004 and 2002–2004. In this study, nine meteorological stations are selected (Fig. 1 and Table 1): Pula-airport, Opatija, Rijeka, Senj, Malinska, Rijeka-airport, Mali Lošinj, Rab and Zadar. Near the base of the Istrian peninsula, Pula-airport is situated 10 km west of the sea, surrounded by a flat and open landscape. Opatija is placed at the eastern coast of Istria in the Rijeka Bay bellow the mountain of Učka. Rijeka is a city and port in the Rijeka Bay, at the northeastern side of the Rijeka Bay. The mountain range (Risnjak and Snježnik, approximately 1800 m a.g.l.) is placed above Rijeka and continues south by Velika Kapela and Velebit Mountain (over 1700 m high and 160 km long) along the Kvarner Bay in a NW–SE direction. The well-known bora-wind place Senj is seated on the borderline between two mountains – Velebit and Kapela being the shortest natural connection between the inland and the sea. There, due to the geographical position, air-flow is often channeled across the Vratnik pass. Malinska and Rijeka-airport is located at the NW coast of the largest Adriatic island, Krk. At Lošinj island, Mali Lošinj is situated in a narrow zone, on the SE part of a large and well-protected bay. Rab is another insular station at the homonymous island. In the Northern Dalmatia, Zadar is placed surrounded by a flat hinterland. Zadar is separated from the open sea by the Zadar Archipelago and Zadar Peninsula.

Table 1. Stations specifications at the northern Adriatic used in the study. The sites are shown in Fig. 1

Station	Latitude	Longitude	Altitude (m)	Distance from the coast (km)	Measurement height (m, a.g.l.)	Description of the position
Rijeka	45°20′	14°27′	120	1	10	Northeastern side of Rijeka Bay
Opatija	45°20′	14°19′	5	0.01	15	Northwestern side of Rijeka Bay
Rijeka-airport	45°13′	14°35′	85	2	9	Krk island
Malinska	45°7′	14°32′	1	0.1	10	Krk island
Senj	45°0′	14°54′	26	0.5	10	Northeastern side of the Velebit channel
Pula-airport	44°54′	13°55′	63	10	8	Tip of Istria
Rab	44°45′	14°46′	24	0.2	15	Rab island
Mali Lošinj	44°32′	14°28′	53	0.3	10	Lošinj island
Zadar	44°8′	15°14′	5	0.03	13	Nortern Dalmatia

Table 2. The central (ideal) sea breeze–land breeze (SB–LB) axis and the number of analyzed days (*N*) with surface measurements from June to September during 1991–2004. For Pula-airport and Rijeka-airport, the geographical direction of the nearest coastline is considered. Next two columns give the mean sea–land temperature difference (ΔT) between daily maximum air temperature over land and the daily sea surface temperature, for all and selected datasets (Eqs. (1)–(3)). The estimation of the PBL height (*H*, Eq. (4)), the SB frequency (*f*) and the mean SB duration (t_{SB}) in hours are in the next columns, respectively

Station	SB–LB central axis	N	mean ΔT (°C)		ΔT_{diff} (°C)	H (m)	f (%)	t_{SB} (h)
			before screening	after screening				
Rijeka	205°–25°	1528	3.8	5.7	1.9	1400	52	10
Opatija	105°–285°	603	4.7	6.0	1.3	1500	60	10
Rijeka-airport	270°–90°	877	5.0	5.7	0.7	1400	55	10
Malinska	320°–140°	611	5.0	5.7	0.7	1400	55	11
Senj	253°–73°	1225	6.9	7.2	0.3	1800	37	7
Pula-airport	230°–50°	853	2.9	4.2	1.3	1100	49	9
Rab	200°–20°	855	4.0	5.0	1.0	1300	56	10
Mali Lošinj	225°–45°	896	3.4	4.5	1.1	1100	45	10
Zadar	230°–50°	998	4.6	5.6	1.0	1400	62	11

2.2 Selection of days during which SLB prevails

Possible although still subjective criteria for the selection of the SB days from the larger data set are in Borne et al. (1998) and Furberg et al. (2002). Here the choice is made by screening the surface measurements of the wind speed and direction, the air pressure, sea and air temperatures, and cloudiness from June to September for the period 1991–2004. Borne et al. (1998) and Furberg et al. (2002) pointed out that diurnal change in the wind direction is the most important criterion for the SLB selection. The following conditions for the SLB extraction are used:

(I) during nighttime, a majority of the hourly winds have to be offshore or calm;
(II) during the daytime, the winds have to be onshore for at least four consecutive hours showing the persistence of the SB. This criterion is very important for small wind speed.

Wind direction toward the coast or toward the sea is determined according to the geographical placement of the shoreline. Central (ideal) SB-land breeze (LB) axes for all stations are in Table 2. The SLB are considered as all wind directions that deviate around central axis by ±90°.

To exclude days when frontal or traveling baric systems pass over the area:

(III) diurnal air pressure amplitude has to be less than 5 hPa;
(IV) $N_{\text{mean}} \leq 4/10$, where N_{mean} is the mean daily cloudiness;
(V) $\Delta T = T_a - T_s > 3\,^{\circ}\text{C}$, recommended by Borne et al. (1998), where T_a is the daily maximum of the air temperature over land and T_s is the daily sea surface temperature at 14 h local time. T_s is not available at all stations. Therefore, for the purpose of the analysis at Rijeka, Rijeka-airport, and Pula-airport, T_s data obtained in Opatija, Malinska and Pula are used, respectively. At Malinska, Opatija and Zadar hourly measurements of T_s are available while the others have instantaneous (at 7, 14 and 21 h) T_s data. All data are in local time.

The aim of the application of the above criteria is to obtain as large as possible physically sound set of the SLB days which makes a database for the SLB climatology. According to the selected dataset in Zadar, the available radiosoundings, from 2002 to 2004, were also examined to evaluate the mean vertical SLB characteristics.

3. Results

3.1 Mean temporal and spatial characteristics of the SLB dataset

Table 2 shows several parameters describing the spatial SLB climatological characteristics for the whole study period, 1991–2004. The first one is the main governing force for the SLB development, ΔT. The overall mean ΔT reveals that Senj has the largest difference while the lowest

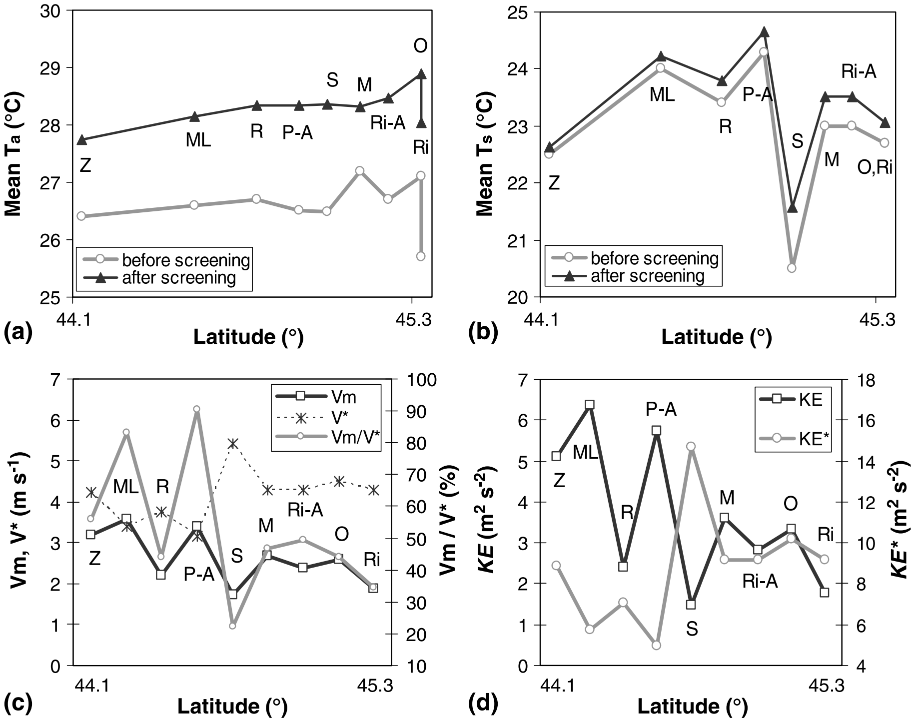

Fig. 2. (**a**) Maximum of the mean daily air temperature (mean T_a) and (**b**) the mean daily sea surface temperature (mean T_s), before and after screening, (**c**) the maximum of the mean sea breeze surface wind speed (V_m) and a ratio of V_m and characteristic speed (V^*), (**d**) measured surface kinetic energy ($KE = 1/2V_m^2$) and estimated KE^* (Eq. (6)) of the selected dataset from June to September during the period 1991–2004. The station abbreviations from south to north are: Z (Zadar), ML (Mali Lošinj), R (Rab), P-A (Pula-airport), S (Senj), M (Malinska), Ri-A (Rijeka-airport), O (Opatija) and Ri (Rijeka)

is observed for Pula-airport and Mali Lošinj. A smaller temperature difference at Pula-airport originates from the higher T_s (Fig. 2a and b). The location of the station at the tip of the Istrian peninsula surrounded by the sea affects the T_a. Since the station is 10 km far from the sea, the daily temperature amplitude could be higher. At Mali Lošinj station, both the higher T_s and the slightly lower T_a than at the other stations are responsible for the lower ΔT. The highest magnitudes in Senj are mainly due to anomalous low values of T_s rather than the spatial variations in T_a. The long-term T_s analysis made by Supić and Orlić (1992) showed that the summer T_s distribution along northern Adriatic are fairly uniform with the singularity near Senj. They obtained that the T_s drop can be about 3.5 °C in August compared to the other locations at the northern Adriatic.

The analyzed data did not show any significant connection between ΔT and the latitude (coefficient correlation r (φ, ΔT) = 0.19 and 0.34 before and after screening, respectively). The ΔT is highly dependent of the local terrain characteristics. Furthermore, the screening criteria allow us to extract days with significant large scale disturbance (e.g. fronts or traveling baric systems). Therefore, a comparison between the mean T_a and T_s, before and after screening procedure:

$$\Delta T_a = T_a \text{ (after screening)} - T_a \text{ (before screening)}, \quad (1)$$

$$\Delta T_s = T_s \text{ (after screening)} - T_s \text{ (before screening), and} \quad (2)$$

$$\Delta T_{\text{diff}} = \Delta T \text{ (after screening)} - \Delta T \text{ (before screening)}, \quad (3)$$

shows the effect of the large scale disturbance on the surface temperatures at the measurement sites in the northern Adriatic (Fig. 2a and b). According to the results, the mean T_a of the selected SLB dataset is higher toward the north, in the Kvarner Bay (r (φ, T_a) = 0.69) as well as ΔT_a and ΔT_s (r (φ, ΔT_a) = 0.52; r (φ, ΔT_s) = 0.42). At the first glance, the influence of the large scale disturbance on the ΔT, (ΔT_{diff} in Table 2), mostly weakens toward the south ranging from 1.9 °C for Rijeka to 1.0 °C for Zadar, respectively. A deeper examination reveals that stations inside the Rijeka Bay and Velebit channel (Opatija, Rijeka, Rijeka-airport, Malinska, Senj) are characterized by the considerable influence of the synoptic disturbances on ΔT ($r(\varphi, \Delta T_{\text{diff}}) = 0.89$). Still, the other stations do not show so much obvious relationship in the selected dataset. This result agrees with the distribution of the greatest mean values of cloudiness in July over the Rijeka Bay (Penzar et al., 2001) and confirms the hypothesis made by Orlić et al. (1988) that the smaller ΔT in the northern Adriatic (at Rijeka and Senj) compared to the mid-Adriatic, appears partly from the large scale disturbance effects.

During SB, planetary boundary layer (PBL) height over land (H) is evaluated according to the ΔT (in the selected dataset). The *SB* height is approximately equal to the convective H which can be estimate as the height where the potential temperature (θ) over land and over sea are equal (Brière, 1987; Prtenjak and Grisogono, 2002). The air above the land is warmer than the air above the sea. Therefore, the air over the land is lifting and cooling adiabatically (therefore θ is constant) and marine air, that is more statically stable, is changing by the θ lapse rate of approximately $0.4°/100\,\text{m}$. The marine θ lapse rate is chosen according to the results of both the experimental (Finkele et al., 1995; Stephan et al., 1999) and numerical studies (see fig. 1 in Prtenjak and Grisogono, 2002) that showed ranging of the marine θ lapse rate behind the SB front from approximately $0.35°/100\,\text{m}$ to $0.45°/100\,\text{m}$. At 2 m height, T and ΔT are equal to θ and $\Delta\theta$, respectively and H is calculated from:

$$H = \frac{\Delta\theta}{\frac{0.4°}{100\,\text{m}}}. \tag{4}$$

The estimations for H vary from 1100 m for Pula-airport to ~1800 m for Senj with spatial variations among the stations (Table 2). The H values agrees very well with the PBL height at the other locations (e.g. at the Baltic coast, Tjernström and Grisogono, 1996).

At each station in the selected dataset, the average SB maximum surface wind speed (V_{m}) is estimated and the surface kinetic energy ($KE = 1/2V_{\text{m}}^2$) is depicted as a function of latitude (Fig. 2c and d). The estimated *KE* (and V_{m}) of the SB along the northern Adriatic decreases toward the Rijeka Bay in agreement with rotary analysis of the measurement (Orlić et al., 1988) and with the results of the linear theory (Rotunno, 1983). The correlation coefficient r (φ, *KE*) is −0.61. The stations Mali Lošinj and Pula-airport have the largest *KE* despite the smallest mean ΔT. These stations are placed closely to the open sea implying that the *KE* is dependent also on the distance from the coast toward the open sea that is in agreement with Penzar et al. (2001).

According to the SB enegetics, for each station, a mesoscale available potential energy (*MAPE*) can be estimate by H (Green and Dalu, 1980; Brière, 1987; Dalu, 1996). The SB energetics supposes that *MAPE* can be converted to the SB kinetic energy which is distributed across the region up to height H. Green and Dalu (1980) defined a characteristic speed V^* as:

$$V^* \approx \left(0.11 \cdot \frac{g \cdot H^2 \cdot \gamma}{\theta}\right)^{1/2}, \tag{5}$$

where g is acceleration due to gravity and $\gamma = 2.5\,\text{K}\,\text{km}^{-1}$ and the estimation of KE^* is calculated by:

$$KE^* = \frac{1}{2}(V^*)^2. \tag{6}$$

According to the used presumptions, V^* and KE^* depend most on H (namely $\Delta\theta$ and θ). The results in Fig. 2c and d show similar V^* and KE^* for Zadar and Opatija implying that there is no obvious dependence V^* and KE^* with latitude. The estimated V^* presumably responds on the maximum SB wind speed that is usually achieved between 100 m and 300 m above the ground. Stations Pula-airport and Mali Lošinj have the lowest H (Table 2) and V_{m} is very close to V^* (see ratio in Fig. 2c). If the SB height (and H) is lower, as in Pula-airport, the V_{m} and V^* would be more similar. At the stations with the mountainous hinterland, (e.g. Opatija, Rijeka, Senj) the difference between V_{m} and V^* is higher (i.e. ratio is lower in Fig. 2c), since the maximum SB wind speed occurs at higher altitude (e.g. Darby et al., 2002; Prtenjak et al., 2006). The etesians also influence significantly the SB strength at Mali Lošinj, since the selected criteria is not capable to distinguish the difference between the SB and the etesians.

In Table 2 the frequency of occurrence of SLB days (f) defined as the ratio between the selected and all analyzed days, and the mean duration of the SB in hours mostly follow the mean ΔT. Thus, the SLB is the most frequent in Zadar and Opatija (Table 2). The high frequency of SLB occurrence and its steadiness in Opatija is due to the interaction between local circulations that are generated by the very complex shore (as suggested by Fig. 1). The SLB screening procedure can not distinguish the SLB from the slope winds since the same weather conditions influence their development in this area. Here, f in the range of 40–60% confirmed the findings by Prtenjak (2003) for the summer season. This value is also in agreement with the SLB occurrence in Sardinia (around 40% according to Furberg et al., 2002) and is somewhat lower than on the island of Mallorca where Ramis and Romero (1995) reported the SB frequency of 80% in July and 76% in August.

The longest SB is measured in Malinska and Zadar and the SB duration is similar at the other measurement sites except Pula-airport and Senj (Table 2). With only small both the spatial and monthly differences, the SB at most stations starts around 8 h and lasts until 19 h. This is in agreement with Furberg et al. (2002) who reported the average SB duration in the range of 8–9 h during summer season. The smaller SB duration in Pula airport is due to low steadiness of the SB onset. In Senj it is found the shortest and the rarest SB, despite the highest mean ΔT. The channeling effect in the Velebit channel and a mountain pass between Velebit and Kapela play very important role in the wind pattern above the Senj (Prtenjak et al., 2006). As the station is located in the foot of the mountain, the bora wind portion is highly represented in the annual wind cycle decreasing opportunity for the development of the local thermal circulations (Lukšić, 1989).

The relationship between the temperature information and the SB strength as a measure for the SLB development were analyzed by a number of empirical studies (Miller et al., 2003). The relatively straightforward method for a quantitative SLB estimation is based on the climatological records of wind speed and ΔT only. Still, the result of this method is limited for the each measurement site. In Fig. 3, the $V - \Delta T$ graphs are depicted for three stations that have hourly ΔT data: Opatija, Malinska and Zadar. Since, the several wind speeds are matched with one positive ΔT value in the selected dataset (from 8 to 20 h) yielding more than 4000 points per graph, we evaluated the mean wind speed ($\overline{V}$) and the maximum wind speed (V') every 0.1 °C. For each station, the nonlinear regression lines relating the two data sets (both $\overline{V} - \Delta T$ and $V' - \Delta T$) are fitted in Fig. 3. Somewhat surprisingly, all stations show very similar functional parabolic relationship between ΔT and V'. Firstly, the V' increases slightly up with the ΔT increase. For all stations the common characteristic is that the V' is for relatively low ΔT around 4.5 °C without exception. For the further ΔT increase ($\Delta T > 6$ °C), the V' decreases, with the only marginal SB cases when $\Delta T > 10$ °C (no more than 1% of all selected days). The $\overline{V}$ and ΔT display also the nonlinear relationship for each forecast site which

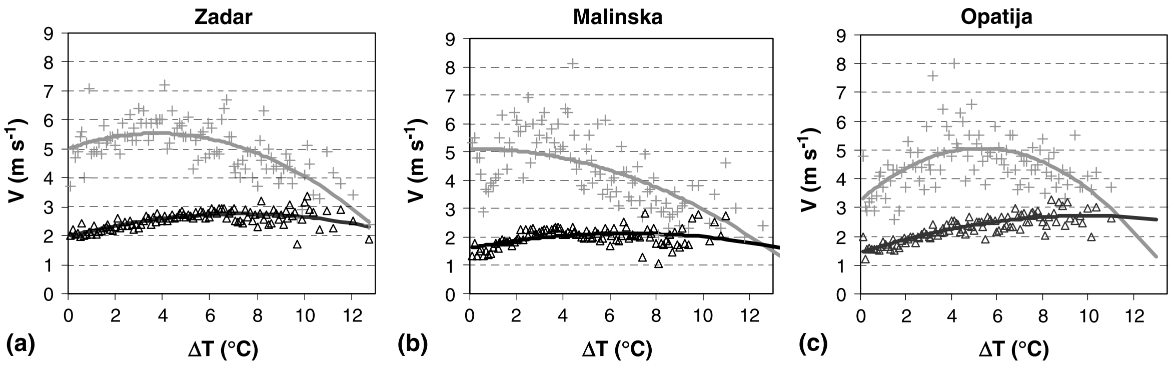

Fig. 3. From June to September during the period 1991–2004. A nonlinear fit (gray line) to the maximum wind speed (V',m s^{-1}) (gray crosses) and a nonlinear fit (black line) to the mean wind speed (V', m s^{-1}) (black triangles) every 0.1 °C of ΔT: (**a**) Zadar ($V' = 5.097 + 0.041 \cdot \Delta T - 0.026 \cdot \Delta T^2$; $\overline{V} = 1.660 + 0.185 \cdot \Delta T - 0.018 \cdot \Delta T^2$), (**b**) Malinska ($V' = 5.114 + 0.004 \cdot \Delta T - 0.022 \cdot \Delta T^2$; $\overline{V} = 1.605 + 0.156 \cdot \Delta T - 0.012 \cdot \Delta T^2$) and (**c**) Opatija ($V' = 3.267 + 0.676 \cdot \Delta T - 0.064 \cdot \Delta T^2$; $\overline{V} = 1.434 + 0.255 \cdot \Delta T - 0.013 \cdot \Delta T^2$)

agrees with Miller et al. (2003). The results show that the SB is the strongest and very frequent for the 3 °C < ΔT < 8 °C and the light large scale wind that agrees quite well with the results for other locations (e.g. see fig. 4.2. in Simpson 1994). These regression lines in Fig. 3, confirm the nonlinear connection between the SB speeds and the temperature field. During the day, when ΔT exists, pressure gradients form as well, creating onshore flow. The consequence is the advection of the cold marine air above the station. The cold air advection decreases the ΔT there, the cause of the SB evolution, and the wind speed decreases.

Figure 4 shows both the mean ΔT and the frequency of the SLB by month. Concerning the mean monthly ΔT, all individual stations show a prime peak in August, except Zadar where the maximum is in June. At stations in Rijeka Bay and Pula-airport, the mean monthly ΔT has secondary maximum in June because in this part of Adriatic coast, the cloudiness is higher in July than in June or August (Penzar et al., 2001). The values vary by 5 °C degrees in average among the stations during the examined period; from the smallest temperature differences at Pula-airport to the largest ones displayed for Senj. The mean monthly ΔT follows the behavior of

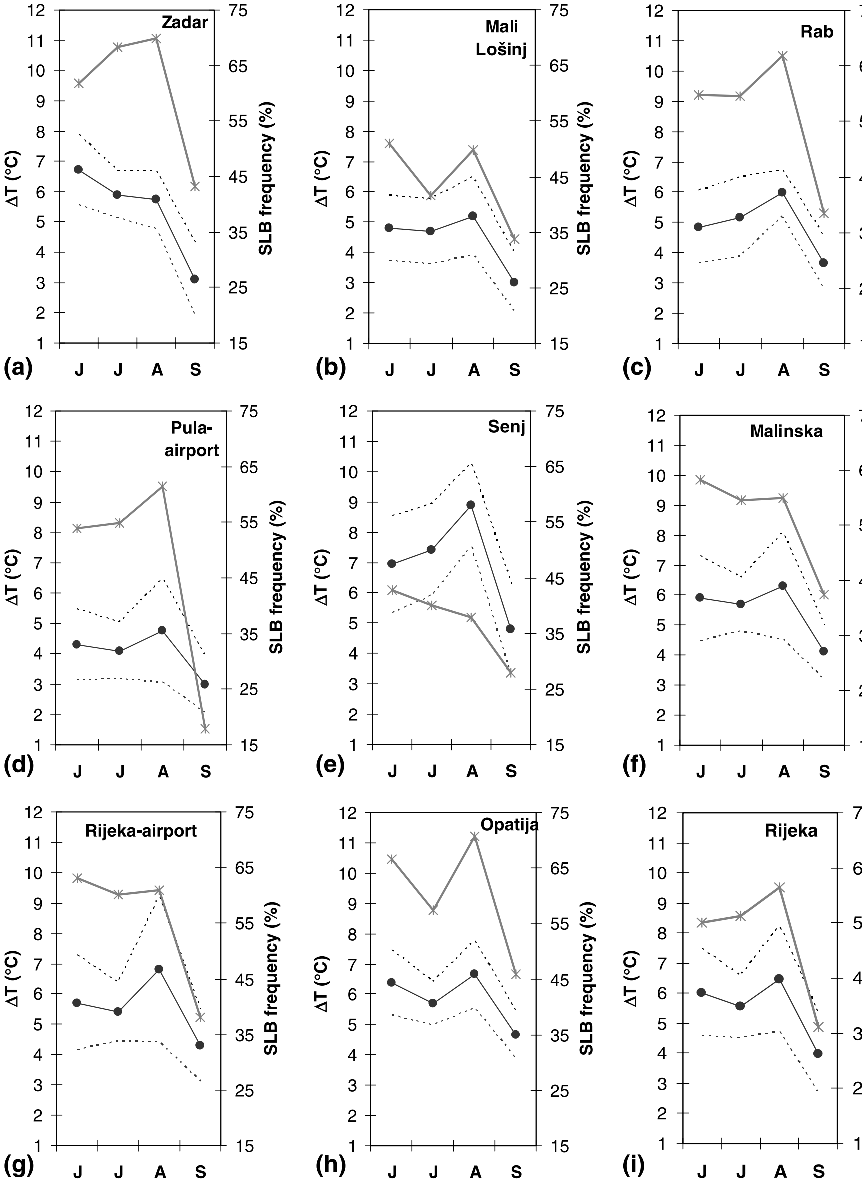

Fig. 4. The mean monthly ΔT (°C) (black solid line with circles) and ± standard deviation range (dashed lines) and the monthly frequency (%) of SLB days (grey solid line with stars) from June to September (JJAS, 1991–2004) for the station considered

the maximum values in the average daily cycles of both T_a and T_s.

In Fig. 4 the frequencies of occurrence of SLB days by month bear a close resemblance to the form of monthly ΔT. These two parameters are highly correlated for almost each station with the correlation coefficient r (f, ΔT) more than 0.80; the exception is Senj (r (f, ΔT) = 0.67) with lower but still significant value. At most stations SLB is most frequent in August, except in Malinska and Senj where SLB frequency reach its maximum in June with decreasing in the following months. From August to September, all stations are characterized by a sharp decline in the SLB occurrence (Fig. 4). This monthly statistics agrees reasonably well with those made for Sardinia (Furberg et al., 2002).

3.2 Diurnal wind hodographs

The mean wind hodographs according to their specific characteristics are sorted in several groups.

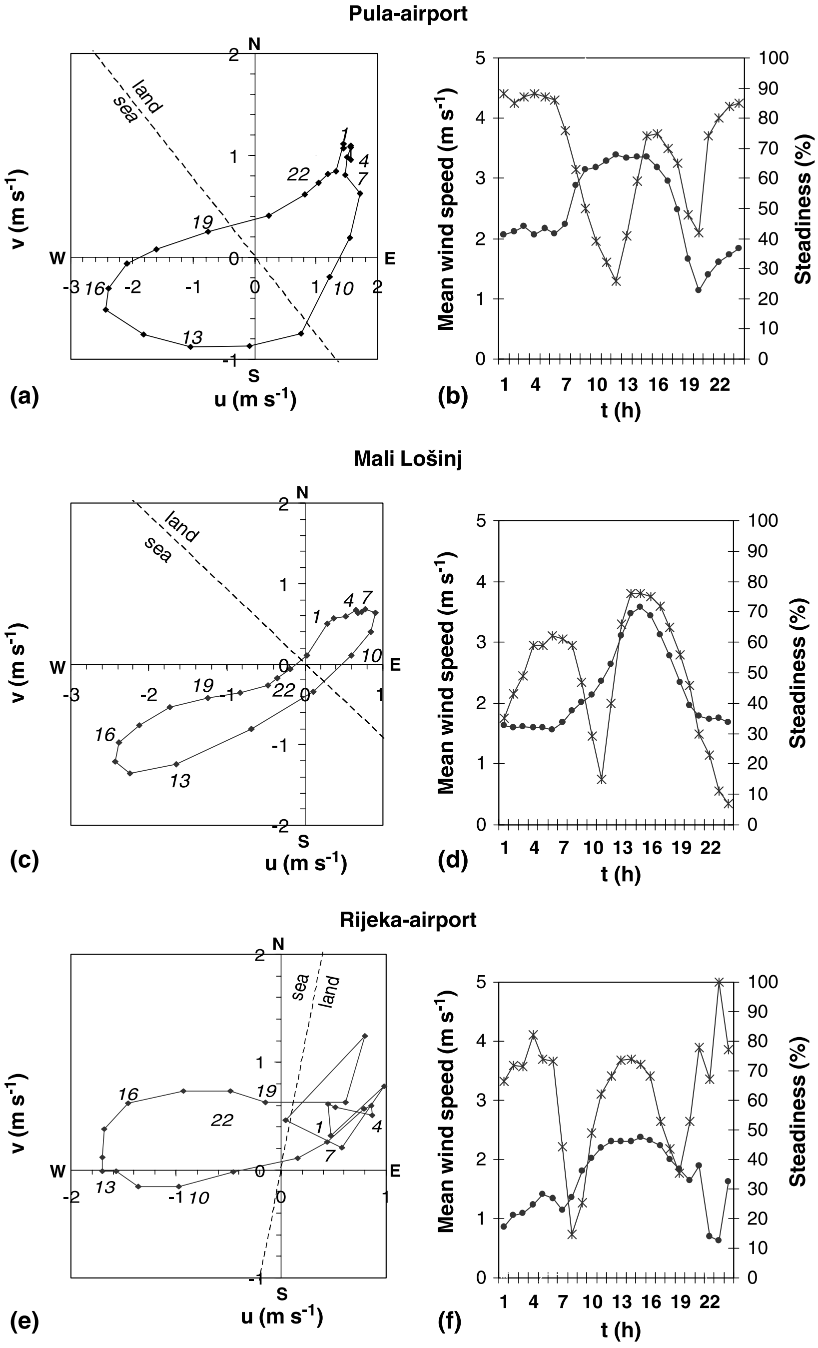

Fig. 5. (**a**) The hodograph of the climatological observed surface wind vectors ($\mathrm{m\,s^{-1}}$) calculated for the selected SLB dataset for Pula-airport from June to September for the period 1991–2004. The wind vectors are directed toward the origin of the coordinate system. A dashed line represents the orientation of the nearest coastline. The numbers represent local time. (**b**) The daily mean wind speed ($\mathrm{m\,s^{-1}}$) for the selected SLB dataset for Pula-airport (black solid line with circles) with daily steadiness (%) (black solid line with stars), (**c**, **d**) Mali Lošinj, (**e**, **f**) Rijeka-airport

The first group of hodographs with clockwise rotation (Fig. 5) is characterized by the late steadiness of SB and they are obtained for the Pula-airport, Mali Lošinj and Rijeka-airport. The hodographs in Fig. 5 show the nighttime LBs that are from NE-NNE, and SW-WSW daytime SBs which become more persistent relatively late, after 13 h (steadiness >50%). These shapes of the wind hodograph are very similar to those obtained by Prtenjak (2003). The SB strength is around 3.5 m s^{-1} for Pula-airport (Fig. 5b) and Mali Lošinj (Fig. 5d) while is lower for Rijeka-airport, around 2.5 m s^{-1} (Fig. 5f). The LBs are almost twice weaker than the SBs, at each station. Low steadiness of early SBs at stations is due to interactions of several SB from different coasts. The simulations in Prtenjak et al. (2006) showed that in the morning above Istria, the SBs prevail from the southern and southeastern shores (Fig. 1). When the local circulations matured, the SB from the western peninsula coast merges with the southern and south-eastern SBs forming a broad and deep CZ along Istria. The position of the CZ, which is partly dependent on the large scale conditions, in the vicinity of Pula-airport determines the final wind direction. In the afternoon, the western SB becomes stronger than the other SBs dominating over the Pula-airport. In the climatological sense, day to day variability in the position of the CZ can be seen in its low steadiness in the late morning (Fig. 5b). Contrary to the SB at noon, the prevailing western SB is characterized by high steadiness in the afternoon. Relatively unsmoothed nighttime shape of the wind hodograph in Rijeka-airport results from the lack of measurements (Fig. 5e). During examined period, the maximum SB wind speed is recorded in the different part of the summer: 8 m s^{-1} at Pula-airport in June, 6.2 m s^{-1} at Rijeka-airport and 8 m s^{-1} at Mali Lošinj in August.

For another insular station, Rab, the hodograph shows quite regular SLB breeze regime (Fig. 6). The LB diminishes in the morning and it is continued by SB which is predominantly SW with wind speed around 2.5 m s^{-1}. The hodograph has clockwise rotation and the diurnal directions at Rab are very similar to those at Mali Lošinj (compare Figs. 5, 6). The maximum wind speed of 5.5 m s^{-1} during 1991–2004 is measured in August.

Hodographs for Opatija and Rijeka are in Fig. 7 showing clockwise rotation. Both stations are affected by the interaction between SLB and downslope/upslope winds due to their placement at the mountainous shoreline (Fig. 1). A common feature is a relatively early beginning of the daytime onshore flow, influenced by the hinterland which can be seen in the fast transition between the daytime and nighttime wind regime (see steadiness in Fig. 7b and d). Furthermore, the maximum wind speed measured is in the same month, in June; 8 m s^{-1} in Opatija and 5.3 m s^{-1} in Rijeka, respectively.

In Fig. 7a and b, the southerly SB in Opatija is around 2.5 m s^{-1} during daytime with relatively weak northwesterly LB. In Opatija, two channeling effects play an important role in the SB development: the channeling of the air flow between Istria and the island Cres and through the mountain pass between Učka and Risnjak. The daytime onshore flow is more persistent than the nocturnal flow (Fig. 7b). The LB is somewhat stronger than in Prtenjak (2003).

Rijeka is characterized by the weak local circulations (Fig. 7c and d). The daytime SB from SW does not overcome 2 m s^{-1} and is only

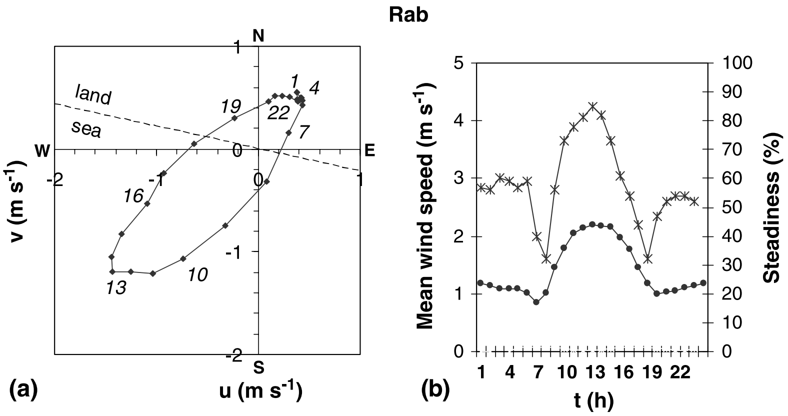

Fig. 6. Same as in Fig. 5 except for Rab

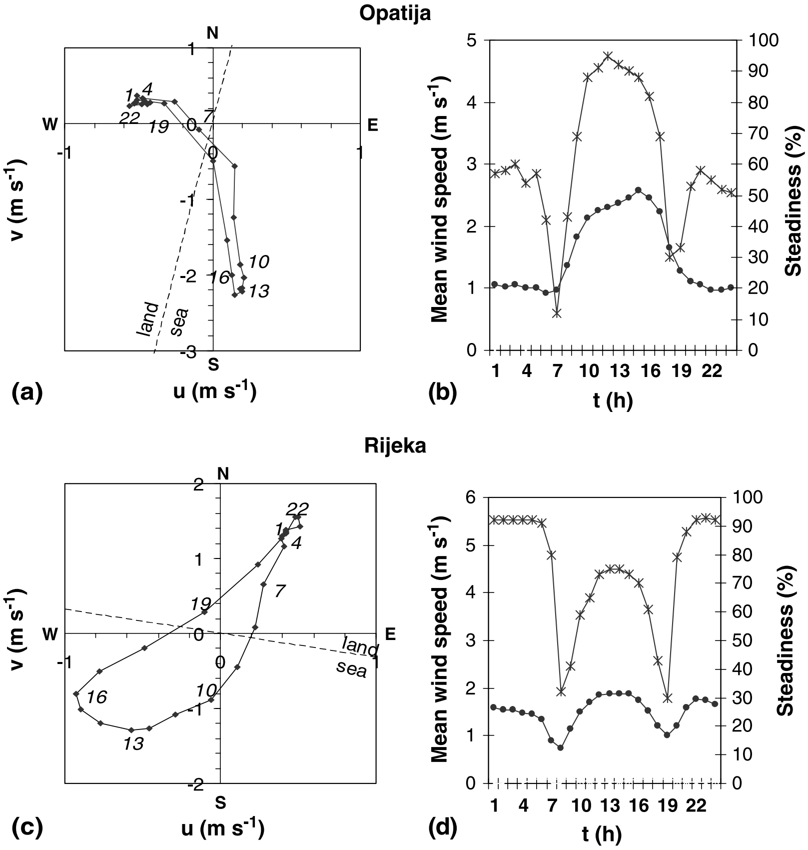

Fig. 7. Same as Fig. 5 except (**a**, **b**) for Opatija and (**c**, **d**) for Rijeka

slightly stronger than the nighttime NE offshore flow. Opposite to Opatija, Rijeka has more persistent nighttime flow comparing with its daytime speed values (Fig. 7b). The nocturnal and diurnal wind vectors for Rijeka coincide very well with those obtained by Pandžić and Likso (2005) and the hodographs are very similar to those in Prtenjak (2003).

Another considerable channeling effect on the wind field is observed in Zadar (Fig. 8). This is due to the Zadar Archipelago and Zadar Peninsula. The wind hodograph that has clockwise rotation represents very elongated ellipse there. During nighttime the prevailing offshore E flow has relatively high steadiness and rather low velocity (Fig. 8). At the beginning of the SB development, the W winds are perpendicular to the shore. In the afternoon, the wind speed around 2.5 m s^{-1} is turning toward NW and blows almost parallel to the coastline in the evening. During 1991–2004, the maximum wind speed of 7.2 m s^{-1} is measured in July.

Available radiosoundings at 12 UTC in Zadar for the selected dataset (52 in the period 2002–2004) give the approximate snapshot values of the additional vertical SB characteristics such as: the mean SB height (H_s) the mean PBL height (H) the mean maximum SB wind speed (VH_m) and the mean height of VH_m (h) (Fig. 8 and Table 3). Here the estimations were based on the wind speed and wind direction and virtual θ (θ_V). For SLB days with radiosounding, ΔT and H (according to the Eq. (4)) and mean surface scalar wind speed (V) at 1200 UTC are assessed to be comparable with the mean radiosoundings SB characteristics in 1200 UTC. The mean measured H_{PBL} is higher than the very simple H estimated in Table 2, but it agrees quite well with H in Table 3. The comparison between the surface scalar wind speed, V and VH_m shows approximately 20% increase in the wind speed, in the first 250 m a. g. l. This result is in good agreement with the results of the numerical studies (e.g. Tjernström and Grisogono, 1996; Prtenjak and Grisogono, 2002; Darby et al., 2002; Prtenjak et al., 2006).

Except the prevailing anti-clockwise rotation, the hodographs for Malinska and Senj display quick switches between the onshore and the offshore flow (Fig. 9). The type of rotation and the quick periodic daily exchange are in agreement

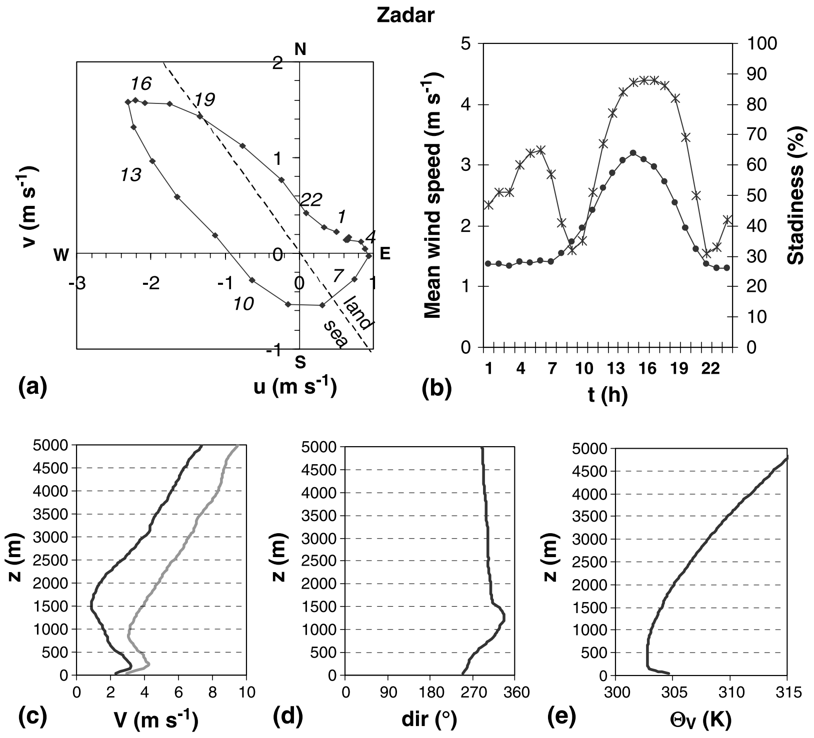

Fig. 8. (**a**, **b**) Same as Fig. 5 except for Zadar. The mean profile of the radiosoundings in Zadar for the selected sea/land breeze days (2002–2004): (**c**) the mean scalar wind speed ($\mathrm{m\,s^{-1}}$) (gray) and the mean speed of the wind vectors ($\mathrm{m\,s^{-1}}$) (black), (**d**) the direction of the mean wind vectors (°) and (**e**) the mean θ_V (K)

Table 3. Mean vertical sea breeze (SB) characteristics from the radiosoundings at 1200 UTC in Zadar for the selected SLB days during 2002–2004: the mean SB height (H_s), the mean PBL height (H_{PBL}), the mean maximum SB wind speed (VH_m) and the mean height of VH_m (h). Last three values present the estimated H according to Eq. (4) for the sea–land temperature difference (ΔT) and mean surface scalar wind speed (V) at 1200 UTC on SLB days with radiosoundings

Station	H_s (m)	H_{PBL} (m)	VH_m ($\mathrm{m\,s^{-1}}$)	h (m)	H (m)	ΔT (°C)	V ($\mathrm{m\,s^{-1}}$)
Zadar	750	1800	4.3	250	1700	6.7	3.4

with other studies (Orilć et al., 1988; Prtenjak, 2003). During examined period, the wind speed maxima are observed at the same month, in August; $8\,\mathrm{m\,s^{-1}}$ in Malinska and only $3.5\,\mathrm{m\,s^{-1}}$ in Senj, respectively.

In Malinska, the weak SE nocturnal flow transforms into almost three times faster daytime SB flow from NW (Fig. 9a and b). Numerical simulations (Nitis et al., 2005; Prtenjak et al., 2006) suggested that the SB in Malinska develops at the crossway upon the influence of two mesoscale features; upon the daytime mesoscale eddy influence inside Rijeka Bay (which causes clockwise rotation) and upon the CZ influence (and anti-clockwise rotation) above the NE part of the island of Krk. Therefore, the hodograph is highly distorted with a shape almost like a line. The anti-clockwise rotation of the wind hodograph is mostly due to CZ generated east of Malinska. The morning NW winds are twisted toward east during the afternoon.

As the station with the rarest SLB, Senj is still influenced by this phenomenon (Fig. 9c). The onshore flow as the superposition of the SB, upslope and valley winds from the SSW is rather weak (Fig. 9d). The highly persistent joined LB, mountain and downslope winds generate a twice stronger nocturnal NE flow compared to the daytime one. By objective approach, Pandžić and Likso (2005) show very similar behavior of the SLB in Senj (see their fig. 5). This is the only station with the stronger nighttime winds than the daytime ones compared to the other stations in this study.

Prtenjak (2003) argued that the anti-clockwise rotation is preferable in the first part of the summer (June and July) in Malinska and in the second part of the summer (August and September)

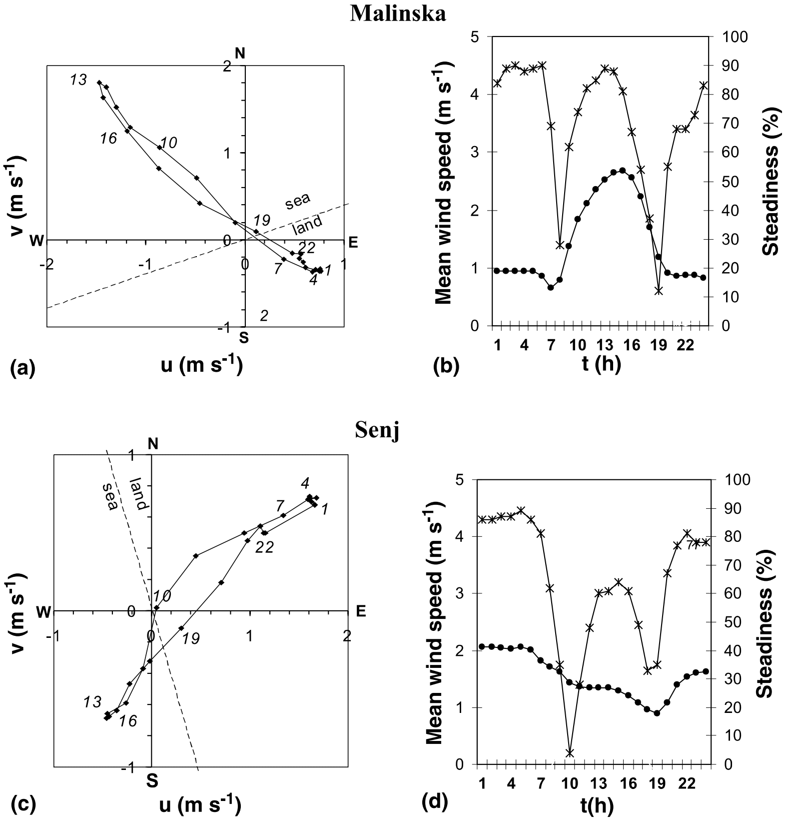

Fig. 9. Same as Fig. 5 except for (**a**, **b**) Malinska and (**c**, **d**) Senj

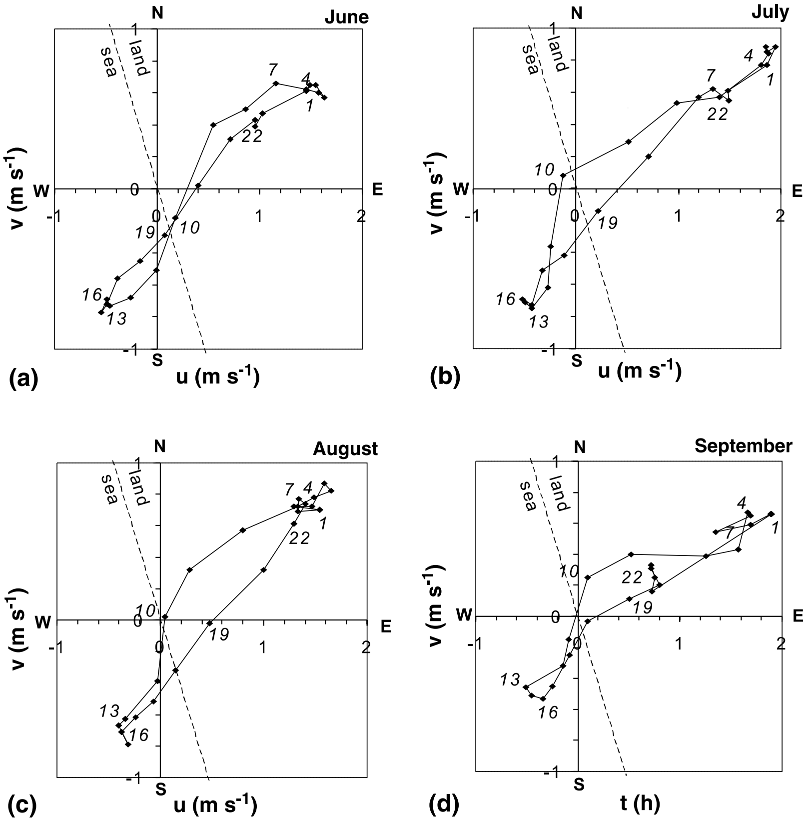

Fig. 10. The hodograph of the climatological observed surface wind vectors ($\mathrm{m\,s^{-1}}$) calculated for the selected SLB dataset for the period 1991–2004 for Senj: (**a**) June, (**b**) July, (**c**) August and (**d**) September. The wind vectors are directed toward the origin of the coordinate system. Dashed line represents the orientation of the coastline and the numbers represent local time

in Senj. Here, the longer dataset confirms the above hypothesis for Senj only (Fig. 10). Presumably the ‘‘bay’’ circulation (according to Lukšić, 1989) that develops over the Kvarner Bay is responsible for this monthly anti-clockwise variability. During the day, the lower air inside the bay circulation moves from south towards the Kvarner Bay due to significant island surface. During the night, the lower air blows in the opposite direction, toward the south. Lukšić (1989) found that the favorable conditions for the bay circulation are in July. The anti-clockwise turning in Senj is registered more frequent when bay circulation is weak or does not exist since the bay circulation in Senj has a direction parallel to the coast: daytime SSE versus nighttime NNW. Therefore, the anti-clockwise in Senj is more frequent in August and September (Fig. 10).

The measurements show that the SB reaches its maximum speed very frequently between 14 and 15 h. In Senj as the exception, the SB wind speed reaches its maximum at 11 h due to the air channeling between mainland and island of Krk (Prtenjak et al., 2006). The strongest SB is found in Pula-airport and Mali Lošinj while the weakest in Senj. The magnitude of the maximum speed agrees well with these reported by Furberg et al. (2002) for Sardinia and Bigot and Planchon (2003) for northern France.

4. Conclusions

Daily climatological characteristics of nine chosen meteorological stations (Zadar, Mali Lošinj, Rab, Pula-airport, Senj, Malinska, Rijeka-airport, Opatija and Rijeka) were analyzed for the summertime sea/land breeze (SLB) circulation. For this purpose standard available surface measurements from June to September for the period 1991–2004 (the wind speed and wind direction, the surface pressure, the sea and air surface temperature and the cloudiness) and radiosounding in Zadar (from 2002–2004) are used. The analyses were based on the selected SLB dataset which was obtained employing the several criteria. The selected SLB dataset were used to determine the SLB climatological characteristics at the northern Adriatic and to obtain climatological wind hodographs that have not been analyzed before. Despite their subjective character, the screening criteria gave very similar results for Rijeka and Senj compared with the objective approach made by Pandžić and Likso (2005). Furthermore, although somewhat unexpected, using much longer data set, the many similar wind characteristics are obtained here as in Prtenjak (2003).

The daily SLB climatological characteristics showed that the strongest SLB is observed in Pula-airport and Mali Lošinj, the most frequent SLB is in Opatija and Zadar (about 60%) and the rarest and the weakest is in Senj (about 37%). An average duration of the sea breeze is 10 h starting at 8 h with small spatial and temporal differences. The measurements of all stations showed that the sea breezes reached maximum wind speed between 14 and 15 h. At Senj as an exception again, the sea breeze reached its maximum at 11 h (due to channeling of the air flow though the Velebit channel) and the nighttime winds were doubled compared to the daytime values. Both, the SLB frequency and the sea breeze strength as well as the sea breeze duration agree well with the other locations in temperate latitudes, for Mallorca (Ramis and Romero, 1995), Sardinia (Furberg et al., 2002) or northern France (Bigot and Planchon, 2003). Although at some stations the relatively weak phenomenon, the SLB frequency in the northern Adriatic is about 50% of all days in the summer period.

The analyzed dataset did not reveal the significant relationship of the sea–land temperature difference (ΔT) with latitude in the northern Adriatic. The ΔT is highly dependent on the local terrain and other coastal characteristics. The smallest ΔT is observed in Pula-airport due to relatively low maximum of the air surface temperature (T_a) while the largest is in Senj due to the anomalous low maximum of the sea surface temperature (T_s).

The straightforward method based on the climatological records of wind speed and ΔT only, showed for three stations (Opatija, Malinska and Zadar) that the maximum measured SB wind speed occurred for ΔT around 4.5 °C. The ΔT ranging from 3 to 8 °C in the selected dataset, allowed the frequent SB development. The results confirm the nonlinear relationship between the SB speeds and the ΔT during the day.

The influence of the large scale disturbance (e.g. fronts or traveling baric systems), which was roughly estimated as a difference of T_a and T_s

before and after screening of the dataset, was increased with higher latitude, as we expected. Regarding the ΔT, the difference before and after screening of the dataset is partly dependent on latitude; for the stations in the Rijeka Bay and Velebit channel. This finding is in agreement with the hypothesis made by Orlić et al. (1988). Furthermore, at most stations, the usual clockwise rotation (for the Northern hemisphere) of the wind hodograph is observed. The hodographs for Senj and Malinska displayed the opposite, anti-clockwise rotation. While the hodograph for the Pula-airport, Rijeka-airport and Mali Lošinj showed the effects of the interaction among several SLB circulations, results for Zadar, Senj and Opatija demonstrated considerable topographic influence due to the nearby channeling of the air flow. In Senj, the much longer dataset confirmed the monthly anti-clockwise rotation variability of the wind hodograph, as argued by Prtenjak (2003), while in Malinska this monthly variability of the hodograph rotation was not observed.

Acknowledgments

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Authors' address: Maja Telišman Prtenjak (e-mail: telisman@irb.hr), Branko Grisogono, Andrija Mohorovičić Geophysical Institute, Department of Geophysics, Faculty of Science, University of Zagreb, Horvatovac bb, Zagreb, Croatia.