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THE CLIMATOLOGY OF SEA BREEZES ON SARDINIA

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ABSTRACT

Hourly wind speed and direction data from 12 coastline stations on Sardinia, Italy, are analysed in order to characterize sea breezes in the region. A set of criteria based on the diurnal reversal of wind direction, and the thermal gradient necessary to drive the circulation, is used to identify sea breeze days. Statistics are presented that describe the occurrence, duration, and strength of the sea breezes. On a stationwide basis, sea breezes are most frequent in the summer months (May–August), when they appear on more than one-third of the days. Sea breeze occurrence and duration are the greatest for the stations on the east coast of the island. The all-station average sea breeze duration reaches a maximum of about 9 h in June. The strength of the sea breezes is roughly 3 m s^{-1} during summer months on average over all stations in the sample.

An analysis of mean daily hodographs for the stations in the sample shows clearly the onshore–offshore nature of the sea breeze circulation, and the response of the sea breezes to the local coastline. Sea breezes are shown to develop simultaneously on all coasts of the island under appropriate synoptic conditions. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: Sardinia; data analysis; sea breezes

1. INTRODUCTION

Sea breezes on straight coastlines have been subjected to considerable study over many years. More recent studies investigate the effects of coastline irregularities on the sea breeze circulation (Simpson, 1994). There are, however, relatively few investigations of sea breezes on islands that show strong effects of the island coastline. It should be expected that the occurrence and dynamics of sea breeze circulations on an island would be most strongly expressed if the island dimension is comparable to, or slightly larger than the horizontal scale length of the sea breeze circulation. Steyn (1998) provides an analytical expression for the horizontal scale length of sea breeze circulations, and gives data that show this length to be 50 to 100 km in mid-latitude sea breezes.

This study focuses on the sea breeze climatology of the island of Sardinia, located in the western Mediterranean Sea between 39 °N and 41 °N and 8 °E and 10 °E. Sardinia was chosen because sea breezes are known to be fairly frequent in the Mediterranean region (Colacino and Dell'Osso, 1978; Dalu and Cima, 1983; Ramis and Romero, 1995), and its size (270 km by 140 km) is such that sea breeze circulations should interact strongly across the island.

The topography of Sardinia is quite complex, with many mountains and valleys, as can be seen in Figure 1. Since two out of three of its major mountain ranges are located in the eastern part of the island (Chessa *et al.*,

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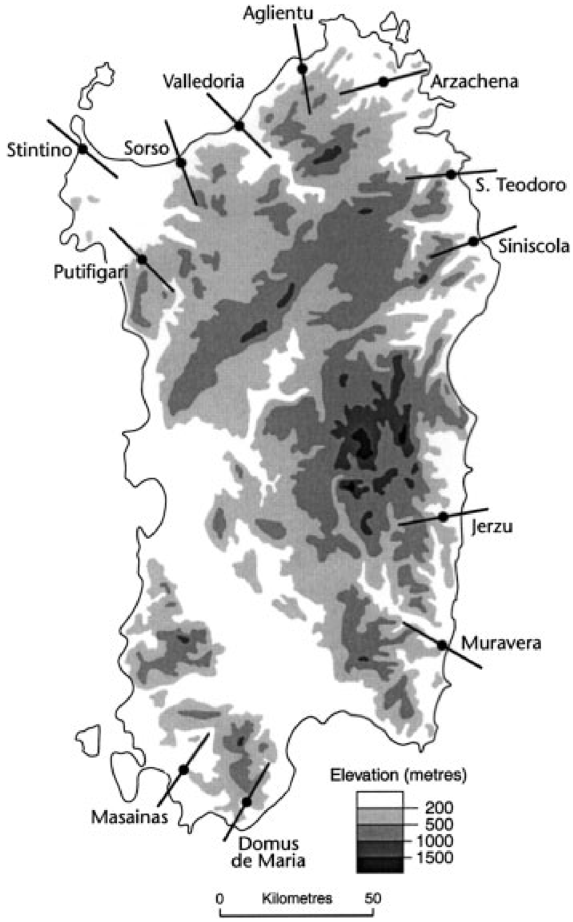

Figure 1. Topographic map of Sardinia showing locations of the 12 meteorological stations employed in this study. Also displayed is the central direction for onshore–offshore flow sectors for each station

1999), steep slopes are a predominant feature of the eastern coastline. The highest point is 1834 m in the mountain range located on the central east coast (Melas *et al*., 2000). To the north is another mountain range that crosses the island from the west coast to the northeast coast, reaching elevations of 1000 m. A valley runs from the west coast to the south coast, through which northwesterly winds are channelled. The southwest of that valley is confined by a smaller mountain range.

The wind climatology of Sardinia is dominated by the *mistral*, which is channelled between the Alps and the Pyrenees and reaches Sardinia from the northwest (Dalu and Cima, 1983). The *mistral* appears on as many as four-fifths of all days, and carries dry cold air, bringing stable conditions and clear skies over the island. On the remaining days, the *sirocco*, from the southeast, and the sea–land breeze occur with equal frequency. The *sirocco* is a rather warm wind that typically occurs in wintertime, when a cyclonic pattern in North Africa causes warm air to be advected towards the northwest. This air is initially dry, but in crossing the Mediterranean it becomes very humid and unstable. Therefore, the *sirocco* is associated with overcast conditions and continuous rain inland, and with rough sea near the coast. Sea–land breezes are most common in summer and are expected to be less frequent than in other Mediterranean regions, due to the prevalent northwesterly wind that acts to minimize the thermal gradient that gives rise to the sea breeze circulation (Dalu and Cima, 1983).

Simpson (1994) gives a brief review of some of the investigations of island sea breezes that have been completed. In the early 1950s, sea breezes were investigated on the small island of Malta (26 km long and

12 km broad), located southeast of Sardinia in the Mediterranean Sea. The result of that study was an increased knowledge of the formation of convergence zones over the island in different synoptic wind conditions (Lamb, 1955). Almost a decade earlier, information obtained from local farmers and fishermen was used to compile a streamline map featuring the summertime sea breeze pattern on Majorca (Jansa and Jaume, 1946). Measuring 65 km long and 65 km wide, Majorca is significantly larger than Malta, and features a mountain range near the northwest coast. The resulting convection pattern is a product of coastal and anabatic breezes combined.

The structure of the sea breeze circulation on Majorca was later reproduced by Ramis and Romero (1995), using numerical simulations. Topography and the soil moisture were identified as the principal factors determining the structure and development of the sea breeze. In a follow-up study of the same island, Ramis and Romero (1996) discussed the effect of the breeze cycle on the transport and diffusion of pollutants.

Dalu and Cima (1983) used a numerical model to simulate the airflow over Sardinia for typical meteorological situations, and found that sea breezes are usually advected eastward by the prevailing winds. Model simulations presented by Melas *et al*. (2000) for Sardinia show how a sea breeze system develops at virtually every coastline under weak synoptic forcing and clear skies during summer, and interacts with topographically induced drainage flows. Their model results are shown to agree relatively well with observations from a limited number of sites located in a rather restricted area near the west coast of the island.

Mathematical models have been used to investigate the influence of land mass size on the intensity of the sea breeze development using the vertical wind velocity as a measure of intensity. Neumann and Mahrer (1974) found that the sea breeze from a 'small' island of radius 26 km produced much smaller vertical velocities than a 'large' island of radius 50 km. The effect of geometry and size of an island was also demonstrated by Mahrer and Segal (1985), who showed that a circular island gives rise to stronger vertical velocities than an elongated island of equal width. In simulations of the effect of width of landmasses on sea breeze development, Xian and Pielke (1991) concluded that the maximum sea breeze convergence is obtained with a land width of 150 km.

Sea breeze climatological studies, such as the present one, aim at determining one or more key characteristics of the sea breeze, such as its frequency of occurrence, its intensity, and its duration, and its time of onset and cessation. Because the diurnal evolution of the sea–land breeze circulation is an essential aspect of the phenomenon, it is important to represent wind speed and direction in a way that effectively preserves their temporal variability on a diurnal time scale. Clearly, mean wind roses are unsuitable for this task. Steyn and Faulkner (1986), in a climatological study of sea breezes in the Lower Fraser Valley, Canada, used composite diurnal hodographs to represent the evolution of the sea–land breeze circulation. This study will use the same graphical device.

Pioneering work by Haurwitz (1947) showed, by use of a simplified linear model, that hodographs during sea breeze conditions should be ellipses for which diurnal rotation is always clockwise (in the Northern Hemisphere), due to the effect of the Coriolis force. However, actual sea and land breeze observations result in wind hodographs that are usually not elliptic but quite irregular (Kusuda and Abe, 1989). Sea breeze hodographs measured in the Northern Hemisphere mostly show clockwise rotation with time, but there are also stations with a clear anticlockwise rotation (Simpson, 1994). Dynamical studies by Kusuda and Alpert (1983) and Steyn and Kallos (1992) have focused on the magnitudes of the individual terms of the wind direction tendency equation in order to explain the differing directions of rotation of the hodographs.

The overall objective of this work is to undertake a climatological study of sea breezes in Sardinia. This objective will have the following components:

(i) To devise a statistical climatology (frequency of occurrence, strength, timing) of sea breezes on Sardinia. This climatology will resolve diurnal and seasonal variability, based on data collected over approximately 16–26 months at a network of 12 coastal stations operated by the Servizio Agrometeorologico Regionale per la Sardegna (SAR).
(ii) To examine diurnal hodograph rotation at coastal stations on a climatological basis.
(iii) To examine the diurnal evolution of a case (or cases) of sea breezes that occurred on all coasts of Sardinia.

2. DATA AND METHODS

2.1. Data set

Meteorological data for this study were collected and supplied by SAR. SAR manages a network of 50 meteorological stations on Sardinia, from which a subset of 12 stations was chosen for the sea breeze analysis based on their close proximity to the coastline (see Figure 1 and Table I). (Details of the network are available at www.sar.sardegna.it.) For each of these stations, SAR supplied hourly temperature, relative humidity, and surface wind speed and direction data from the time of the initial station start-up to 2300 UTC on 30 June 1998. Measurements at Putifigari, Siniscola, and Sorso stations commenced on 1 January 1995, at 0000 UTC. Owing to initial malfunctioning or missing instruments, the data sets for these stations were reduced in the earlier parts of the record. The remaining nine stations were brought into operation during the first quarter of 1997. As a result, the observational length of record available for the sea breeze analysis ranged from 16 to 26 months for the individual stations. Temperature and relative humidity were measured at a height of 2 m, and wind speed and direction at a height of 10 m. The latter data are 10 min vector averages, in order to reduce variance due to turbulent fluctuations.

2.2. Identification of sea breeze occurrences in the data set

In order to select the subset of sea breeze days from the larger data set, criteria must be established that will separate sea breeze days from non-sea-breeze days. A simple method based on six different filters was used by Borne *et al*. (1998), whose primary criterion was the occurrence of a distinct change in surface wind direction within a 24 h period. Steyn and Faulkner (1986) employed a set of three filters for the extraction of sea breeze data. The prime criterion was based on the diurnal reversal of surface wind direction associated with the sea breeze circulation. Two secondary criteria, based on the thermal forcing necessary to drive the sea breeze circulation, used the total hours of sunshine and the lake breeze index proposed by Biggs and Graves (1962) to screen out non-sea-breeze days. By examining rejection statistics, they concluded that the wind reversal criterion is the most important one.

In this study, the main filter for extracting sea breeze days is a surface wind reversal criterion virtually identical to the one employed by Steyn and Faulkner (1986). It is designed to detect the shift from offshore to onshore surface flow in the morning or early afternoon and the subsequent reversal later in the day that are characteristic of the sea breeze circulation. The filter was implemented in the following manner:

Table I. Station coordinates and lengths of record (courtesy of A. Delitala, SAR)

Station name	Coast	Longitude	Latitude	Distance from closest sea (km)	Height above sea level (m)	Length of record (months)
Aglientu	N	9°04′34″	41°06′13″	2.75	110	15.6
Arzachena	N	9°23′19″	41°03′52″	6.27	20	17.9
Domus de Maria	S	8°51′48″	38°57′46″	6.46	133	15.9
Jerzu	E	9°36′23″	39°47′35″	5.58	46	16.8
Masainas	W	8°37′38″	39°03′29″	5.20	90	16.8
Muravera	E	9°35′55″	39°25′09″	2.06	4	17.0
Putifigari	W	8°27′37″	40°32′49″	9.47	423	26.2
San Teodoro	E	9°38′44″	40°47′36″	2.17	13	17.0
Siniscola	E	9°43′47″	40°35′45″	2.07	14	24.5
Sorso	N	8°36′35″	40°49′51″	1.97	57	20.9
Stintino	N	8°13′53″	40°52′15″	0.94	35	16.4
Valledoria	N	8°49′56″	40°56′24″	1.09	5	17.0

(a) a majority of the hourly winds must be offshore (or calm) during the hours from (sunrise − 6 h) to (sunrise + 2 h);
(b) the wind must blow onshore for at least two consecutive hours during the hours from (sunrise + 2 h) to (sunset + 2 h); and
(c) a majority of the hourly winds must be non-onshore (or calm) during the hours from (sunset + 2 h) to (sunset + 8 h).

Categories (a)–(c) correspond directly to categories (a)–(c) in Steyn and Faulkner (1986). However, we have chosen more generous time margins to accommodate for the change in latitude. We have also allowed calm winds in categories (a) and (c), under the assumption that the land breeze is weaker than its daytime counterpart.

The range of directions for onshore and offshore flow was determined subjectively by reference to the direction of the local coastline and to the large-scale isothermal pattern over the island in summer (Chessa and Delitala, 1997). The central directions of onshore–offshore flow for each station are depicted in Figure 1. For the purposes of this study, wind in the 90° sectors centred on the main onshore–offshore direction as portrayed in Figure 1 may be considered onshore and offshore flow respectively.

It is recognized that the reversing flow criterion does not exclude days with sea-breeze-like conditions caused by the passage of frontal systems. An attempt to remove such days was made by adding a filter based on the land–sea temperature difference necessary to drive the sea breeze circulation. Borne *et al.* (1998) used a filter defined by $T_{\text{land}} - T_{\text{sea}} > 3\,^{\circ}\text{C}$, where T_{land} is the daily maximum temperature over land and T_{sea} is the sea surface temperature. In this study, the filter was implemented as $T_{\text{land}} - T_{\text{sea}} > 0\,^{\circ}\text{C}$, where T_{land} is the daily averaged daytime (between sunrise and sunset) temperature at each station. When the distinction in the definition of T_{land} is taken into account, the two filters are indeed very similar. T_{sea}, the air temperature over water, was approximated by the sea surface temperature, in a similar fashion to Steyn and Faulkner (1986) and Borne *et al.* (1998). For the purposes of this study, monthly averaged sea surface temperatures (Picco, 1990) in the immediately offshore waters adjacent to each station were used in lieu of daily values. The conservative nature of sea surface temperatures in the Mediterranean acts to keep errors due to this approximation at a minimum.

The reversing flow criterion and the thermal forcing criterion in combination form a fairly conservative method of separating sea breeze days from non-sea-breeze days. Although our set of filters does not take into account the upper air conditions, the reversing flow filter will, in effect, exclude days of strong overriding geostrophic winds. Because of the conservative nature of our set of filters, this method will most likely underestimate the sea breeze frequency. Nevertheless, the data subset that will have passed both filters will provide a sound basis for constructing a sea breeze climatology.

3. SEA AND LAND BREEZE CLIMATOLOGY

Having performed the sea breeze day extraction process described in Section 2 on the data set, we now turn to examine the characteristics of the sea and land breezes that were found. Section 3.1 offers an overview of the temporal and spatial characteristics of the following statistics:

- mean frequency of occurrence of sea breeze days by month,
- mean time of onset and cessation of the sea breeze by month,
- mean daily duration by month, and
- mean wind speed during sea breeze and land breeze by month.

The above statistics can be found in detailed tabulated form in Furberg (2000). In addition to these monthly statistics, hodographs representing the mean hourly wind vectors during sea breeze days are presented in Figure 8, and are discussed in Section 3.2.

3.1. Mean monthly statistics

3.1.1. Frequency of occurrence of sea breeze days. Figure 2 shows the monthly variations in land–sea temperature differences that provide the main driving force for the sea breeze circulation. Owing to the time lag of warming between sea and land, the largest land–sea temperature differences typically occur in spring. Indeed, the greatest temperature difference between the daytime air temperature over land and the sea surface temperature, averaged over all stations in the sample, arises in the month of May (Figure 2). The mean monthly sea breeze frequency of occurrence, averaged over all stations in the sample, is therefore expected to reach its maximum in that month. The variation in land–sea temperature difference between the stations in the sample is mainly due to spatial variations in overland air temperature, rather than spatial variations in sea surface temperature. The latter typically varies by 1 to 2 °C from one location to another in a summer month, but can vary by up to 3 °C in a winter month (Picco, 1990).

A majority of the individual stations in the sample show a peak in mean monthly land–sea temperature difference in the month of May, with a decreasing trend for the remaining summer months. The Putifigari station exhibits the smallest land–sea temperature difference of all stations in the sample for May and June. Similarly, the Stintino and Sorso stations, located near Putifigari in the far northwest corner of the island (see Figure 1), reveal smaller than average land–sea temperature differences for summer months. The northeastern Arzachena station, on the contrary, displays the largest mean monthly land–sea temperature difference of all stations for May, July and August.

From October to February, the mean monthly land–sea temperature difference stays well below zero for all stations in the sample. As we shall see, sea breezes still take place on individual days when the overland air temperature exceeds the sea surface temperature for a given station. However, during the winter season the presence of cold air masses over the region, and the occurrence of frequent and strong northwesterly winds (Serra, 1958), act to prevent the onset of the sea breeze circulation.

Figure 3 shows the observed mean monthly frequency of occurrence of sea breeze days, averaged over all stations in the sample. Firstly, note that the shape of the curve outlined by the mean monthly sea breeze frequency values bears a close resemblance to that of the curve in Figure 2. On an average over all stations, sea breezes are most frequent in the period May through to August, during which time they appear on approximately 40% of all days. The sea breeze frequency peaks in the month of May, as was predicted earlier. A sharp decline in sea breeze frequency takes place from August to October, and in November and December the sea breeze days are very rare. There is a gradual increase in mean monthly sea breeze

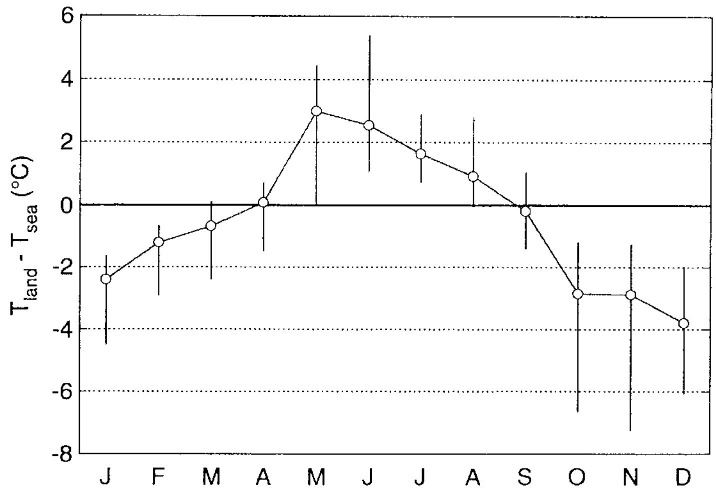

Figure 2. Land–sea temperature difference by month averaged over all stations in the sample. T_{land} is the mean monthly daytime air temperature over land and T_{sea} is the mean monthly sea surface temperature in the immediately offshore waters. Also displayed is the range of land–sea temperature differences for the different stations

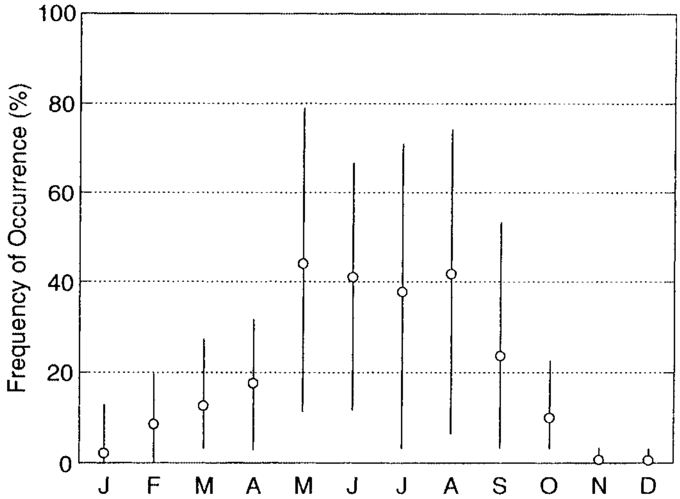

Figure 3. Monthly frequency of occurrence of sea breeze days averaged over all stations in the sample. Also displayed is the range of monthly frequencies of occurrence of sea breeze days for the different stations

occurrence from January until April. From April to May, the mean monthly sea breeze frequency jumps from 18 to 44% on an average over all stations.

The all-station average monthly frequencies of occurrence of sea breeze days (Figure 3) are somewhat lower than those communicated by Ramis and Romero (1995) for Mallorca. They report sea breeze occurrences from April to October and almost every day during July and August. At a higher latitude, Steyn and Faulkner (1986) discovered a maximum of ten sea breeze days in August and a minimum of 1–3 days in December–January for the Lower Fraser Valley on Canada's west coast. In a summary of several sea breeze climatological studies, Simpson (1994) documents that tropical sea breezes occurred on at least two-thirds of the days in the non-monsoon season. The observed sea breeze frequencies on Sardinia thus seem reasonable with regard to its mid-latitude location.

There is significant variation in mean monthly sea breeze frequency of occurrence between the stations in the sample (Figure 3). Figure 4 displays the mean monthly sea breeze frequency in summer months (May–August) for all 12 stations. At the Stintino station, sea breezes are notably infrequent. They are virtually non-existent in winter months, and occur on less than 10% of summer days on average (Figure 4). Part of the explanation can be found in the relatively small mean monthly land–sea temperature differences available to drive the sea breeze circulation at this location, as was discussed above. More importantly, the Stintino station is located at the base of a narrow peninsula (see Figure 1) and is effectively surrounded by water on two sides. This narrow section of land has too small a horizontal extent for sea breeze circulations to arise readily. Similarly, the neighbouring Putifigari station displays monthly sea breeze frequencies that are well below the all-station average for all months of the year. At this location, mean monthly land–sea temperature differences are at a minimum. In addition, the mountains surrounding the station act to obstruct the sea breeze flow from reaching Putifigari, and, as a result, sea breezes only appear on about one-fourth of summer days on average (Figure 4). A similar blocking effect by surrounding mountains keeps the sea breeze frequency of occurrence at the Masainas and Domus de Maria locations in the southwest to about one-fourth to one-third of summer days (Figure 4).

Sea breezes are most frequently observed on the east coast of Sardinia, where they appear on roughly half of all summer days (Figure 4). At Jerzu, sea breezes occur on as many as four-fifths of all days in May (Figure 4). A likely explanation for this high observed frequency of occurrence is that sea breezes on the east coast are indistinguishable from katabatic–anabatic flow cycles. Furthermore, slope winds are thermally driven and, therefore, will be most frequent under synoptic conditions that favour the occurrence of sea–land breezes. The two phenomena are closely related, and will be inextricably linked in any statistical climatological study like the present one. On the north coast, Sorso and Valledoria stations display sea breeze

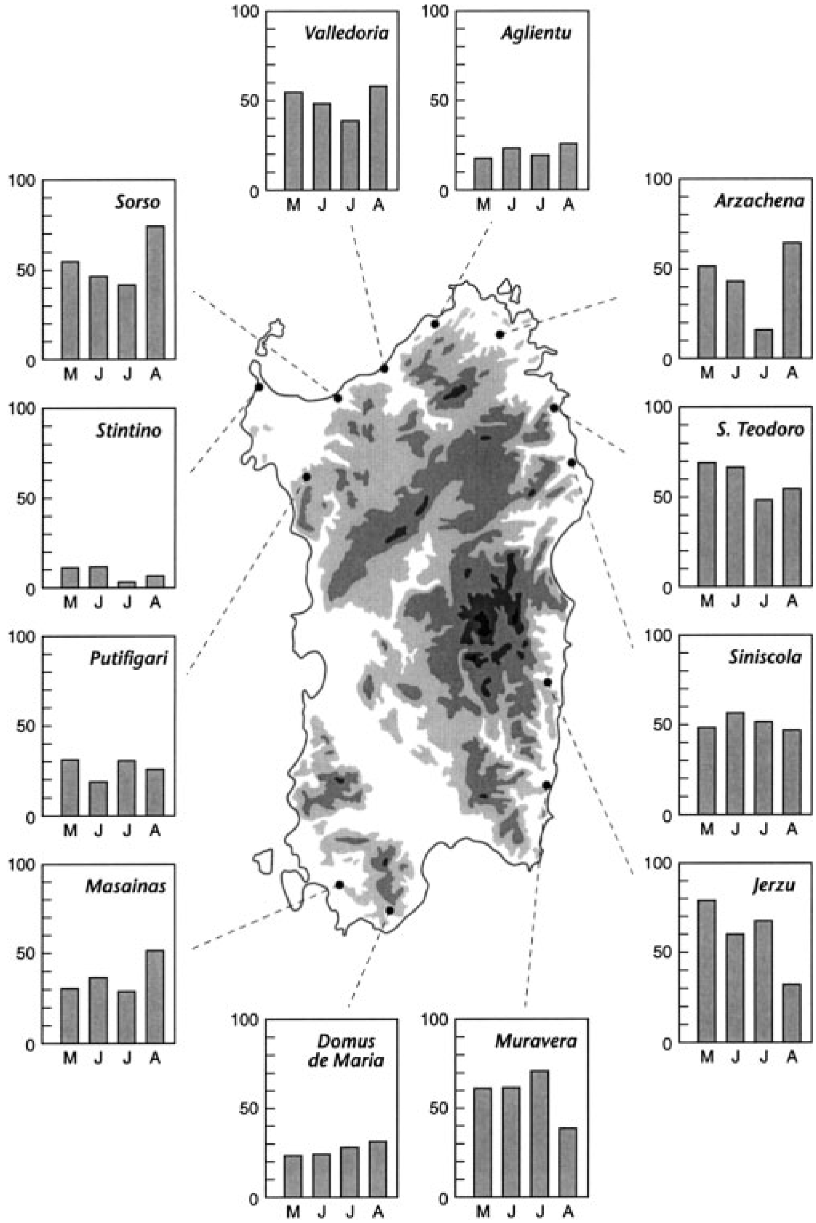

Figure 4. Monthly mean frequency of occurrence of sea breeze days (%) in summer (May–August) for each of the 12 stations

frequencies in the same range as for the east coast of the island (Figure 4). However, the neighbouring Aglientu station, also on the north coast, exhibits sea breezes on only about one-fifth of summer days (Figure 4). A possible explanation is that the Aglientu station, which lies in the 12 km wide strait of *Bocche di Bonifacio* between Corsica and Sardinia, experiences the effects of airflow channelling through the strait. This channelling would be superimposed on the sea breeze circulation along opposing coastlines of the two islands. Corsica is smaller than Sardinia, with dimensions about 180 km north to south and 80 km east to west, with about 1000 km of coastline. The climate of the island is typically Mediterranean, with prevailing winds southwesterly, westerly and northwesterly, called the *libeccio* and the *mistral*. The *sirocco* blows on the east coast from the southwest, the *levante* from the east, the *grecale* from the northeast and the *tramontane* from the north. Corsica is an extremely mountainous island, even more so than Sardinia. The main Corsican mountain range lies north–south on the island, with regions above 1500 m above sea level having alpine climates. The steep orography of the island is the major factor influencing its microclimates, and results in several distinct temperature and precipitation subregions. As in Sardinia, sea breezes occur prevalently during the warm season at all coastal sites, with strong interaction with other local features like valley- and downslope-winds.

3.1.2. Duration and times of onset and cessation of the sea breezes. Having established that sea breezes occur at all stations in the sample, it is of interest to investigate the daily temporal dimensions of the sea breeze flow. Figure 5 displays the mean monthly times of onset and cessation of the sea breeze, as well as its mean daily duration by month, averaged over all stations in the sample. For reference, sunrise and sunset times are also shown. From March until September the onset of the sea breeze flow takes place approximately 4 h after sunrise (Figure 5). This lag of sea breeze onset relative to solar heating is commonly observed, and is due to the time taken for vertical and horizontal adjustment of the atmospheric boundary layer across the coastline. The sea breeze flow ceases within an hour of sunset (Figure 5). The all-station average times of onset/cessation exhibit the expected minimum/maximum during summer months. The observed times of onset and cessation on Sardinia are comparable to corresponding data for mid-latitude locations as summarized by Atkinson (1981). He reports sea breeze times of onset ranging from 0700 to 0800 hours in summer for Kinloss, Scotland, and Athens, Greece. In Athens, sea breezes stated to end at 2100 hours in summer.

The all-station average daily duration of sea breeze flow exhibits a marked seasonal variation (Figure 5). The maximum mean monthly daily duration is observed in the month of June, and is approximately 9 h, averaged over all stations in the sample. Close examination of Figure 5 reveals an apparent discrepancy between the daily duration and the temporal interval between the time of onset and cessation. The latter appears to exceed the former by roughly an hour. This is due to the different methods of calculation of these values. The mean monthly time of onset/cessation represents the time when the mean monthly sea breeze hodograph enters/exits the sector of direction of sea breeze flow. The daily duration of sea breeze flow was calculated by (a) determining the daily sea breeze duration for each day of the month, and (b) taking the average of those values. The conservative manner in which this was done may explain the consistent bias between the two quantities.

As was the case for the sea breeze frequency of occurrence, the duration of the sea breeze flow also varies significantly from station to station (Figure 6). There is an apparent positive correlation between the mean

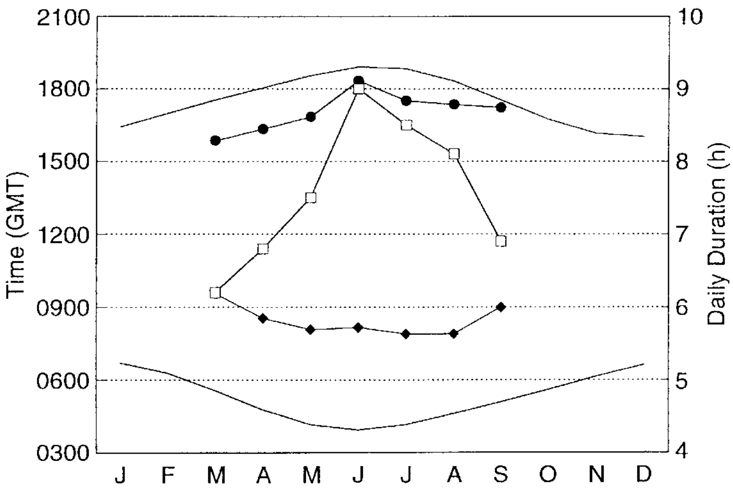

Figure 5. Ensemble mean time of onset (♦) and cessation (●), and mean daily duration (□) of sea breezes by month averaged over all stations in the sample. (The values for January, February, October, November, and December are indeterminate due to sparse data.) Times are given in UTC (local time on Sardinia is UTC + 1 h, or +2 h with daylight saving time). Sunrise and sunset times in UTC (solid lines) are given for comparison

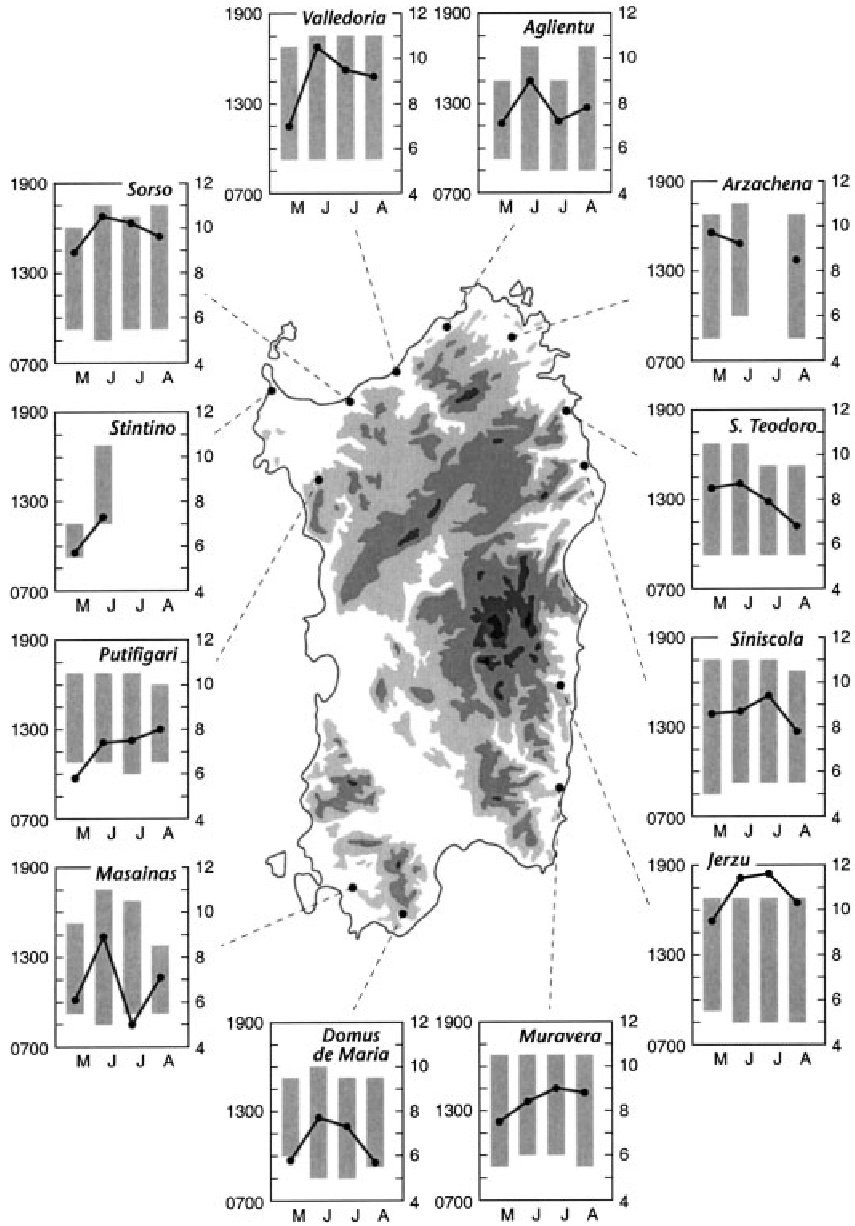

Figure 6. Ensemble mean time of onset and cessation (grey bars) and mean duration (black curve) of sea breezes by month in summer (May–August) for each of the 12 stations. (Values for Stintino station (June and July), and for Arzachena station (July), are indeterminate due to sparse data.) Note that time of day (UTC) is read to the left-hand axis, and daily duration (h) to the right-hand axis

monthly frequency of occurrence of sea breezes at a station and its mean daily duration of sea breeze flow by month. For instance, at Putifigari and Stintino, where sea breezes are relatively rare, the daily duration of the sea breeze flow does not exceed 8 h in the summer months (Figure 6). The Putifigari station is located furthest from the coast of all stations in the sample (see Table I), and Figure 6 shows that sea breeze flow reaches this station later in the day than any of the other stations. At the Domus de Maria and Masainas stations, where sea breezes are partly obstructed by the surrounding mountains, the daily duration of sea breeze flow is below the all-station average in summer months, with the exception of the somewhat peculiar peak of 9 h at Masainas in June (Figure 6). In contrast, the stations on the east coast of Sardinia display daily sea breeze durations that are on or above average. In particular, the Jerzu station, where sea breezes are especially frequent, exhibits a daily duration of sea breeze flow of over 11 h in June and July (Figure 6). Once again, as was the case with the sea breeze frequency of occurrence, the Aglientu station falls well below the range of its neighbouring stations for the daily duration of sea breeze flow. Masainas is located in a valley with 800–1000 m high mountains on the east-northeast sides, and is often affected by strong winds from the south, especially during summer, with the result that local winds like sea breezes are often masked by these larger-scale flows. The wind intensity peak shown in Figure 6 can thus be explained as the superposition of local sea breeze and wind flowing from the south along the valley.

3.1.3. Strength of the sea and land breezes. The mean monthly strengths, or wind speeds, of the sea and land breezes averaged over all stations in the sample are displayed in Figure 7. The strength of the land breeze flow is roughly 1.5 m s^{-1} with very little monthly variation, with the exception of the month of March when the mean land breeze wind speed is 2.1 m s^{-1} (Figure 7). The strength of the sea breeze flow, however, shows a marked seasonal variation. Starting at 2 m s^{-1} in March, the mean monthly sea breeze wind speed grows in strength to roughly 3 m s^{-1} in June, July and August (Figure 7). In September, it reduces in strength once more.

Not all stations follow the all-station mean pattern of seasonal variation of the strengths of the sea and land breezes. The Masainas station, for instance, displays a sharp peak in sea and land breeze wind speeds in the month of June, reaching a mean sea breeze wind speed of 8.8 m s^{-1} and a mean land breeze wind speed of 5.2 m s^{-1} (Figure 7). This sudden peak may be partly explained by the larger than average land–sea temperature difference in June at this location. At other stations, the strength of the flow stays fairly constant from month to month. This is the case of the Domus de Maria and Valledoria stations, where the mean monthly sea breeze wind speeds remain roughly 3 m s^{-1} throughout the year. At the Sorso station, the sea and land breezes are of comparable strength for all months except June, July and August, when the sea breeze wind speeds are stronger. At the San Teodoro station, sea and land breeze wind speeds are consistently below the all-station average. In late summer, land breezes are weak to the point of being undetectable at this location.

Steyn and Faulkner (1986) report mean wind speeds of roughly 3 m s^{-1}, with very little monthly variation, during sea breezes in the Lower Fraser Valley, Canada. Atkinson (1981) reports an average speed of the sea breeze at the time of onset at Bombay of 4.4–4.7 m s^{-1}. The observed sea breeze wind speeds on Sardinia are in reasonable accord with these values.

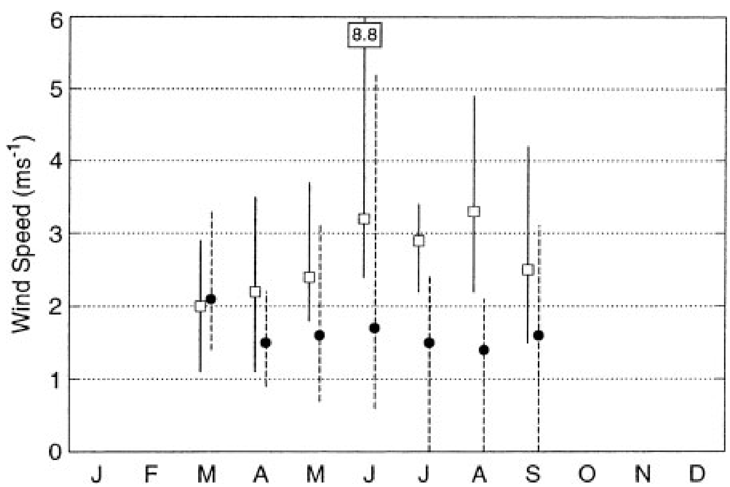

Figure 7. Monthly mean wind speeds of the sea (□) and land (●) breeze averaged over all stations in the sample. Also displayed are the ranges of monthly sea–land breeze wind speeds for the different stations. (The values for January, February, October, November, and December are indeterminate due to sparse data)

3.2. Mean hourly behaviour

The statistics discussed in Section 3.1 give an indication of the occurrence and behaviour of the observed sea breezes on a seasonal time scale. Because the essence of a sea–land breeze cycle is evolution of wind speed and direction on a diurnal time scale, the observed sea and land breezes will now be examined on an hourly basis.

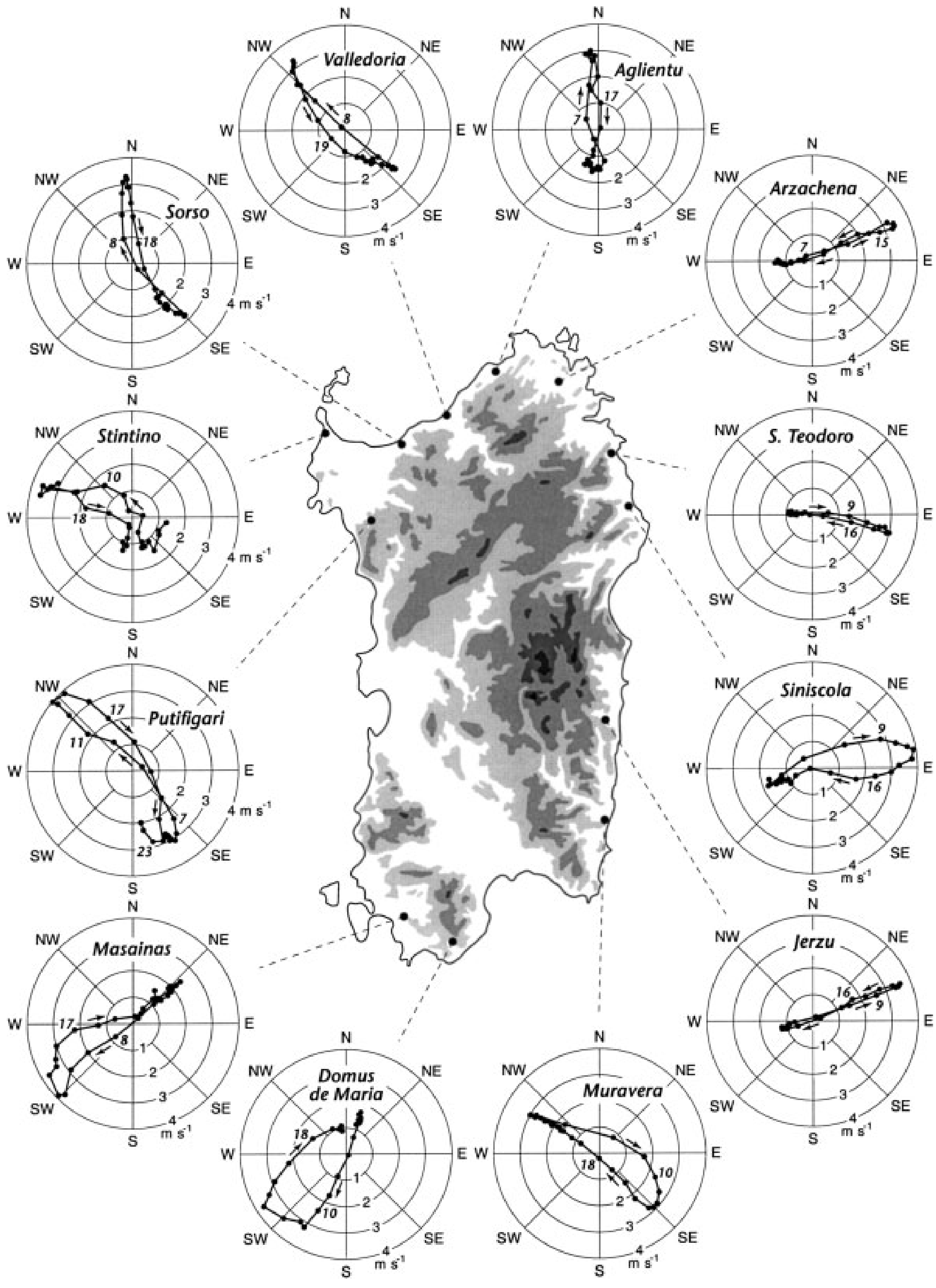

Figure 8. Mean hourly hodographs averaged over all sea breeze days for each station. Numbers near data points indicate time of day in hours (UTC), and arrows indicate the direction of rotation

3.2.1. Mean sea breeze hodographs. Hodographs have often been used to illustrate the diurnal rotation of the wind direction of sea breezes (Kusuda and Alpert, 1983). Figure 8 shows the mean sea breeze hodograph for each station in the sample. The hodographs were calculated by averaging the hourly wind vectors over all observed sea breeze days for each location. The total number of observed sea breeze days varies by station (Table II), and determines the smoothness of the mean sea breeze hodographs. For instance, at the Stintino station, only 23 days in the original data set met the sea breeze criteria (Table II), explaining the somewhat irregular shape of its mean sea breeze hodograph (Figure 8).

All of the hodographs in Figure 8 show clearly the onshore–offshore nature of the sea–land breeze circulation. Many of the stations (Arzachena, San Teodoro and Jerzu on the east coast, and Aglientu on the north coast) show no clear diurnal rotation of wind direction, but rather display very quick switches between onshore and offshore flow. Stations that display a marked diurnal rotation are Siniscola and Muravera on the east coast, and Domus de Maria and Masainas on the south coast. These stations manifest clear clockwise diurnal rotation, in agreement with Haurwitz's (1947) predictions for sea breeze circulations in the Northern Hemisphere. As has been shown by Kusuda and Alpert (1983), Kusuda and Abe (1989) and Steyn and Kallos (1992), in locations with significant topography, or complex coastline, local topographically induced pressure effects can be responsible for the absence of the expected clockwise (in the Northern Hemisphere) sea breeze rotation. It is reasonable to assume that similar effects can also be responsible for a sharp switch, rather than gradual rotation of wind direction. For most of the stations, the sea breeze reaches its maximum speed between 1100 and 1300 UTC (Figure 8). The exception is the Putifigari station, where the sea breeze wind speed peaks between 1400 and 1500 UTC, due to its relative distance to the coastline (see Table I).

The hodographs in Figure 8 present evidence of the response of the sea breeze flow direction to the local coastline. The sea breeze flow direction stays roughly perpendicular to the local coastline on all sides of the island. Though this seems intuitively reasonable, Figure 8 provides observational confirmation of this observation.

4. SEA BREEZE HODOGRAPHS ON 21 JUNE 1998

In order to study the dynamics and interactions of sea breeze circulations on Sardinia, we set out to find days when sea breezes occurred simultaneously on all coasts of the island. As was mentioned earlier, an island of Sardinia's dimension should permit sea breeze circulations to develop fully along all coastlines at once, under the appropriate synoptic conditions. Indeed, sea breezes were observed at ten or more of the 12 stations in the sample on 4.1% of all sea breeze days, i.e. days when sea breezes were observed at at least one station.

Table II. Number of days with sea breeze flow used to calculate the mean hourly wind vectors in Figure 8

Station	$\sum$days
Aglientu	49
Arzachena	124
Domus de Maria	73
Jerzu	162
Masainas	99
Muravera	160
Putifigari	97
San Teodoro	163
Siniscola	183
Sorso	146
Stintino	23
Valledoria	153

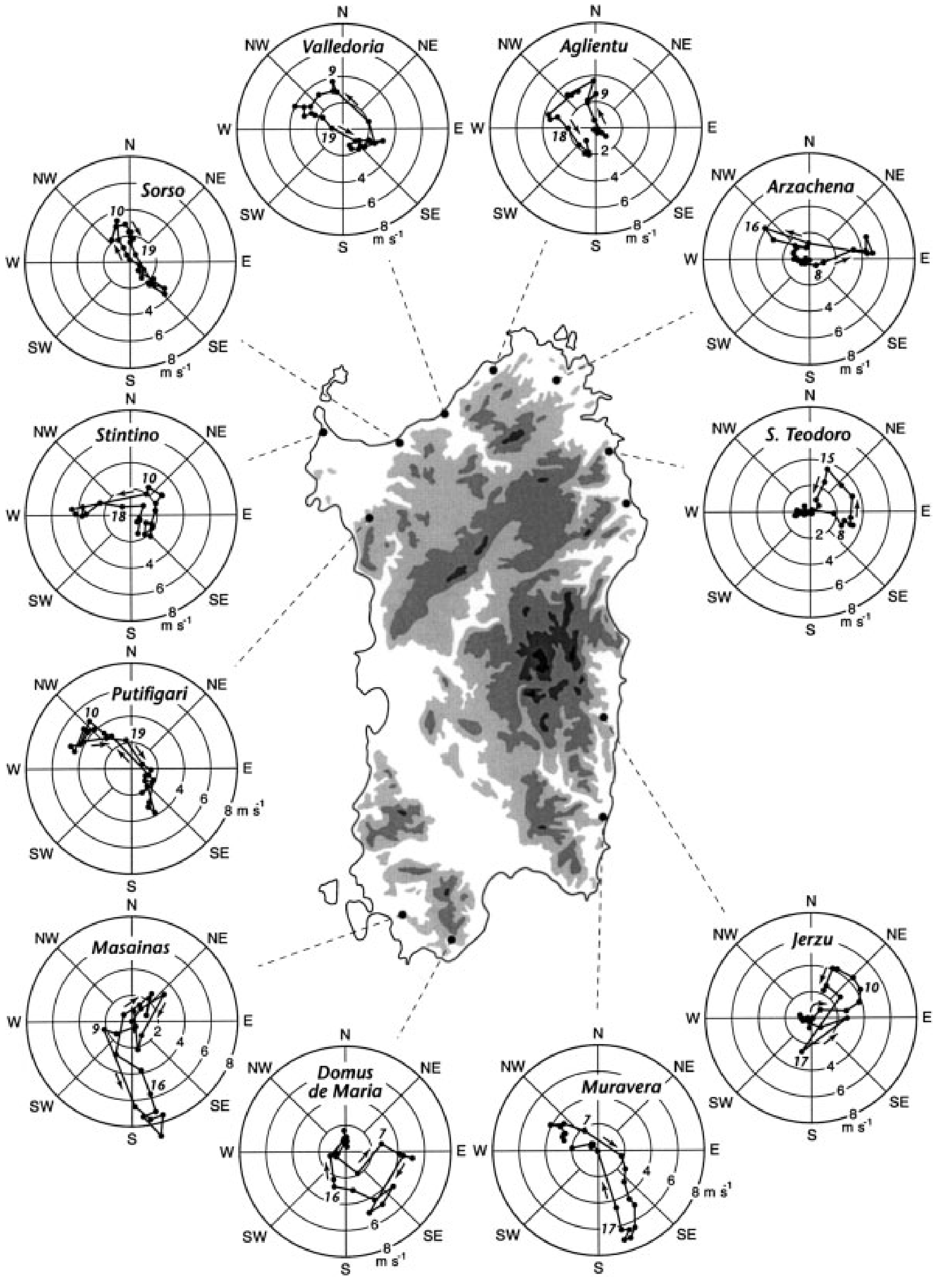

Figure 9. Case study of hourly hodographs on 21 June 1998 for the 11 stations in the sample that displayed sea breeze on that day (Siniscola station did not, and was therefore left out). Numbers near data points indicate time of day in hours (UTC), and arrows indicate the direction of rotation. Note that the wind velocity scale is double that of Figure 8

For the purpose of elucidating the dynamics of the coexisting sea breeze circulations, the sea breeze day of 21 June 1998 was chosen as a case study. On this particular day, all stations in the sample, except Siniscola, met our sea breeze selection criteria. Figure 9 displays the hodographs for each station (except Siniscola) on the day in question. Firstly, note the ragged appearance of these hodographs compared with the mean sea breeze hodographs displayed in Figure 8. The smoothness of the latter is due to the averaging process that was used to produce them. Despite the raggedness of the hodographs in Figure 9, their diurnal rotation is, in most cases, clearly discernible. The Domus de Maria and Muravera hodographs in Figure 9 show a distinct clockwise diurnal rotation, in agreement with the climatological hodographs. On the same day, the sea breeze rotation is anticlockwise at Aglientu and Valledoria stations on the north coast, and at Jerzu and San Teodoro stations on the east coast.

Figure 9 carries great value, in that it is a first representation of observed sea breezes occurring simultaneously on all coasts of an island of this size. A similar, but modelled, representation for sea breezes on Sardinia can be found in Melas *et al*. (2000). Our observations could serve as a starting point for a modelling study analysing the dynamics behind the observed diurnal rotations.

5. CONCLUSIONS

The present study has demonstrated the existence in all seasons of sea breeze circulations on the island of Sardinia. The descriptive statistics of mean monthly conditions show behaviour (in terms of frequency of occurrence, duration, and strength) similar to that observed in other mid-latitude non-island regions. The onshore–offshore nature of the observed sea breeze circulation was verified by an examination of the mean sea breeze hodographs for all stations in the sample. These hodographs provide an observational indication of the response of the direction of sea breeze flow to the local coastline. It was shown that, given the appropriate synoptic conditions, sea breeze circulations can and do develop on all coasts of the island at once.

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