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Development of selection algorithms and databases for sea breeze studies

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Abstract We present an automated and manual algorithm for identifying past sea breeze episodes in the Bay of Alicante (southeastern coast of the Iberian Peninsula, IP, Spain) for a 6-year study period (2000–2005). The main goal was to provide databases for better understanding the functioning of sea breezes, which have a crucial influence on weather and climate in both coastal and inland areas and therefore affect human life in many ways. The algorithms apply a well-defined set of criteria based on meteorological and sea surface temperature measurements in order to detect past occurrences. The automated and manual identification techniques successfully identified a total of 475 and 1414 sea breeze events, respectively. A large database containing the significant characteristic parameters measured (onset time, cessation time, duration time, maximum wind speed, inland penetration, etc.) for these 475 sea breeze days is presented. We evaluated the accuracy of both selection techniques by means of comparison with independent objective and subjective techniques. Both databases are the major contribution of this paper and have been used in some climatological sea breeze studies and are also presented here for any coastal expert interested in numerical–theoretical, observational–experimental and climatological wind studies.

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1 Introduction

Methodologies and filter techniques for reliably identifying past sea breeze episodes are decisive in the construction of good quality databases aimed at gleaning greater knowledge of sea breezes. Over the last few decades, algorithms for the identification and forecasting of sea breezes have garnered much attention in the context of atmospheric research. Ramis et al. (1990) pointed out that few studies predict the occurrence of sea breezes. Hall (1954), Biggs and Graves (1962) and Lyons (1972) performed pioneering research work in the design of statistical forecasting techniques for lake breezes. Hall (1954) used a simple criterion based solely on the pressure difference between three sites in the State of Wisconsin (USA); nearly clear sky; light winds; and a centre of high pressure over Illinois. Biggs and Graves (1962) expounded a dimensional analysis based on an accurate lake breeze index which compares

opposing background flows with the land–sea temperature difference:

$$\sigma = \frac{V^2}{(C_p \Delta T)} \qquad (1)$$

where V^2 is the average hourly opposing wind speed (in metres per second) between 1000 h and 1600 h at an inland site; C_p is the specific heat coefficient of dry air at constant pressure (1,003 J kg^{-1} K^{-1}); ΔT is the difference (in Kelvin) between maximum inland air (T_1) and lake surface water (T_w) temperatures; and σ is an empirically derived constant called the lake breeze index. The index is a ratio of the controlling forces, i.e. the inertial and buoyancy forces, and was proposed for identifying lake breezes on the western shore of Lake Erie. Lyons (1972) improved the lake breeze index for the southwestern shore of Lake Michigan (Chicago, Illinois, USA) and used as the inertial force the geostrophic wind speed (V_g in metres per second) at 12 UTC surface analysis:

$$\sigma = \frac{V_g^2}{(C_p \Delta T)} = \frac{12.71 \times 10^6}{[\Delta N^2 (T_1 - T_w)]} \qquad (2)$$

where ΔN is the 4-mb isobar spacing (in kilometres) from the 06 UTC surface chart. For large index values, V^2 dominates and hence sea breezes will not develop in a situation of opposing winds. For small index values, ΔT is large and sea breezes are to be expected (Simpson 1994). Biggs and Graves (1962) and Lyons (1972) found critical values of $\sigma=3.0$ and 10.0 m^2 s^{-2} K^{-1} for delineating days with and without lake breezes, respectively. Simpson (1994) reported an index value of $\sigma=7$ m^2 s^{-2} C^{-1} for sea breezes at Thorney Island (UK). Other observational studies found different values of σ (Miller and Keim 2003) in relation to techniques used for obtaining V_g. Tijm (1999) defined a new sea breeze index which differs from that in Eq. 1. The method describes the sea breeze index as a function of the large-scale offshore component of the wind and the difference in surface layer sensible heat flux ($\Delta w'\theta'$, in metre Kelvin per second) instead of the temperature difference. Porson et al. (2007) conducted a scaling analysis in order to develop an index for sea breeze speed and inland occurrence in a situation of offshore flows, similar to the Biggs and Graves index. These previous statistical forecasting techniques have been added to other diagram filters for the identification of past sea breeze events using routinely collected observations. For example, Steyn and Faulkner (1986) studied sea breezes in the lower Fraser Valley (Canada) applying the Biggs and Graves's method as a test criterion for finding past sea breeze episodes. Laird et al. (2001) found critical index values of $\sigma=2–6$ m^2 s^{-2} C^{-1} and concluded that these forecasting techniques usually overpredict the number of

sea breeze events and are difficult to apply to climatological datasets or for using large suites of data variables. A stochastic prediction scheme was proposed by Frysinger et al. (2003). This is the latest statistical sea breeze prediction algorithm based on wind and air temperature forecasts from synoptic models and observed sea surface temperature (SST) for Charleston (South Carolina, USA).

The current research focuses upon methodologies for identifying past sea breeze occurrences with the overall aim of creating multiyear high-quality databases for sea breeze studies. The particular aims of this paper were: (1) to present a background review on test criteria for selecting past sea breeze events; (2) to develop and evaluate accurate automated and manual filter techniques; and, principally, (3) to create two databases of past sea breeze days for numerical–theoretical, observational–experimental and climatological wind studies. The applications of both databases are also discussed here. The sea breeze datasets presented in this study are available for any expert interested in the meteorological modelling and climatological study of sea breezes.

2 Background review of sea breeze methodology

Table 1 summarises a background review concerning test criteria proposed in an attempt to establish a manual or objective selection method. The techniques are performed in order to ensure that the changes measured in meteorological variables were produced exclusively by sea breeze frontal passages (Ryznar and Touma 1981). The meteorological measurements employed are as follows:

1. *Wind data*: Surface wind speed (WS) and direction (WD) data are the most important meteorological variables with regard to distinguishing sea breezes. The passage of this local wind is characterized by a rapid shift in WS and WD from calm or light offshore winds to light to moderate onshore flows. The changes in WS and WD data from rawinsonde observations at 700 hPa have also been used for rejecting synoptic-scale disturbances (Borne et al. 1998). In addition, Laird et al. (2001) employed average WS in the morning (0500–0700 LST) of <5.5 m s^{-1} as an automated criterion for the identification of lake breeze events.

2. *Air and sea surface temperature data*: A positive temperature difference (ΔT) between air over the land and over the sea is the most prominent physical factor involved in the initiation of sea breezes (Gustavsson et al. 1995). Whilst air temperature data over seas or lakes are still quite sparse and not always consistent, most studies use SST for computing this objective criterion. A decrease in diurnal air temperature development is also a particular sea breeze feature used as a selection filter.

Table 1 Background review of overall test criteria used for both automated and manual methodologies for detecting sea or lake breezes

References	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11
Biggs and Graves (1962)	✓	✓									
Lyons (1972)	✓	✓		✓			✓				
Barbato (1978)	✓		✓(b)		✓		✓				
Brittain (1978)		✓									
Ryznar and Touma (1981)	✓		✓(b)	✓	✓	✓					
Prezerakos (1986)	✓		✓	✓							
Steyn and Faulkner (1986)	✓	✓					✓				
Banfield (1991)	✓										
Redaño et al. (1991)	✓		✓	✓							
Gustavsson et al. (1995)	✓		✓(b)		✓	✓					
Borne et al. (1998)	✓(a)	✓									
González et al. (1998)										✓	
Tijm (1999)									✓		
Laird et al. (2001)	✓	✓									
Furberg et al. (2002)	✓	✓									
Miller and Keim (2003)	✓		✓(b)	✓				✓			
Salvador and Millán (2003)	✓	✓	✓(b)								
Steyn (2003)									✓		
Bowers (2004)	✓				✓	✓					
Prtenjak and Grisogono (2007)	✓	✓		✓							✓
Azorin-Molina and Lopez-Bustins (2008)			✓								

Test 1: rapid shift in WS and WD at surface or upper levels (denoted by letter a); Test 2: ΔT land–sea–air; Test 3: weak surface pressure gradient. Synoptic weather chart (denoted by letter b); Test 4: cloudiness; Test 5: decrease in TEMP; Test 6: increase in RH; Test 7: hours of sunshine; Test 8: PCPN or thunder report; Test 9: $\Delta w''$; Test 10: overall wind convergence; Test 11: air PRES amplitude

3. *Air humidity data*: An increase in vapour pressure or air relative humidity a short time after sea breeze frontal passage has been used as a follow-up criterion for selecting past sea breezes from meteorological measurements.

4. *Air pressure data*: A weak pressure gradient at surface level is a primary condition for the onset of local winds. Manual revision of synoptic weather charts and computation of diurnal air pressure amplitude (Prtenjak and Grisogono 2007) have been used to exclude days influenced by the passing of frontal or baric systems.

5. *Total cloudiness and hours of sunshine data*: The presence of nearly clear skies, which must usually be <4/8 (Prezerakos 1986), and therefore a large percentage of hours of sunshine enhances the development of sea breezes.

6. *Precipitation data*: This meteorological measurement serves as an additional parameter for detecting an unstable atmosphere accompanied by overcast skies and rain showers, which prevent sea breeze development. Miller and Keim (2003) used a test criterion based on unappreciable precipitation (one or two brief light showers were permissible) within the 6-h period prior to the onset of sea breezes.

3 Measurements and study area

The province of Alicante is located on the southeast fringe of the Iberian Peninsula (IP, south of the Valencia region), as well as in the Western Mediterranean basin. The Bay of Alicante was chosen because of the key role played by sea breezes and the lack of research in relation to this subject in this area. Most sea and lake breeze studies have obtained data during rather short surface observations (i.e. less than or around 6 years; Laird et al. 2001). Therefore, the 6-year study period used here represents a reasonable but laborious task for the application of a detailed manual revision on a daily basis.

Figure 1 shows the study area, which corresponds to the Bay of Alicante and the surrounding district called *Campo de Alicante*: a coastal plain where the Prebetic mountain ranges (1000–1600 m of height) are located between 10 and 15 km inland. Thermally-driven flows on heated slopes of low steepnees may couple with sea breezes increasing horizontal and vertical wind speeds and an earlier inland sea breeze frontal passage. In contrast, a heated slope of high steepness will block the inland propagation of sea breezes and decrease the horizontal and vertical wind speeds as reviewed Crosman and Horel (2010). The blocking of the

Fig. 1 Map of the province of
Alicante showing the Bay of
Alicante and locations of the
RS, the CJ and the SST mea-
surement site (Albufereta
beach). The *inset* photographs
correspond to the surface
weather observation reference
station at the Laboratory of
Climatology of the University of
Alicante (**a**), the automatic
recording station with the wind
cup and wind wane at the right-
hand end of a cross beam (**b**)
and the mechanical wind
recorder or anemograph (**c**). Sea
and land breeze central axes
with respect to the coastline are
given in the lower central part
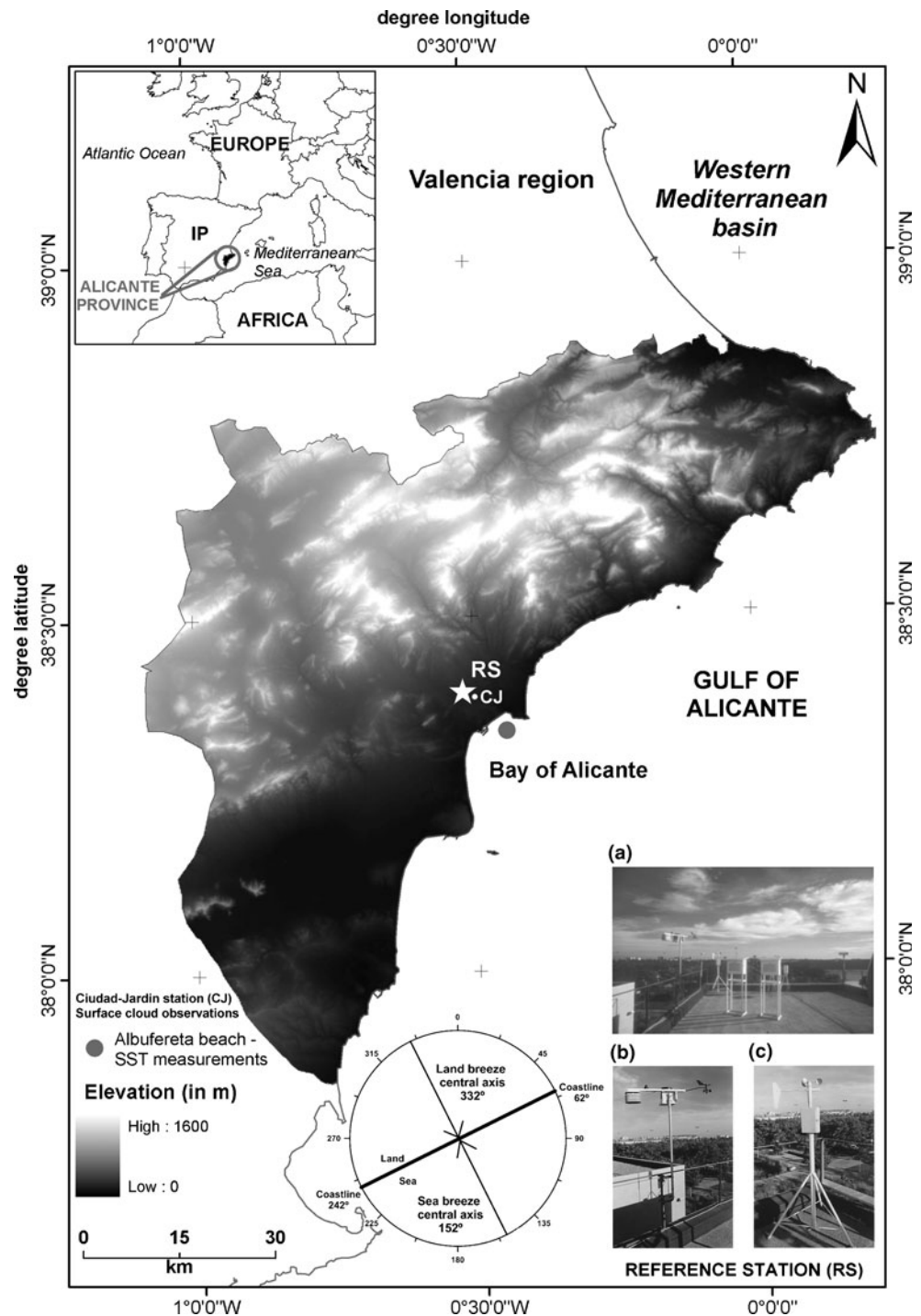
flow by the mountain ranges will have some impact on the
local winds in the study area.

The primary procedure in which to objectively or
subjectively select past sea breezes involved the routine
collection of surface observations. The automatic meteoro-
logical station situated at the Laboratory of Climatology of the
University of Alicante (38°23′ N, 0°31′ W, 102 m above sea
level and 5.1 km from the shore belonging to the University
Institute of Geography; http://www.labclima.ua.es) was cho-
sen as the reference synoptic station (hereafter RS) for sea
breeze studies. The 30-min observations of WS (in metres
per second) and WD (in degrees and stored in 1° steps);
temperature (TEMP, in degree Celsius); relative humidity
(RH, in per cent); pressure (PRES, in millibars or hecto-
pascals); and precipitation (PCPN, in millimetres) were used
here over a 6-year study period (2000–2005). The WS and
WD data, as well as all meteorological variables, were
collected at a height of 10 m. Additional data from a

mechanical wind recorder or anemograph, a thermo-hygrograph and a rain gauge were used to fill missing values in half-hourly data, which are <5%. Finally, the sunrise and sunset times were calculated for each day applying the *Ortocaso* software programmed by the Spanish Meteorological Agency (AEMET).

Monthly SST measurements were acquired from the Institute of Coastal Ecology of El Campello (http://www.ecologialitoral.com/). The SST data are measured 0.4 km offshore and at a bathymetric elevation of 4–5 m on the Albufereta beach (38°21′ N, 0°26′ W). This location is 6.3 km to the RS site. Daily SST data were computed by linearly interpolated values from monthly measurements. This is the most reliable SST data given that 1-h TEMP data from the nearest buoy have been available since July 2006 (Cabo de Palos buoy; 37°39′ N, 0°19′ W; http://www.puertos.es/es/oceanografia_y_meteorologia/redes_de_medida/index.html).

Total cloud cover (amount in eights) collected at the Alicante–Ciudad Jardin synoptic station (CJ; 38°22′ N, 00°29′ W; 82 m above sea level and 3.3 km from the shore; AEMET) in January, April, July and November 2004 enabled us to apply an independent automated selection technique in Section 5.

4 Sea breeze selection algorithms

4.1 Methodology design

The interaction of sea breezes with factors at synoptic scale, local spatial scale and at mesoscale hinders the design of an accurate methodology. Basically, the accuracy of the past sea breeze days selected depends on the (a) objectives of the study; (b) definition of a sea breeze episode by each researcher (i.e. sea breezes or sea and land breeze cycles); (c) available data and test criteria used; and (d) features of the study area.

Previous empirical knowledge of sea breezes were acquired in the Bay of Alicante by means of extensive fieldwork (Olcina-Cantos and Azorin-Molina 2004). The geometry of the coastline is considered to define the central sea and land breeze axes (Gustavsson et al. 1995; Furberg et al. 2002; Prtenjak and Grisogono 2007). The local orientation of the shoreline adjacent to the RS is assumed to be 62.0°–242.0° (Fig. 1) despite the concave land–water boundary of the Bay of Alicante. The sea and land breeze central axes are therefore 152.0° and 332.0°, respectively. However, observational campaigns detected that the local geometry and topography of the coastline cause certain changes in the direction of sea breezes (Miao et al. 2003). Consequently, sea breezes blow in the range from 45.0° to 180.0°, and the Coriolis force (Neumann 1984) can produce sea breezes from 180.0° to 225.0° in the late evening, i.e.

almost parallel to the coastline. Land breezes (not regarded in this study) usually blow from 247.5° to 22.5°. Brief transitions periods (Salvador and Millán 2003) occur between sea and land breeze passages. These are defined by a 30-min mean WS of <1.5 m s^{-1} or a WD which is usually from 23.0° to 44.0° or from 181.0° to 247.0°.

4.2 Manual selection algorithm

Figure 2a shows the flow diagram of the manual selection filters proposed for the identification of past sea breeze events for the 6-year study period (2000–2005). The manual procedure chooses tests 1, 5, 6 and 8 tabulated in Table 1 and discussed in Section 2. The examination of the daily time series (graphs and databases) of 30-min observations of WS, WD, TEMP, RH and PCPN was considerably laborious. The following six empirical criteria need to be accomplished in order to detect sea breeze passages (filters 1 to 3) and to confirm (filters 4 to 6) a sea breeze event:

Filter 1: The WS_x and WS_{max} curves present a steady increase from after sunrise until noon, and a gradual decrease occurs from afternoon until sunset. WS_x and WS_{max} are the 30-min mean and maximum WS, respectively.

Filter 2: WD_x ranges from 45.0° to 180.0°, i.e. onshore flows after sunrise. WD_x is the 30-min mean WD. The landward-moving wind shift is a distinctive feature that practically ensures stable synoptic conditions with weak large-scale flows and positive ΔT values.

Filter 3: D_t of sea breezes must be ≥2 h. D_t is the duration of onshore flows detected during the daytime.

The change in WS is applied as filter 1 as nocturnal offshore winds (land breezes) do not usually blow in summer months over the Bay of Alicante because probably the cooling is not so strong (Azorin-Molina 2007). In these cases, sea breeze passages are not associated with a reversal in WD, but rather with a typical increase in WS as a function of positive ΔT values. Most experts state that nocturnal offshore large-scale flows are required in order to identify true sea breeze passages, a requirement that is not satisfied with regard to finding sea breezes in the Bay of Alicante. Moreover, large-scale onshore flows can be removed manually because ambient winds are moderate to strong and blow without a gradual veering.

Filter 4: ≤$TEMP_x$ after initiation of sea breezes, where $TEMP_x$ is the 30-min mean TEMP, i.e. an abrupt decrease in the diurnal air temperature curve.

Filter 5: ≥RH_x after initiation of sea breezes, where RH_x is the 30-min mean RH, i.e. an abrupt increase in the diurnal relative humidity curve.

a

MANUAL SELECTION METHOD
Input data: WS, WD, TEMP, RH and PCPN

WIND SPEED AND DIRECTION

Change in WS
WS_x and WS_{max} curves — FILTER 1

Onshore WD
WD_x in the range of 45.0º to 180.0º — FILTER 2

Duration onshore flows
$D_t \geq 2$ hours — FILTER 3

TEMPERATURE, HUMIDITY AND PRECIPITATION

PASSED   REJECTED

Shift in TEMP
$\leq TEMP_x$ after onset — FILTER 4

Shift in RH
$\geq RH_x$ after onset — FILTER 5

PCPN report
No $PCPN_x$ before onset — FILTER 6

SEA BREEZES:
1414 events — DATASET — NO SEA BREEZES:
778 events

b

AUTOMATED SELECTION METHOD
Input data: LSR, LSS, WS, WD, PRES, TEMP and SST

SUNRISE, SUNSET, WIND SPEED and DIRECTION

ONSET — Sunrise
LSR +01 h to LSR +07:30 h — FILTER 1

Change in WS
$WS_x \geq 1.5$ m s^{-1} — FILTER 2

Shift in WD
WD_x in the range of 45.0º to 180.0º — FILTER 3

Previous WS and WD
$WS_x <1.5$ m s^{-1} or
WD_x in the range of 181.0º to 44.0º — FILTER 4

CESSATION — Sunset
LSS -01 h to LSS +05 h — FILTER 5

Change in WS or WD
$WS_{max} <1.5$ m s^{-1} or
WD_x in the range of 226.0º to 44.0º — FILTER 6

SYNOPTIC FLOWS — Maximum WS
$WS_{max} \leq 13.9$ m s^{-1} — FILTER 7

PASSED — SEMI-DIURNAL PRESSURE WAVE — REJECTED

Increase in PRES
$(C_{pres}) - (Min_{pres}) \geq 1$ mb — FILTER 8

Aerial tide
$(Atide_{daily}) - (Atide_{general}) \geq -0.5$ — FILTER 9

SEA SURFACE TEMPERATURE

ΔT
$(AirT_{10m}) - (SST) \geq 0$ ºC — FILTER 10

SEA BREEZES:
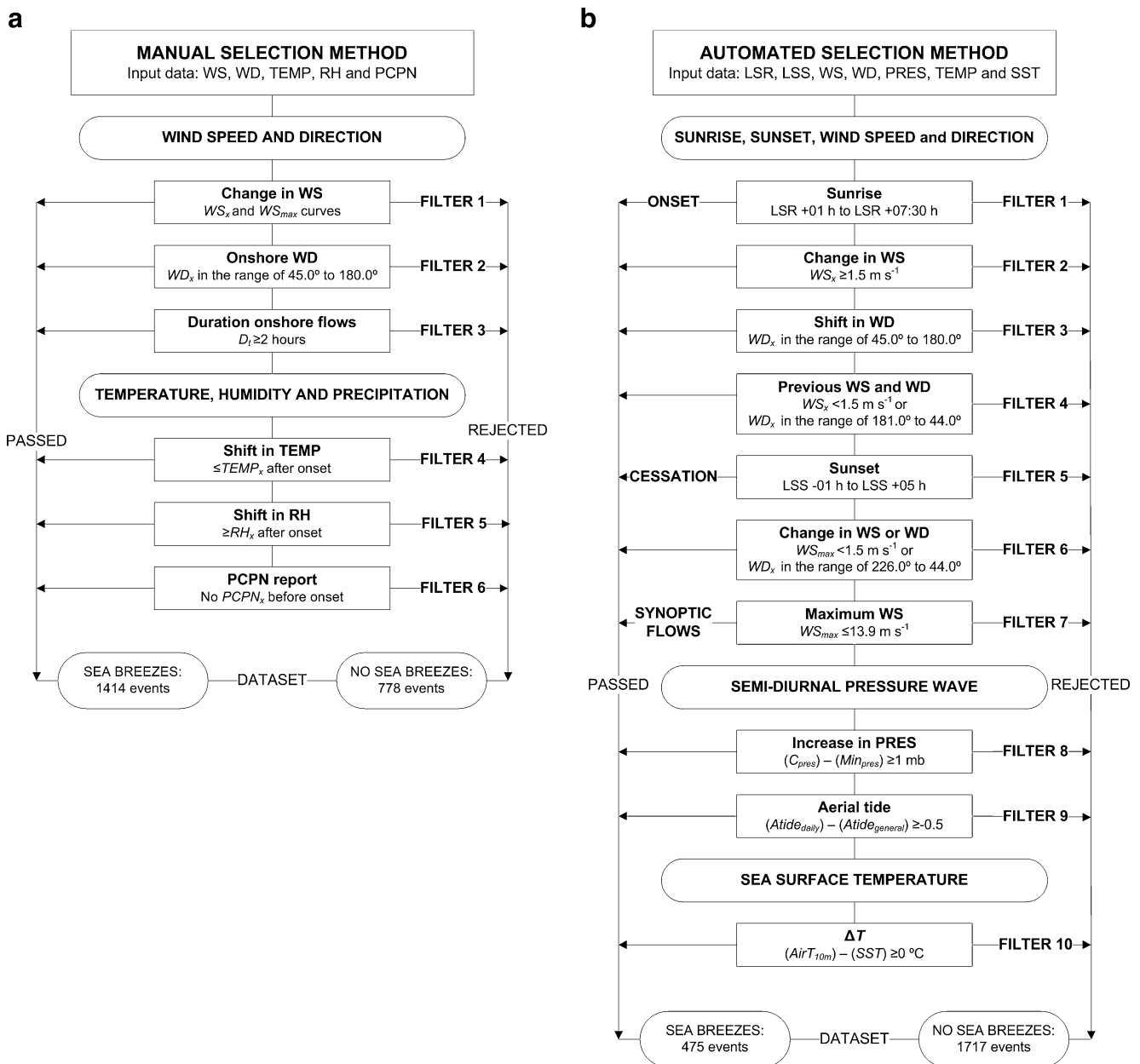475 events — DATASET — NO SEA BREEZES:
1717 events

Fig. 2 **a** Flow diagram showing filters employed in the manual selection methodology for finding past sea breeze episodes for the 6-year study period (2000–2005). Acronyms are defined in the text. **b** As in **a**, except for the automated selection methodology

Filter 6: No $PCPN_x$ is measured prior to the onset of sea breezes, where $PCPN_x$ is the 30-min amount of PCPN.

A stabilization and a slight downward inflection of TEMP curves and a stabilization and an upward inflection of RH curves are other features for finding sea breezes. These changes are not exclusive to sea breezes since they can also be caused by large cumulus clouds shading the sun on a warm day (Ryznar and Touma 1981). However, cloud-induced changes do not meet the requirement filters 1 to 3. A few hours after sea breeze initiation (usually in the

afternoon), some reports of PCPN might be associated with the development of sea breeze fronts and thunderstorms, and those days were therefore not removed.

If the requirements of manual filters 1 to 6 were not met, the day was excluded entirely from the dataset. The manual method discretizes meteorological data into two categories: (a) sea breezes (SB) and (b) non-sea breezes (NSB).

4.3 Automated selection algorithm

Figure 2b displays the flow diagram of the objective computer-based filters proposed for identifying past sea breeze episodes

for the 6-year study period (2000–2005). The automated procedure chooses tests 1, 2 and 11 tabulated in Table 1 and discussed in Section 2. Apart from surface WS, WD and TEMP measurements, we also used 30-min observations of PRES, daily SST, as well as local sunrise (LSR) and sunset (LSS) data (in UTC) from the RS. The LSR and LSS data were employed in order to ensure the selection of sea breezes within a complete diurnal cycle. The automated selection diagram is made out of ten filters in order to accurately detect sea breezes and create a database for sea breeze studies. The filters are grouped into two main categories: (a) distinctive features in WS and WD, and (b) physical processes of sea breezes. The first filter group employs the characteristic rapid shift in WS and WD, which is the most important feature in the use of surface meteorological measurements, in order to detect the onset (filters 1 to 4) and cessation (filters 5 and 6) of sea breezes and to reject moderate to strong onshore large-scale flows (filter 7).

Filters 1 to 4: LSR+0100 hours to LSR+0730 hours (UTC). The onset is defined by the sea breeze passage between 0100 hours (i.e. summer months) and 0730 hours (i.e. winter months) after LSR (filter 1). The onset occurs when the WS_x is ≥ 1.5 m s^{-1} (filter 2; Salvador and Millán 2003), which ensures that sea breezes are completely established, and WD_x ranges from 45.0° to 180.0° (filter 3) simultaneously. Previous WS_x and WD_x must be <1.5 m s^{-1} or from 181.0° to 44.0° (filter 4), respectively. The WS_x is established as an initial condition in filter 4 as land breezes do not usually blow in summer months, as has been stated above. The onset time (O_{time}), onset lag (O_{lag}), onset speed (O_{ws}) and onset direction (O_{wd}) were tabulated in the database presented in Section 4.4.

Filters 5 and 6: LSS −0100 hours to LSS+0500 hours (UTC). The cessation is defined by the sea breeze front retreat between 0100 hours (i.e. winter months) before and 0500 hours (i.e. summer months) after LSS (filter 5). The cessation occurs when WS_{max} is <1.5 m s^{-1} or the WD_x is from 226.0° to 44.0° (filter 6). WS_{max} was employed instead of WS_x as it best represents sea breeze cessation. Albeit infrequently, the WS_x of sea breezes can be lower than 1.5 m s^{-1}, and sea breeze retreats would therefore be detected too early. WS_{max} constitutes a reasonably

reliable test for establishing the cessation of sea breezes. As in filter 4, WD_x constitutes a secondary criterion as reversal wind change from onshore to offshore direction does not always occur at the end of the day. Cessation time (C_{time}) and cessation lag (C_{lag}) were also computed in the database.

Filter 7: $WS_{max} \leq 13.9$ m s^{-1}. Sea breeze gust intensities rarely rise above 14.0 m s^{-1} in the Bay of Alicante (Azorin-Molina et al. 2011). We calculated the WS_{max} for each sea breeze episode for the database.

The second filter group uses two novel filters based on semi-diurnal pressure waves in combination with a positive ΔT. The pressure field is of primary importance as it supplies the driving force for low-level sea breeze development (Simpson 1994). This thermal wave is caused by temperature variation in the boundary layer of the atmosphere, which differs from land to sea. Figure 3 represents the mean atmospheric tide in the RS for the 6-year study period, showing a regular daily variation: a maximum at 1000 hours (1018.0 mb) and a minimum at 1600 hours (1016.2 mb), with a second maximum at 2200 hours (1017.8 mb) and a second minimum at 0400 hours (1016.9 mb), of lower amplitude. Van Delden (1993) and Tijm and Van Delden (1999) conducted in-depth research of the role played by sound waves in the onset of sea breezes using a linear numerical model. Furthermore, some investigations (Millán 2002) emphasise the important role played by the diurnal thermal low developing over the centre of the IP, resulting from diabatic heating (Simpson 1994; Tijm 1999), and favours sea breeze circulations in the summer months. Prtenjak and Grisogono (2007) have been
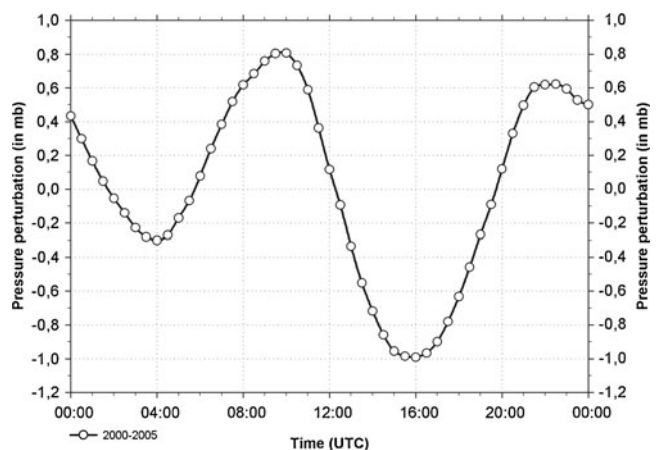

Fig. 3 Daily cycle of the surface pressure perturbation from the 30-min mean surface pressure at the RS for the 6-year study period (2000–2005)

the only researchers (Table 1) to employ surface pressure data (diurnal pressure amplitude <5 hPa) as a selection test. The identification of the thermal wave was used here as an alternative criterion for selecting calm weather conditions with no appreciable synoptic changes or large-scale flows, which generally disturb sea breezes. Filters 8 and 9 were used to ensure the detection of the daily aerial tide at the RS.

Filter 8: $(C_{pres}) - (Min_{pres}) \geq 1$ mb, where C_{pres} is the PRES at the time of cessation of sea breezes and Min_{pres} is the minimum PRES measured from O_{time} to C_{time}. The filter test detects the increase in PRES between the minimum around 1600 hours and the secondary maximum at 2200 hours. The threshold for this criterion was set to ≥ 1 mb.

Filter 9: $(Atide_{daily}) - (Atide_{general}) \geq -0.5$, where $Atide_{daily}$ and $Atide_{general}$ are the semi-diurnal pressure waves for each sea breeze day selected by the first filter group and for the 6-year study period (Fig. 3), respectively. The threshold value (greater than or equal to −0.5) was found the same as filter 8. The most negative values (less than −0.5) represent days with noteworthy synoptic changes and were therefore rejected. The $Atide_{daily}$ and $Atide_{general}$ values were computed as follows:

$$Atide = (P10 + P22) - (P04 - P16) \tag{3}$$

where P04, P10, P16 and P22 are the PRES at 0400, 1000, 1600 and 2200 hours UTC, respectively. The $Atide_{general}$ from values plotted in Fig. 3 resulted in 2.72.

Finally, the ΔT provides the local forcing for the development of sea breezes (Simpson 1994). The comparison of the mean monthly maximum and minimum air TEMP with the corresponding SST curve for the 6-year period have been plotted in Fig. 4. The mean monthly SST curve is below the mean monthly maximum air TEMP, and sea breezes are therefore likely to be triggered throughout the whole year. April and June have the biggest ΔT (4.4°C), whereas the smallest ΔT are found in September (0.9°C) and December (1.3°C). The ΔT was employed as a last filter as daily SST data interpolated from monthly data were used. This criterion, which does not require large temperature

differences (Laird et al. 2001; Segal and Pielke 1985; Arritt 1987; Simpson 1994), was formulated as follows:

Filter 10: $(AirT_{10m}) - (SST) \geq 0$, where $AirT_{10m}$ is the screen daily maximum air temperature at the RS.

The automated method distinguishes between (a) SB days when the ten filters are fulfilled and (b) NSB events, when at least one requirement is not satisfied.

4.4 Sea breeze databases and applications

Table 2 displays a summary of the monthly number (N) and probability ($P_1 = [1]/N$) of sea breeze episodes identified by both automated and manual selection algorithms for the 6-year study period. A subset of 475 and 1414 sea breeze events was identified in the RS by means of the automated and manual techniques, respectively. The objective method found only one third of sea breezes selected by the subjective diagram, which means that the applications of both datasets for sea breeze studies must be different. The objective and subjective natures of the automated and manual methods create a margin of error that tends to strongly underestimate and slightly overestimate the results, respectively.

The manual selection technique does not demand information on the O_{time} and C_{time} of sea breezes. Figure 5 illustrates five typical sea breeze situations as sea breeze events without land breezes at night (Fig. 5a). The subjective method correctly counts late afternoon initiations when moderate to strong offshore synoptic winds are weakened during the morning hours (Lyons 1972; Fig. 5b); early evening cessations when outflows from well-developed thunderstorms interrupt sea breezes (Hewson and Moroz 1966; Fig. 5c); increase of *Strocumulus* clouds over the area,
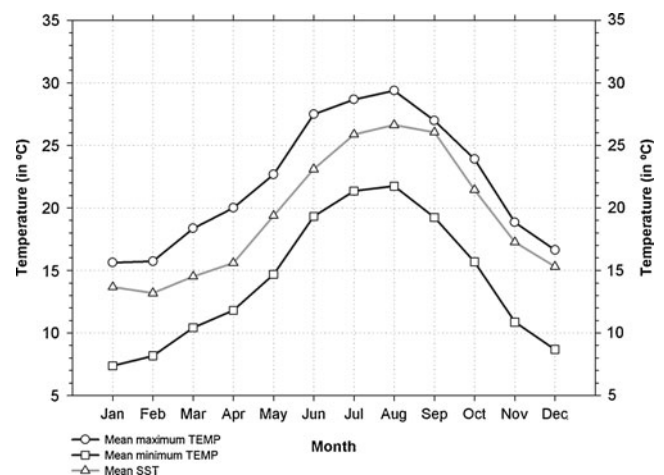

Fig. 4 Mean monthly maximum and minimum air TEMP at the RS and mean monthly SST at the Albufereta beach for the 6-year study period (2000–2005)

Table 2 Monthly number and probability (P_1) of sea breeze days detected by the automated and manual selection algorithms for the 6 years (2000–2005)

	January SB days A	M	P_1 A	M	February SB days A	M	P_1 A	M	March SB days A	M	P_1 A	M	April SB days A	M	P_1 A	M	May SB days A	M	P_1 A	M	June SB days A	M	P_1 A	M
2000	3	26	0.10	0.84	0	25	0.00	0.86	3	23	0.10	0.74	2	15	0.07	0.50	14	26	0.45	0.84	15	27	0.50	0.90
2001	0	6	0.00	0.19	3	15	0.11	0.54	1	18	0.03	0.58	6	23	0.20	0.77	9	27	0.29	0.87	13	28	0.43	0.93
2002	9	21	0.29	0.68	8	24	0.29	0.86	4	18	0.13	0.58	7	21	0.23	0.70	7	22	0.23	0.71	14	24	0.47	0.80
2003	2	13	0.06	0.42	3	10	0.11	0.36	8	19	0.26	0.61	7	17	0.23	0.57	11	24	0.35	0.77	12	25	0.40	0.83
2004	8	12	0.26	0.39	5	16	0.17	0.55	2	12	0.06	0.39	6	12	0.20	0.40	8	22	0.26	0.71	18	25	0.60	0.83
2005	9	24	0.29	0.77	2	10	0.07	0.36	3	14	0.10	0.45	9	17	0.30	0.57	8	25	0.26	0.81	13	28	0.43	0.93
Mean	5.2	17.0	0.17	0.55	3.5	16.7	0.12	0.59	3.5	17.3	0.11	0.56	6.2	17.5	0.21	0.58	9.5	24.3	0.31	0.78	14.2	26.2	0.47	0.87

|	July SB days A	M	P_1 A	M	August SB days A	M	P_1 A	M	September SB days A	M	P_1 A	M	October SB days A	M	P_1 A	M	November SB days A	M	P_1 A	M	December SB days A	M	P_1 A	M
2000	20	30	0.65	0.97	3	30	0.10	0.97	3	25	0.10	0.83	2	19	0.06	0.61	0	5	0.00	0.17	1	16	0.03	0.52
2001	12	29	0.39	0.94	15	30	0.48	0.97	0	23	0.00	0.77	8	24	0.26	0.77	1	13	0.03	0.43	3	17	0.10	0.55
2002	12	27	0.39	0.87	14	29	0.45	0.94	5	26	0.17	0.87	5	21	0.16	0.68	2	11	0.07	0.37	2	15	0.06	0.48
2003	16	25	0.52	0.81	16	28	0.52	0.90	3	20	0.10	0.67	3	8	0.10	0.26	1	11	0.03	0.37	2	13	0.06	0.42
2004	14	27	0.45	0.87	14	25	0.45	0.81	7	25	0.23	0.83	6	13	0.19	0.42	6	16	0.20	0.53	0	4	0.00	0.13
2005	9	25	0.29	0.81	5	26	0.16	0.84	8	19	0.27	0.63	4	15	0.13	0.48	1	7	0.03	0.23	0	3	0.00	0.10
Mean	13.8	27.2	0.45	0.88	11.2	28.0	0.36	0.90	4.3	23.0	0.14	0.77	4.7	16.7	0.15	0.54	1.8	10.5	0.06	0.35	1.3	11.3	0.04	0.37

A automated, M manual
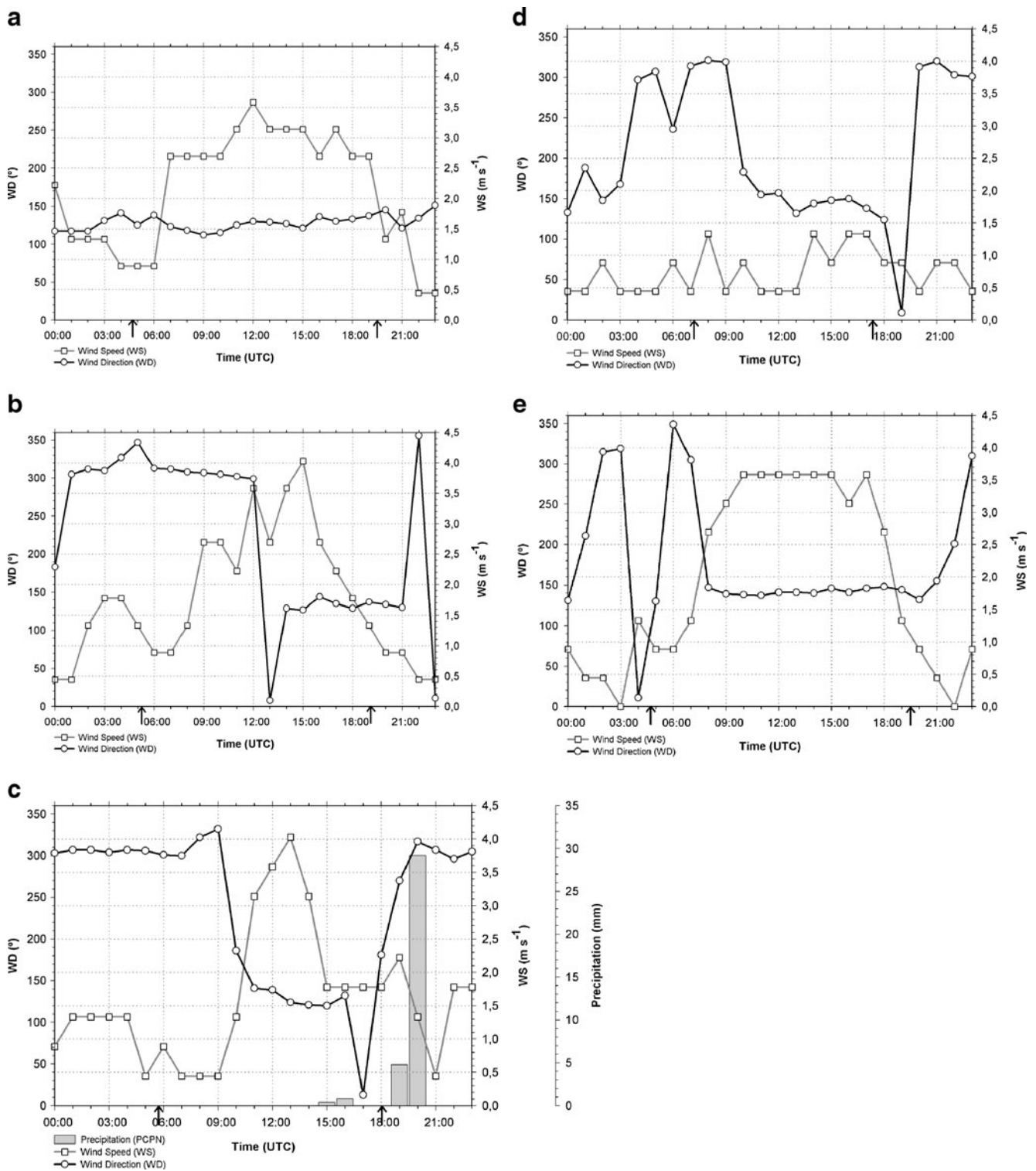
Fig. 5 WS, WD and PCPN for typical sea breeze situations illustrating discrepancies between the manual and automated selection methods: **a** sea breeze event without land breezes at night (3rd July 2004, selected by both methods); **b** late afternoon initiation (11th August 2005, selected by the manual method); **c** early evening cessation (21st September 2002, selected by the manual method); **d** increased low cloudiness (3rd February 2004, selected by the manual method); **e** strengthening of a sea breeze episode (3rd July 2003, selected by the manual method). *Small arrows* show hours of sunrise and sunset (in UTC)

which brings down the ΔT and therefore weakens sea breezes (Fig. 5d); and a strengthening of sea breezes by the coupling of onshore large-scale winds (Fig. 5e), among many other non-pure sea breeze situations. We therefore

took sea breezes in complete and incomplete diurnal cycles into account. Consequently, the sea breeze dataset constructed by means of the manual selection technique potentially enabled the study of the daily occurrence and persistence of sea breezes in the Bay of Alicante (Azorin-Molina and Martin-Vide 2007). The high occurrence of sea breezes and persistence of sea breeze spells is the main factor controlling air pollution dynamics and problems of air quality in Mediterranean cities. This database is being used by the Programme of Atmospheric Pollution at the University Institute CEAM-UMH (http://www.ceam.es/). Nevertheless, this subset is not useful for the study of the main sea breeze parameters and physical factors controlling this local wind because non-pure sea breeze events disturb mean statistics.

The automated selection method removes the synoptic influence and the other aforementioned disturbing factors. The objective algorithm has the added capacity to distinguish most sea breeze events in a complete diurnal cycle. The selection technique was designed to use a set of seven tests in the first filter group in order to increase accuracy and to construct a sea breeze database. Table 3 shows the magnitudes of the main sea breeze characteristics and other parameters from 2nd to 8th June 2005. The sea breeze dataset constructed by means of the automated procedure has enabled the mean characteristics (Azorin-Molina et al. 2009, 2011) and physical factors (Azorin-Molina and Chen 2009) of sea breezes to be studied. The data compiled in the Table 3 could serve to validate whether meteorological models accurately represent the sea breeze characteristics observed.

5 Validity of the sea breeze selection algorithms

The accuracy of the manual and automated selection methods was evaluated by means of comparison with an independent subjective and objective technique, respectively. The SB and NSB events selected by the proposed (subscript "p") techniques and the independent (subscript "i") methods are set into a matrix similar to that of Laird et al. (2001). We computed four calculations from the matrix taking the number of the equal (SB_pSB_i and NSB_pNSB_i) and different (SB_pNSB_i and NSB_pSB_i) detections. The probabilities calculated range from 0 to 1, where 1 indicates the equal or different detections of sea and non-sea breeze events.

(a) *Probability of equal detections of sea breezes* (PSB_pSB_i): The number of equal detections of sea breezes divided by the total number of sea breezes selected by both methods.

$$PSB_pSB_i = \frac{SB_pSB_i}{SB_pSB_i + SB_pNSB_i + NSB_pSB_i} \quad (4)$$

(b) *Probability of equal detections of non-sea breezes* ($PNSB_pNSB_i$): The number of equal detections of non-sea breezes divided by the total number of non-sea breezes selected by both techniques.

$$PNSB_pNSB_i = \frac{NSB_pNSB_i}{NSB_pNSB_i + SB_pNSB_i + NSB_pSB_i} \quad (5)$$

(c) *Probability of different detections of sea breezes* (PSB_pNSB_i): The number of different detections of sea breezes, i.e. sea breezes detected by the proposed method and non-sea breezes selected by the independent technique, divided by the total number of different detections of sea breezes.

$$PSB_pNSB_i = \frac{SB_pNSB_i}{SB_pNSB_i + NSB_pSB_i} \quad (6)$$

(d) *Probability of different detections of non-sea breezes* ($PNSB_pSB_i$): The number of different detections of sea breezes, i.e. non-sea breezes detected by the proposed method and sea breezes selected by the independent technique, divided by the total number of different detections of sea breezes.

$$PNSB_pSB_i = \frac{NSB_pSB_i}{SB_pNSB_i + NSB_pSB_i} \quad (7)$$

The independent manual selection technique was performed by an experienced sea breeze researcher from the Regional Climate Group (http://rcg.gvc.gu.se/) of the University of Göteborg (Sweden). The 30-min observations of surface WS, WD, TEMP, RH and PCPN recorded in the RS were used by this researcher who defined her own filters for finding sea breeze passages. The months of January, April, July and November 2004 were chosen for the evaluation because they cover the four seasons. The characteristics of sea breezes vary throughout the year and should therefore influence manual sea breeze detection. For comparison between the proposed manual method and the independent Regional Climate Group technique (hereinafter RCG method), days were also classified into the two categories (SB and NSB) described above. A SB event groups the "sea breeze" and "possible sea breeze" categories defined by Borne et al. (1998) without using ΔT data.

Table 4 shows the daily selection and the simple probabilities of P_1 and P_0 (the probability of a day without any sea breeze; $P_0=[0]/N$ or $1 - P_1$) computed by the proposed manual selection (M) and the independent RCG method for the 4-month period. A very close connection in P_1 takes place in January (M 38.7% and RCG 41.9%) because reversal in WD from land to sea breezes is easily identified. The connection in P_1 slightly decreases in April

Table 3 Sea breeze database (475 days, 2000–2005) constructed using the automated selection algorithm

Day	Sunrise (UTC)	O_{time} (UTC) (1)	O_{lag}	O_{ws} (m s^{-1})	O_{wd} (deg)	Sunset (UTC)	C_{time} (UTC)	C_{lag}	D_t	WS_{max} (m s^{-1})	WS_{time} (UTC)	WD at WS_{max} (deg)	SB_{ext} (km)
02/06/2005	0439	0830	0351	1.8	45.0	1921	2000	0:39	1130	10.3	1230	111.0	146.5
03/06/2005	0438	0800	0322	1.8	112.5	1922	1900	−0:22	1100	6.7	1100	138.0	95.0
04/06/2005	0439	0830	0351	1.8	180.0	1922	1830	−0:52	1000	6.7	1100	136.0	95.0
05/06/2005	0438	0800	0322	1.8	112.5	1923	2000	0:37	1200	6.7	1030	140.0	105.4
06/06/2005	0438	0900	0422	2.2	112.5	1924	2200	2:36	1300	7.1	1400	116.0	103.6
07/06/2005	0438	0800	0322	1.8	67.5	1924	1900	−0:24	1100	7.1	1100	113.0	111.3
08/06/2005	0438	0900	0422	2.2	135.0	1925	2030	1:05	1130	6.3	1030	140.0	107.2

Day	Max TEMP (C) (2)	Time MaxTEMP (UTC) (3)	Min TEMP (C)	Time MinTEMP (UTC)	Onset TEMP (C) (4)	(2)−(4)	(3)−(1)	SST (C) (5)	ΔT (C) (2)−(5)	Max RH (%)	Time MaxRH (UTC)	Min RH (%)	Time MinRH (UTC)
02/06/2005	27.2	1200	16.6	0400	24.3	2.9	0330	23.0	4.2	76	0100	35	1030
03/06/2005	25.6	1000	17.4	0500	24.4	1.2	0200	23.1	2.5	79	1830	41	0730
04/06/2005	24.5	1230	18.7	0300	22.7	1.8	0400	23.2	1.3	93	2330	70	1100
05/06/2005	24.2	1530	18.6	0500	22.7	1.5	0730	23.3	0.9	94	0130	64	1530
06/06/2005	24.8	1500	18.2	0400	23.8	1.0	0600	23.4	1.4	90	0100	52	1500
07/06/2005	25.0	1030	18.4	0330	23.4	1.6	0230	23.6	1.4	71	0230	47	1030
08/06/2005	26.5	1430	16.3	0500	24.5	2.0	0530	23.7	2.8	68	0130	38	1400

Main characteristics of sea breezes are shown by way of an example from 2nd to 8th June 2005

The onset time (O_{time}), the onset lag (O_{lag}), the WS at the time of onset (O_{ws}), the WD at the time of onset (O_{wd}), the cessation time (C_{time}), the cessation lag (C_{lag}), the duration time of sea breezes (D_t), the maximum WS of sea breezes (WS_{max}), the time of maximum WS of sea breezes (WS_{time}), the WD at the time of WS_{max} and the inland penetration of sea breezes (SB_{ext}) have been tabulated from the automated method. The SB_{ext} was calculated following the formula applied by Salvador and Millán (2003) and Azorin-Molina et al. (2011)

Table 4 Comparison between sea breeze (1) and non-sea breeze (0) episodes found by the manual algorithm (M) and the RCG selection technique for the 4-month period in 2004

Day	January		April		July		November	
	M	RCG	M	RCG	M	RCG	M	RCG
1	0	0	0	1	1	1	0	0
2	0	0	0	0	1	1	0	0
3	1	1	1	1	1	0	0	1
4	1	1	1	1	1	0	0	1
5	1	1	1	1	1	1	0	1
6	1	1	1	1	0	0	0	0
7	1	1	1	0	0	1	0	1
8	0	0	0	0	0	0	1	1
9	0	0	0	1	1	1	0	0
10	0	0	0	1	1	1	0	0
11	1	1	0	0	1	1	0	1
12	0	0	0	1	0	0	0	0
13	0	0	1	1	1	1	0	0
14	0	0	0	1	1	1	1	1
15	1	0	0	0	1	1	1	1
16	0	0	0	0	1	0	1	1
17	0	0	0	1	1	1	1	1
18	0	0	0	0	1	1	1	0
19	1	1	0	0	1	1	1	1
20	0	0	0	0	1	1	1	1
21	1	1	1	1	1	1	1	1
22	1	1	0	0	1	1	1	1
23	0	0	1	1	1	1	1	1
24	0	0	1	1	1	1	1	1
25	0	1	1	1	1	0	1	1
26	0	0	1	1	1	0	1	1
27	0	0	1	0	1	1	1	1
28	0	0	0	1	1	0	1	1
29	0	1	0	1	1	1	0	1
30	1	1	0	0	1	1	0	0
31	1	1	–	–	1	1	–	–
SB days	12	13	12	18	27	22	16	21
P_1 (%)	38.7	41.9	40.0	60.0	87.1	71.0	53.3	70.0
P_0 (%)	61.3	58.1	60.0	40.0	12.9	29.0	46.7	30.0
PSB_pSB_i	0.79		0.50		0.75		0.68	
$PNSB_pNSB_i$	0.85		0.50		0.30		0.53	
PSB_pNSB_i	0.33		0.20		0.86		0.14	
$PNSB_pSB_i$	0.67		0.80		0.14		0.86	

The last seven rows display the number of sea breeze days; the simple probabilities P_1 and P_0; and the probabilities PSB_pSB_i, $PNSB_pNSB_i$, PSB_pNSB_i and $PNSB_pSB_i$

(M 40.0% and RCG 60.0%), July (M 87.1% and RCG 71.0%) and November (M 53.3% and RCG 70.0%) as reversal in WD associated with sea breezes is less discernible. For instance, the PSB_pSB_i and the $PNSB_pNSB_i$ stands at 0.79 and 0.85 in January, respectively. Sea breezes and large-scale flows are easily distinguished in winter months. A higher rate of success was found in PSB_pSB_i in July with 0.75, whereas the $PNSB_pNSB_i$ is not high with 0.30 because the RCG method rejects sea breeze days without land breezes the night before. The comparison is

quite acceptable for April and November months, with a PSB_pSB_i of 0.50 and 0.68 and a $PNSB_pNSB_i$ of 0.50 and 0.53, respectively. The different detections between both manual methods, i.e. number of days set within SB_pNSB_i and NSB_pSB_i, represents <1/3 of days for each month: January (three cases), April (ten cases), July (seven cases) and November (seven cases). We generally found that the RCG method tends to overestimate the number of sea

Table 5 Comparison between sea breeze (1) and non-sea breeze (0) episodes found by the automated algorithm (A) and the PG selection technique for the 4-month period in 2004

Day	January		April		July		November	
	A	PG	A	PG		A	PG	A
1	0	0	0	1	1	1	0	0
2	0	0	0	0	0	0	0	0
3	1	0	1	1	1	0	0	0
4	1	0	1	0	1	0	0	0
5	1	0	0	0	1	1	0	0
6	1	0	0	1	0	0	0	0
7	0	0	1	1	0	1	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	1	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	1	1	0	0	0	0	0
14	0	0	0	0	0	0	1	0
15	0	0	0	0	0	0	0	0
16	0	0	0	0	1	0	0	0
17	0	0	0	0	1	0	0	0
18	0	0	0	0	1	0	0	0
19	0	0	0	0	1	0	0	1
20	0	0	0	0	1	0	1	1
21	1	0	0	1	0	0	0	0
22	1	0	0	0	1	0	0	0
23	0	0	1	1	0	1	1	1
24	0	0	1	1	0	1	1	1
25	0	0	0	1	0	1	1	0
26	0	0	0	1	1	0	1	0
27	0	0	0	1	1	1	0	0
28	0	1	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0
30	1	0	0	0	1	0	0	0
31	0	0	0	0	1	1	0	0
SB days	8	2	6	10	14	8	6	4
P_1 (%)	25.8	6.5	20.0	33.3	45.2	25.8	20.0	13.3
P_0 (%)	74.2	93.5	80.0	66.7	54.8	74.2	80.0	86.7
PSB_pSB_i	0.00		0.33		0.22		0.43	
$PNSB_pNSB_i$	0.68		0.70		0.48		0.86	
PSB_pNSB_i	0.80		0.25		0.71		0.75	
$PNSB_pSB_i$	0.20		0.75		0.29		0.25	

The last seven rows display the number of sea breeze days; the simple probabilities P_1 and P_0; and the probabilities PSB_pSB_i, $PNSB_pNSB_i$, PSB_pNSB_i and $PNSB_pSB_i$

breeze days more than our manual technique in January (PNSB$_p$SB$_i$ 0.67), April (0.80) and November (0.86), except in July, when our manual selection method over-estimates them (PSB$_p$NSB$_i$ 0.86), because it takes sea breeze episodes without nocturnal offshore winds into account. To conclude, the comparison showed that our manual selection is capable of extracting a good dataset.

Moreover, the accuracy of the automated selection method was evaluated by comparison with the sea breeze methodology put forward by Prtenjak and Grisogono (2007) (hereinafter PG technique) for studying sea/land breeze climatological characteristics along the northern Croatian Adriatic coast. We first considered the automated method proposed by Borne et al. (1998), but finally, the PG technique was chosen for the comparison because it is based on the same surface measurements as our automated selection method, with the exception of the cloudiness filter. A detailed description of the five test criteria of the PG method can be found in Prtenjak and Grisogono (2007).

Table 5 shows the daily results and P_1 and P_0 computed by the proposed automated method (A) and the independent PG technique for the 4-month period. It was found that the occurrence of sea breezes is underestimated in comparison with the detections of the manual methodologies. It should be noted that the empirical probability P_1 drastically drops from manual to automated selection methods: January (A 25.8% and PG 6.5%), April (A 20.0% and PG 33.3%), July (A 45.2% and PG 25.8%) and November (A 20.0% and PG 13.3%). The high P_0 values for both algorithms, ranging from 50% to 100%, confirm that automated selection techniques greatly underestimate the occurrence of sea breezes. Evaluation of the accuracy using the probabilities summarised above (Eqs. 4–7) reveals that sea breeze datasets depend on the nature of test criteria and thresholds identified. Compared with the PG technique, our A method yielded 0.0 hindcast accuracy (PSB$_p$SB$_i$) in January, 0.33 in April, 0.22 in July and 0.43 in November. In contrast, the PNSB$_p$NSB$_i$ is rather high, with 0.68 in January, 0.70 in April, 0.48 in July and 0.86 in November. This is also due to the fact that automated algorithms reject many true sea breeze episodes. The different detections between both automated selection techniques, i.e. number of days set within SB$_p$NSB$_i$ and NSB$_p$SB$_i$, is somewhat greater than manual algorithms: January (10 cases), April (8 cases), July (14 cases) and November (4 cases). Our automated method is less demanding and the SB$_p$NSB$_i$ is greater in January (0.80), July (0.71) and November (0.75). However, the PG method selects more sea breeze episodes in April and the NSB$_p$SB$_i$ is therefore 0.75, which might be related to the biggest ΔT throughout the year (Fig. 4). A detailed examination of the filters employed by the PG method revealed that filter V, which uses a ΔT threshold of >3°C,

rejects 80% (January), 9.1% (April), 68.0% (July) and 66.7% (November) of sea breeze episodes detected by filters 1 to 4. To conclude, automated algorithms create a set of true sea breeze events that clearly depend upon the test criteria used and underestimate the occurrence of this local wind.

6 Summary and concluding remarks

We simultaneously developed and evaluated an automated and manual selection method in order to identify past sea breeze events and to increase our knowledge of this local wind in the Bay of Alicante (Spain). A reasonably accurate subset of 475 and 1414 sea breeze days created for the 6-year study period (2000–2005), as along with a large sea breeze database (key variables measured during sea breeze occurrences), are presented for any coastal researcher interested in numerical–theoretical (model validation of different sea breeze episodes), observational–experimental and climatological sea breeze studies. These available sea breeze databases are the major contribution of the paper. Comprehensive datasets are crucial, for instance, for model verification (Mizuma 1995).

Evaluation of both techniques demonstrates that the sea breeze datasets constructed are clearly dependent on the nature of the test criteria employed by each researcher, which is extremely dependent on the measurements available. The main finding is that the manual selection technique enables the occurrence and persistence of sea breezes to be studied (Azorin-Molina and Martin-Vide 2007) because the subjective revision considers sea breeze episodes in complete and incomplete diurnal cycles. In contrast, the automated selection method only distinguishes true sea breeze events and is therefore capable of compiling the climatology of the main characteristics and physical factors controlling sea breezes (Azorin-Molina and Chen 2009; Azorin-Molina et al. 2009, 2011).

To conclude, there is a need for an accurate automated selection method that makes use of a minimum number of variables and can be easily applied to any coastal region in the world. An automated selection filter based on regional sea level pressure difference was recently proposed by Azorin-Molina and Lopez-Bustins (2008).

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