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Department of Astronomy and Meteorology, University of Barcelona, Spain

Main Features of the Sea-Breeze in Barcelona*

A. Redaño, J. Cruz, and **J. Lorente**

With 7 Figures

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Summary

From a data set of sea-breeze observations corresponding to cases of no synoptic-scale flow in Barcelona during the period 1970–89, some features of this wind have been deduced. Maximum velocities of between 6–14 m/s generally occur during 12–16 SLT. Diurnal evolution gives a clockwise rotation of sea breeze so that this wind blows roughly parallel to the shoreline in late afternoon. The rate of the change of direction is in agreement with numerical results from a simple non-linear sea breeze model.

1. Introduction

The understanding of the sea breeze in a Mediterranean coastal zone is a question of great interest, especially near a large city, because it is the most frequent wind and generally the main ventilation mechanism in air pollution episodes. Thus, any pollutant diffusion model needs a statistically valid prediction of the behaviour of this wind, which occurs for any meteorological situation with a weak large-scale pressure gradient and not much cloudiness, as frequently happens in Mediterranean zones of the Iberian Peninsula, sometimes far away from the trajectory of frontal depressions. In addition, local relief and urban heat island effects can significantly modify the land and sea breezes near the city, thus necessitating an adequate local model of this circulation.

From Haurwitz's pioneering studies, land and sea breezes have been widely treated in theoretical and observational studies by numerous authors (see for example Atkinson, 1981 for a review). Different linear (Sun and Orlanski, 1981 a; Rotunno, 1983 among others) and non-linear numerical models (Neumann, 1977; Yang and Anthes, 1986) have been used to explain the main features of this circulation, such as its intensification with increasing meso-scale pressure gradient due to sea-land temperature differences, and its clockwise rotation during the day in the Northern Hemisphere, originated by earth's rotation. The linear theory of land and sea breezes predicts a different behaviour of this turning for latitudes less than or greater than 30°, according to whether the Coriolis parameter f is less than or greater than the angular frequency Ω of the earth. While for zones of latitude greater than 30° the diurnal cycle is in phase with land-sea relative heating, for sites of latitude less than 30° the response to different heating is a wave that produces a dephased flow so that the sea breeze can blow during the night. However, when non-linear models are considered (Sun and Orlanski, 1981 b) the waves resulting for low latitudes are weaker and tend to disappear as the friction increases until they become similar for any latitude.

Because of the difficulty of identifying sea breezes due to the influence of large-scale flows, a systematic observational study of this circulation

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for different geographical areas is not available. In the case of Barcelona only some studies of statistical frequencies of wind (Fontseré, 1917) and others related to the influence of wind on turbidity (Redaño and Lorente, 1984) are available. This work summarizes the results of sea-breeze observations in Barcelona over the last 20 years and gives some comparisons with those corresponding to a simple numerical non-linear model.

2. Application of a Simple Non-Linear Model of Sea-Breeze to Barcelona

Let us consider a simple non-linear model of sea-breeze in which the circulation is due to a pressure gradient originated by differential land-sea heating. Equations of horizontal motion in a local system of reference give

$$\dot{u} = -1/\rho\, \partial p/\partial x + f.v + F_x$$
$$\dot{v} = -1/\rho\, \partial p/\partial y - f.u + F_y \quad (1)$$

where u, v are the zonal and meridional components of wind, p is the pressure, ρ the density, f the Coriolis parameter and Fx, Fy the friction terms. If a denotes the direction of wind in relation to the x-axis, i.e.

$$a = \arctan v/u \quad (2)$$

then following the procedure of Neumann (1977) the rate of change of the direction of the sea-breeze is expressed by

$$\frac{da}{dt} = -f + \frac{1}{V^2}\left[\frac{v\,\partial p}{\rho\,\partial x} - \frac{u\,\partial p}{\rho\,\partial y}\right] \quad (3)$$

with $u^2 + v^2 = V^2$.

The Neumann-parametrization of the friction terms:

$$F_x = -C_D\, u V/h;\; F_y = -C_D\, v V/h$$

where C_D is the drag coefficient and h is the height of the boundary layer, cancels the frictional influence in (3) exactly. Thus the Coriolis force and the gradient of pressure due to heating are the causes of the directional turning of this wind. In the hypothesis that V and p have a sinusoidal variation (considering only the positive part of the curve) for the sea breeze during the day (Atkinson, 1981; Yang and Anthes, 1987)

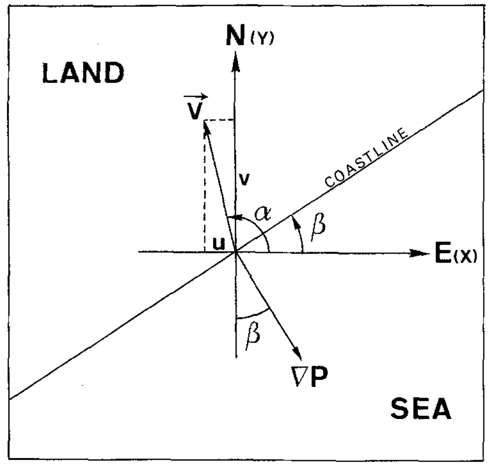

Fig. 1. A scheme of the coordinate system chosen in relation to shoreline

$$V = Vo \sin(\omega t + \rho_1) \quad (4)$$

$$\frac{\partial p}{\partial x} = \frac{\partial p_o}{\partial n} \sin(\omega t + \varphi_2) \sin\beta \quad (5)$$

$$\frac{\partial p}{\partial y} = -\frac{\partial p_o}{\partial n} \sin(\omega t + \varphi_2) \cos\beta \quad (6)$$

where β is the angle between the coastline (Fig. 1) and the x-axis and n is taken normal to the coast. Now, in the assumption that advective terms are negligible (Neumann and Mahrer, 1975; Neumann, 1977), (3) becomes

$$\frac{\partial a}{\partial t} = \frac{1}{\rho V_o} \frac{\partial p_o}{\partial n} \cos(a - \beta) \frac{\sin(\omega t + \varphi_2)}{\sin(\omega t + \varphi_1)} - f \quad (7)$$

3. Observational Results

From wind data collected at our observatory in Barcelona, situated at 5.2 km from the shoreline and at an altitude of 94 m (Fig. 2) during the period 1971–89 sea-breeze circulations were identified. In order to study unambigous sea-breeze cases and avoid synoptic-scale influences, well established onshore flows with typical diurnal evolution and negligible large-scale pressure gradients during the summer have been selected. Sea-breeze in Barcelona is probably enhanced by a coastal chain of mountains parallel to the coastline (Fig. 2) and perhaps by the urban heat island effect. On the other hand, land breeze was generally unobserved because, in addition to its lower intensity, the mountains produce a barrier effect. Thus, the typical breeze circulations consist of a well developed flow during the hours of daylight and calm during night.

Figure 3 a shows the histogram of time at which the sea-breeze begins during the summer. The maximum of frequency occurs between 7–8 Local Solar Time (LST), i.e. two or three hours after sunrise in Barcelona during the summer (04:30 LST for the summer solstice and 05:45 LST for the autumn equinox). In addition, the slope-winds blow before the sea-breeze does, but these winds are light, given the height of chain of mountains parallel to the coastline. Because of the proximity of these hills to the coastline (around 6 km), both winds produce an increase of moisture and it is very difficult to differentiate between them from

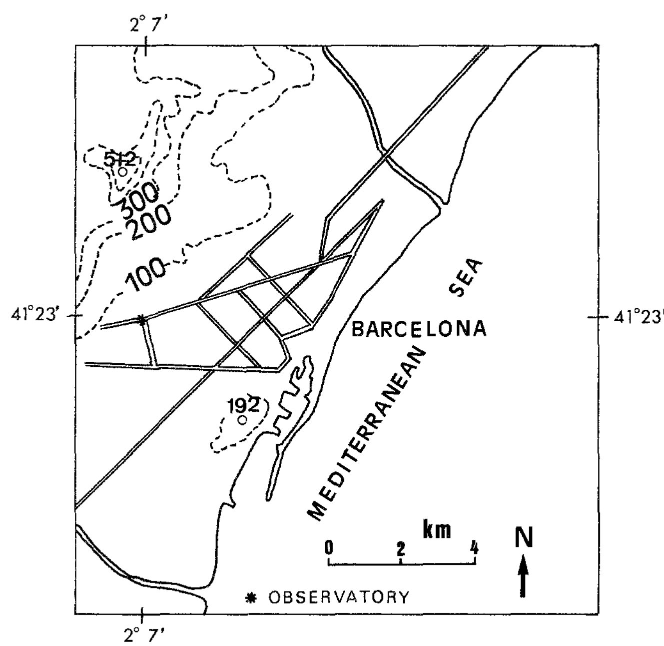

Fig. 2. Schematic map of Barcelona city. Dashed lines represent the isolines of altitude (in m)

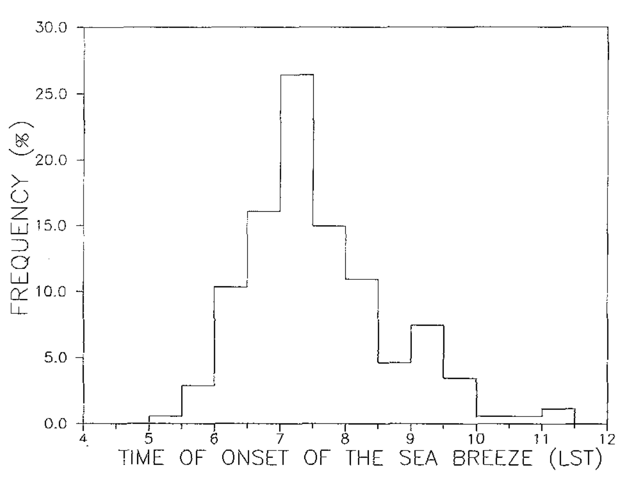

Fig. 3 a. Histogram of time at which the sea-breeze begins during the summer

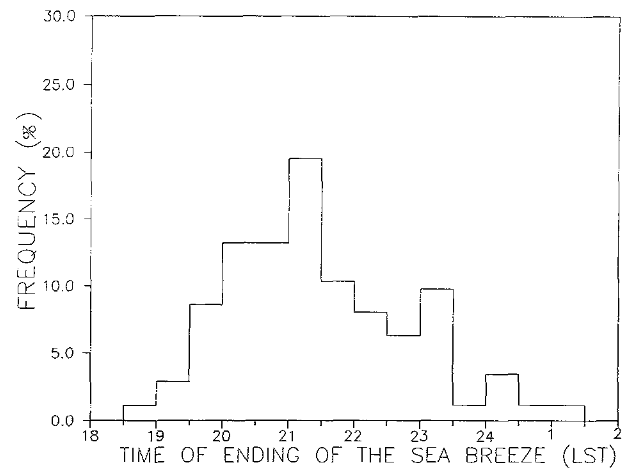

Fig. 3 b. Histogram of time at which the sea-breeze ceases during the summer

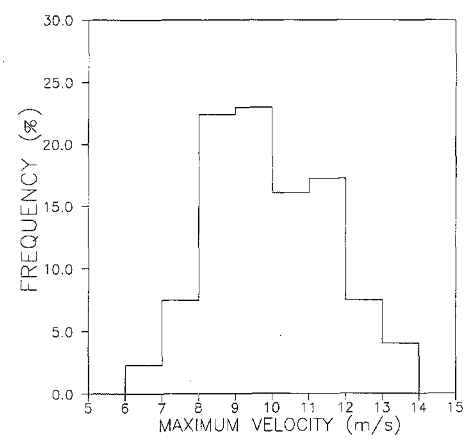

Fig. 4 a. Histogram of maximum velocity of the sea-breeze in Barcelona

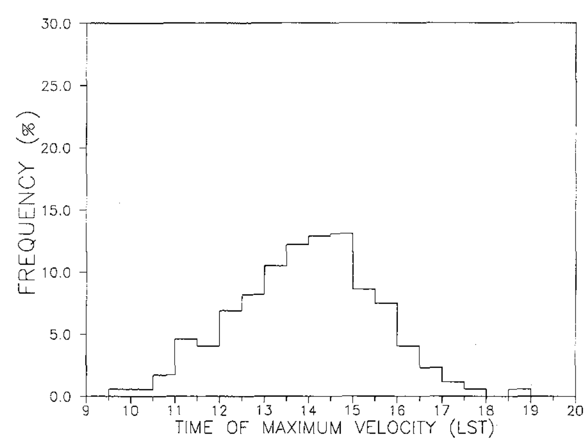

Fig. 4 b. Time in which the sea-breeze reaches its maximum velocity only surface data. In the coastal zones of the Mediterranean countries sea-breezes begin around 07–08 LST during the summer (see for example Met. Office, 1964).

Sea-breezes cease several hours after sunset (Fig. 3 b). Maximum velocity ranges in the 6–14 m/s interval (Fig. 4 a), the most frequent values being 8–10 m/s. The time of maximum velocity is given

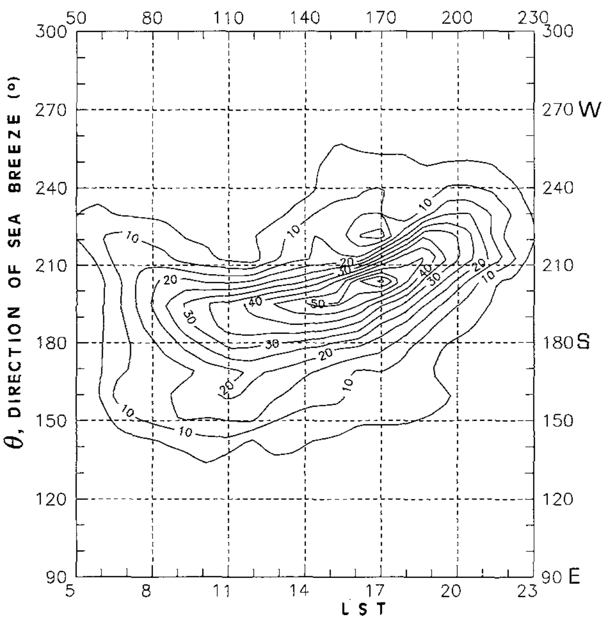

Fig. 5 a. Analysis of sea-breeze directions in relation to time. Ordinate is related with the angle α defined in Fig. 1 by $\theta = 270° - \alpha$. Isolines denote absolute frequencies

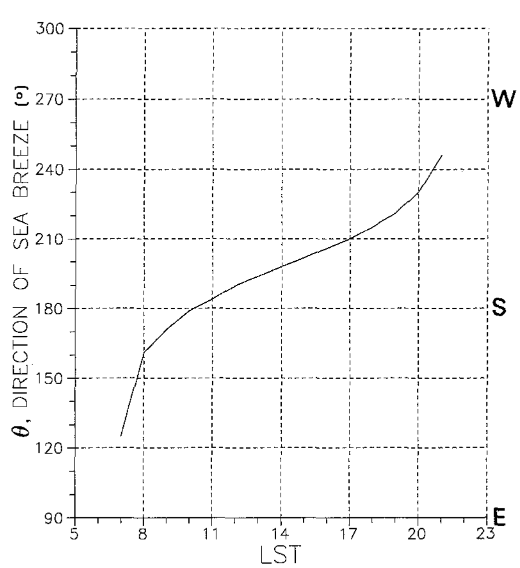

Fig. 5 b. A numerical computation of direction ($\theta = 270° - \alpha$) of the sea-breeze for certain values of variables in Barcelona, based on eq. (7). Initial value: $\alpha(t=0) = 145°$, time step = 10 min

in Fig. 4 b, which shows that the greatest frequency occurs around 14 LST, i.e. between one and two hours after noon and around two hours after the time of maximum temperature.

The direction of sea-breeze in Barcelona shows a clockwise rotation during the day. In agreement with results concerning the rate of turning obtained from Neumann (1977) and Neumann and Mahrer (1984), this is far from uniform in the diurnal cycle. Figure 5 a shows the analysis of directions in relation to time. While the direction change at the beginning and end of the sea breeze is relatively great, during the hours when the sea-breeze is well developed the rate of turning is considerably less.

A numerical computation of the rate of turning can be carried out from (7) calculating the values of ω, φ_1 and φ_2 from the time of beginning and ending of the sea-breeze (0700 and 2200 LST respectively) and assuming that the wind is delayed 1 hour in relation to the pressure gradient, in accordance with observations. Thus:

$$\omega = \pi/54000\,\mathrm{s}^{-1}; \quad \varphi_1 = -7\pi/15, \quad \varphi_2 = -6\pi/15 \tag{8}$$

In addition, the following values of variables have been taken:

$$f = 2\Omega \sin 41°, \quad V_o = 10\,\mathrm{m/s}, \quad \rho = 1\,\mathrm{kg/m^3}, \quad \beta = 55°, \quad \frac{\partial p_o}{\partial n} = \frac{1\,\mathrm{hPa}}{100\,\mathrm{km}} \tag{9}$$

Figure 5 b shows the numerical computation of (7). The curve closely corresponds to the curve which connects the maxima in Fig. 5 a except at the first hours of the breeze, which is caused by the deviation produced by a hill situated on the shoreline (Montjuic mountain) in the same direction as our observatory. Thus, the direction change is relatively fast owing to the Coriolis force in the first and last hours of sea breeze circulation, while this change is slow when the wind has its greatest velocity.

The diurnal evolution of the sea-breeze velocity is given in Fig. 6. These curves represent the frequency of hourly average velocity. The most frequent values during the hours in which the maximum velocity is reached range from 4 to 6 m/s.

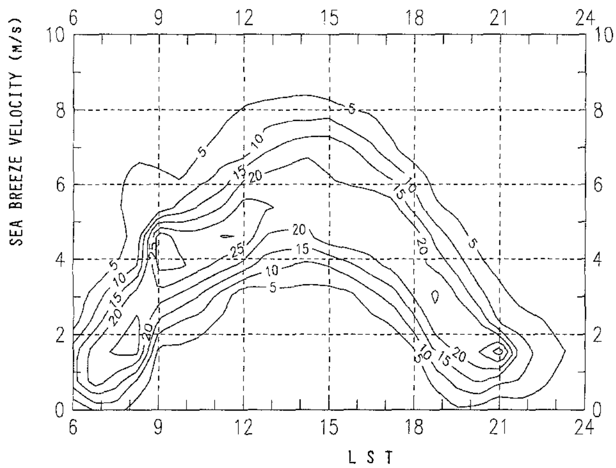

Fig. 6. Diurnal evolution of sea-breeze velocity in Barcelona. Isolines denote absolute frequencies

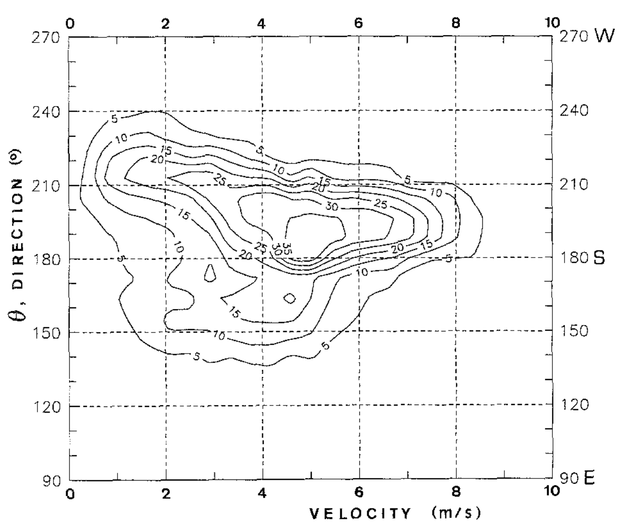

Fig. 7. Relation of direction to velocity of sea-breeze in Barcelona. Isolines denote absolute frequencies

From Fig. 6 a rough symmetry around the maximum value is apparent. Figure 7 gives the relation of direction to velocity. The higher velocities have direction close to 190°, around 25° in relation to the shoreline.

4. Conclusions

The sea-breeze in Barcelona is a very frequent wind, but sometimes it is difficult to observe because the synoptic-scale wind is superimposed. However, during 30% of the summer days there is a well developed sea breeze without larger-scale wind. Most of these circulations begin two or three hours after sunrise, and reach their maximum velocity two hours after noon. The maximum mean hourly velocities range from 4–6 m/s and occur generally when the sea breeze is deflected around 25° in relation to the shoreline. The diurnal rotation observed is clockwise and has a rate that is in agreement with a numerical results obtained from Neumann's non-linear model.

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Authors' address: Dr. A. Redaño, J. Cruz, and Dr. J. Lorente, Departamento de Astronomía y Meteorología, Facultad de Física, Universidad de Barcelona, Avda. Diagonal, 647, E-08028 Barcelona, Spain.