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A climatological study of sea breeze clouds in the southeast of the Iberian Peninsula (Alicante, Spain)

C. AZORIN-MOLINA

Fundación Centro de Estudios Ambientales del Mediterráneo (CEAM), Parque Tecnológico, Charles R. Darwin 14, 46980-Paterna (Valencia), España y Grupo de Climatología, Universidad de Barcelona, Montalegre 6, 08001 Barcelona, Cataluña, España
Corresponding author; e-mail: cazorin@ceam.es

A. SANCHEZ-LORENZO
Grupo de Climatología, Universidad de Barcelona, Montalegre 6, 08001 Barcelona, Cataluña, España

J. CALBO
Grupo de Física Ambiental, Universidad de Girona, Campus Montilivi, EPS II, 17071 Girona, Cataluña, España

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RESUMEN

Las brisas marinas soplan bajo tipos de tiempo anticiclónicos, débiles gradientes de presión atmosférica, radiación solar intensa y cielos prácticamente despejados. Por lo general, la cobertura nubosa total debe ser inferior a 4/8 para que se genere un diferencial térmico y de presión entre el aire sobre las superficies de mar y tierra, lo que permite el desarrollo de esta circulación local de viento. Sin embargo, varios estudios numéricos y de observación han comprobado la habilidad de las brisas marinas para generar nubes en la capa límite interna convectiva y en la zona de convergencia de la brisa marina. En consecuencia, el objetivo de este estudio climático es analizar estadísticamente el impacto de las brisas marinas en los géneros de nubes en la capa límite interna convectiva y en la zona de convergencia de la brisa marina. El área de estudio corresponde al sureste de la Península Ibérica (provincia de Alicante, España) y el trabajo se basa en un periodo de estudio de seis años (2000-2005). Este estudio climatológico utiliza observaciones de nubes anotadas desde superficie en la estación de Alicante-Ciudad Jardín (llano costero central), y una exhaustiva campaña de observación de nubes en la estación de Villena-Ciudad (montaña Prebética) sobre un periodo de estudio de tres años (2003-2005). Los resultados confirman la hipótesis de que el impacto de las brisas marinas en los géneros nubosos es aumentar la frecuencia de nubes bajas (*Stratus*) y convectivas (*Cumulus*). Las brisas marinas disparan la formación de nubes de tormenta (*Cumulonimbus*) en la zona de convergencia de la brisa marina, las cuales también tienen un efecto secundario en el desarrollo de nubes altas (*Cirrus, Cirrocumulus, Cirrostratus*), nubes medias (*Altostratus, Altocumulus*) y nubes bajas (*Stratus, Stratocumulus, Nimbostratus*) asociadas con las nubes cumulonimbos (p. ej., yunque de los cumulonimbos).

ABSTRACT

Sea breezes blow under anticyclonic weather types, weak surface pressure gradients, intense solar radiation and relatively cloud-free skies. Generally, total cloud cover must be less than 4/8 in order to cause a thermal and pressure difference between land and sea air which allows the development of this local wind circulation. However, many numerical and observational studies have analyzed the ability of sea breezes to generate clouds in the convective internal boundary layer and in the sea breeze convergence zone. Accordingly, the aim of this study is to statistically analyze the impact of sea breezes on cloud types in the convective internal boundary layer and in the sea breeze convergence zone. The study area is located in the southeast of the Iberian Peninsula (province of Alicante, Spain) and the survey corresponds to a 6-yr study period (2000-2005). This climatological study is mainly based on surface cloud observations at the Alicante-Ciudad Jardín station (central coastal plain) and on an extensive cloud observation field campaign at the Villena-Ciudad station (Prebetic mountain ranges) over a 3-yr study period (2003-2005). The results confirm the hypothesis that the effect of sea breezes on cloud genera is to increase the frequency of low (*Stratus*) and convective (*Cumulus*) clouds. Sea breezes trigger the formation of thunderstorm clouds (*Cumulonimbus*) at the sea breeze convergence zone, which also have a secondary impact on high-level (*Cirrus, Cirrocumulus*, *Cirrostratus*), medium-level (*Altostratus, Altocumulus*) and low-level clouds (*Stratus, Stratocumulus, Nimbostratus*) associated with the *Cumulonimbus* clouds (e.g., *Cumulonimbus* anvil).

Keywords: Sea breezes, convective internal boundary layer, sea breeze convergence zone, cloud genera, total cloud cover, southeast Iberian Peninsula.

1. Introduction

Sea breezes constitute the most common low-level wind circulation at many coastal locations in the Mediterranean Sea. In such places, and over inland sites varying between 30 and 300 km from the nearest sea (Atkinson, 1981), sea breezes have a marked effect on weather and climate. Moreover, sea and land breeze circulation patterns play a key role in many ways (e.g., particularly on the dynamics of pollutants and air quality; Novak and Colle, 2006) and the short-term forecasting accuracy thereof is crucial for certain sports (e.g., 32nd Edition of the America's Cup 2007 in Valencia, Spain).

Ramis and Alonso (1988) pointed out that sea breezes usually develop in the Western Mediterranean basin under anticyclonic (Reiter, 1975) or calm weather types, weak surface pressure gradients, intense solar radiation, and almost clear skies. Consequently, total cloud cover (TCC) must be less than 4/8 (Prezerakos, 1986) in order to cause a cross-shore mesoscale (2 to 2000 km) pressure gradient created by the thermal difference between land and sea air at low levels in the atmosphere. In spite of the fact that sea breezes blow mostly in conditions of clear skies, their distinctive feature is a line of clouds parallel to the shoreline which develops at the sea breeze convergence zone (SBCZ) on an otherwise cloudless day. This discontinuity represents a low-level convergence zone between sea breezes and offshore large-scale winds, which is known as a sea breeze front. A sea breeze front is a horizontal discontinuity in temperature and humidity marking the leading edge of the intrusion of cooler, moister marine air associated with the lower horizontal arm of sea breeze circulation patterns (Huschke, 1959). Koschmieder (1936) first studied the leading edge of sea breezes (sharp changes in temperature, moisture, and wind) along the Baltic coast using surface and upper strata measurements from pilot balloons at Danzig (Gdansk, Poland). Subsequently, sea breezes and this miniature cold front were studied in depth with the use of numerical-theoretical analyses, particularly in the Florida panhandle (Pielke, 1974), where abundant summertime rainfall is a result of sea breezes. Simpson (1994) developed extensive laboratory measurements in relation to sea breeze frontogenesis using a model of a sea breeze gravity current front (Simpson and Britter, 1979, 1980). Thunderstorms, lightning, heavy rain, and occasionally hail can form along SBCZ in an environment of low static stability or when more than one boundary interacts with another (Purdom, 1976). It is important to highlight that thunderstorms are also of great importance as an input of water. During the summer dry season, this is typically the only source of precipitation in the eastern Iberian Peninsula (IP) (Olcina-Cantos and Azorin-Molina, 2004), bringing an average of 100-125 mm yearly to inland areas (Millán *et al.*, 2005).

Azorin-Molina (2007) reported that the sea breeze blows over the south-eastern coast of the IP for almost two out of every three days. Sea breezes have a high level of occurrence in June (26.2 days), July (27.2) and August (28.0), in contrast to November with a mean number of 10.7 sea breeze days. The mean onset time is 0940 UTC for the whole year. The earliest mean time of the sea breeze passage is 0834 UTC in June (summer solstice) whereas the latest onset time takes place at 1241 UTC in December (winter solstice). The mean cessation time is 2009 UTCthroughout the year. The earliest mean time of sea breeze cessation is at 1718 UTC in December and the latest cessation time is at 2128 UTC in July. Therefore, the mean duration time is 10 h 29' and the daily duration fluctuates from a minimum of 2.5 h in autumn-winter to a maximum of 16.0 h in summer. Sea breeze gust intensities range from a minimum value of 3.6 m s^{-1} to a maximum of 11.6 m s^{-1}, and they are much stronger during the spring months in relation to the biggest land-sea air ΔT.

To our knowledge, no research has as yet attempted to statistically study the effect of sea breezes on cloudiness. The present climatological study aims to verify for the first time the impact of sea breezes on cloud types, an observation put forward in previous empirical sea breeze studies (Planchon, 1997; Olcina-Cantos and Azorin-Molina, 2004). Additionally, this paper was designed to help readers recognize cloud genera in the convective internal boundary layer (CIBL) and the SBCZ.

2. Data and methodology

The central coastal plain (Campo de Alicante district) and the Prebetic mountain ranges in the southeast of the IP (province of Alicante, Spain; Fig. 1) were chosen because they represent a natural laboratory for studying the CIBL and the SBCZ. Sea breeze cloud frequency composites from AVHRR data (Azorin-Molina *et al.*, 2007) revealed that the Prebetic mountain ranges constitute one of the most prominent zones becoming convectively active (hot spot) in the Iberian Mediterranean area. The Prebetic mountain ranges (1000-1600 masl; the highest peak of the Aitana mountain range is 1558 masl) and the most clearly delineated convex land-water boundary in the eastern coast of the IP (Cape of San Antonio and Cape of Nao) enhance low-level convergence, vorticity, vertical motion/uplift processes and cumulus activity/thunderstorms (Neumann, 1951; Pielke, 1974; Purdom, 1976; Strickler, 2003) in the north of the province of Alicante. Sea breezes become convergent from the south of the Bay of Valencia (northeasterly to easterly sea breezes) and the Bay of Alicante (southeasterly sea breezes).

Surface cloud observations made at the Alicante-Ciudad Jardín synoptic station (CJ; 38°22'N and 00°29'W; 82 masl above sea level and 3.3 km from the shore; Spanish Agencia Estatal de Meteorología, AEMET) over a 6-yr study period (2000-2005) with 3-daily observations (07 h, 13 h and 18 h UTC) enabled us to statistically study the effect of sea breezes on cloudiness. This is the closest and therefore most reliable surface cloud observation point in the study area. Clouds in the CIBL and in the SBCZ can be perfectly monitored from this observation point. TCC (amount in oktas) and the well-known 10 cloud genera put forward by the World Meteorological Organization (WMO, 1975, 1987) were the data analyzed herein. In addition to the surface cloud observations at the CJ station, we performed an extensive cloud observation field campaign in the SBCZ at the Villena-Ciudad station (VC; 38°38'N and 00°51'W; 524 masl above sea level and 46.4 km from the shoreline; AEMET) over a 3-yr study period (2003-2005). The VC inland observation point provided valuable data on the formation of low stratiform clouds (*Stratocumulus*, Sc) in the highest zone of the Salinas mountains (south-western Prebetic system mountains), in response to the inland propagation of the CIBL (marine air mass) late in the evening.

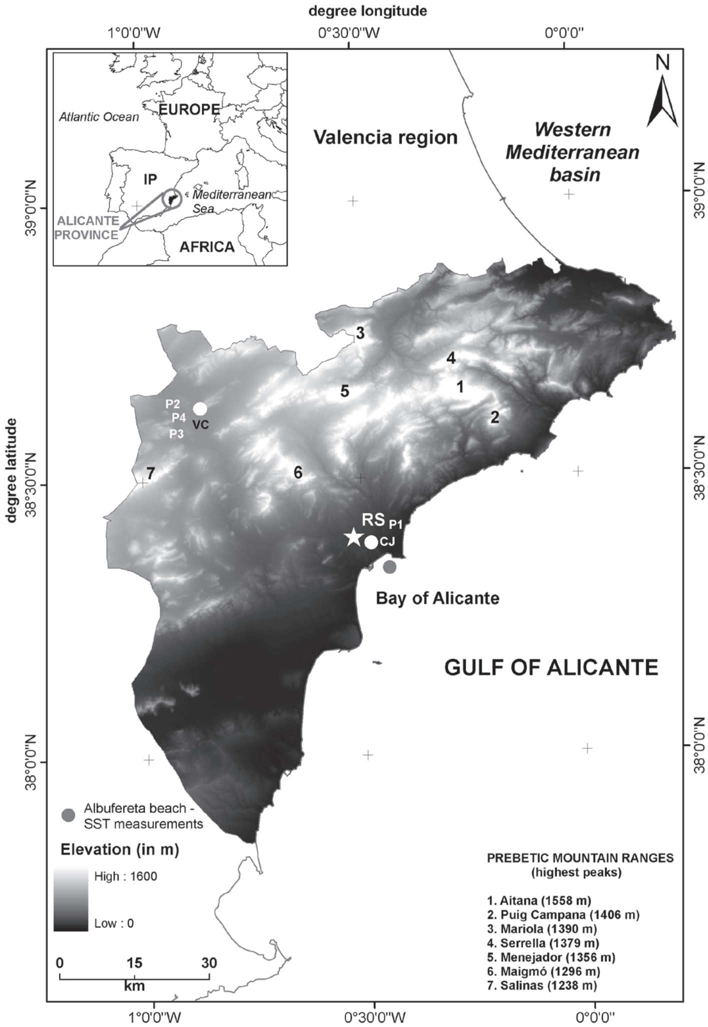


Fig. 1. Topographic map of the province of Alicante showing the coastal plains and the Prebetic mountain ranges in the southeast of the IP, where the CIBL and the SBCZ tipically develop, respectively. The location of the measurement sites within the area is shown: the RS-meteorological data, the CJ-surface cloud observations, the VC-inland station and the SST measurement site (Albufereta beach). P1, P2, P3 and P4 correspond to locations in which the pictures in Fig. 2 were taken.

We used meteorological and sea surface temperature (SST) measurements to apply an automated and manual selection technique in order to create a dataset of past sea breezes days. Meteorological measurements were acquired from the automatic weather station located at the Laboratory of Climatology of the University of Alicante (38°23’N and 0°31’W; 102 masl above sea level and 5.1 km from the shoreline; University Institute of Geography; http://labclima.ua.es). SST data were collected at 0.27 nautical miles offshore at Albufereta beach (38°21’N and 0°26’W; Institute of Coastal Ecology of El Campello, Alicante; http://www.ecologialitoral.com/). We used the large datasets of 475 and 1414 sea breeze episodes created by the automated and the manual selection techniques (Azorin-Molina, 2007; Azorin-Molina and Martín-Vide, 2007), respectively, to classify situations into four categories: a) all days for the 6-yr study period (hereinafter AD); b) non sea breeze days (NSB); c) sea breeze episodes selected by the automated method (SB), and d) sea breeze events identified by the manual technique (PSB). The statistical difference significance between the categories was verified by the chi-square ($\chi2$) test or Student´s t-test at the 95% (α = 0.05) or 99% (α = 0.01) significance levels.

3. Results

3.1. Sea breeze cloud types

Table I summarizes names and abbreviations of genera, species and mother-clouds (WMO 1975, 1987) observed during the extensive field campaign for the observation of sea breeze clouds.

Sea breezes can be classified into two main categories, taking into account their effect on cloud formation. The primary impact of sea breeze flows corresponds to a) low stratiform clouds (St and Sc) formed in the CIBL due to the inflow of moist sea air at lower levels on the coastal and littoral plains, and b) convective clouds (Cu and Cb) which can be observed inland along the SBCZ or sea breeze front (prime location for convective initiation).

Table I. Names and abbreviations of genera, species and mother-clouds observed during the extensive field campaign of sea breeze clouds in the CIBL and in the SBCZ

Genera		Species		Mother-Clouds
Name	Abbreviation	Name	Abbreviation	Abbreviation
Cirrus	Ci	*fibratus*	fib	Cc
		uncinus	unc	Ac
		spissatus	spi	Cb
Cirrocumulus	Cc	*stratiformis*	str	
Cirrostratus	Cs	*fibratus*	fib	Cc
		nebulosus	neb	Cb
Altocumulus	Ac	*castellanus*	cas	Cu
		stratiformis	str	Cb
Altostratus	As			Ac
				Cb
Stratocumulus	Sc	*stratiformis*	str	Cu
		castellanus	cas	Cb
Stratus	St	*nebulosus*	neb	Cu
		fractus	fra	Cb
Nimbostratus	Ns			Cu
				Cb
Cumulus	Cu	*fractus*	fra	Ac
		humilis	hum	Sc
		mediocris	med	
		congestus	con	
Cumulonimbus	Cb	*calvus*	cal	Ac
		capillatus	cap	Sc
				Cu

Mother-clouds, e.g. Stratus cumulogenitus – St cugen

Photographs presented in Figure 2 are illustrative of the diurnal evolution of sea breeze clouds over the study area. The photograph in Figure 2a was taken at 0842 UTC on August 30, 2004 shortly after departing from El Altet airport. The picture shows a distinctive image similar to that presented by Simpson (1994). The SBCZ line was evident early in the morning, as well as the cloudless air in the CIBL, with sea breezes advancing from the southeast over the Bay of Alicante (seaward side), where the city of Alicante is located. Few and small fragments of low clouds (*Stratus fractus*; St fra) appear in the CIBL (moist sea breeze air) with a lower condensation level than large convective clouds (*Cumulus fractus* and *Cumulus humilis*; Cu fra and Cu hum) formed at the leading edge of sea breezes (SBCZ) a few kilometres inland. The uniform banks of fair-weather Cu fra and Cu hum clouds (ragged Cu of little vertical development) formed parallel to the Bay of Alicante indicate initial thermals of rising air during the morning and enable us to measure how far the sea breezes have spread inland: around 5-10 km. The CIBL was propagated further inland by advancing moist southeasterly sea breezes and the fair-weather Cu hum clouds slowly became *Cumulus mediocris* (Cu med), *Cumulus congestus* (Cu cong) and *Cumulonimbus capillatus* (Cu cap) along the convergence line as the day progressed.

Fig. 2a. S*tratus fractus, cumulus fractus and cumulus humilis* clouds showing the advance of southeasterly (on the left-hand side of the photograph) sea breezes over the city of Alicante and surrounding area (within the CIBL) at 0842 UTC on August 30, 2004

Figure 2b shows a typical SBCZ located 40 to 50 km inland over the Prebetic mountain ranges at 1520 UTC on the day before (August 29, 2004). We observed a well-defined convective roll with towering Cu clouds to the left of the photograph from 1200-1300 UTC to 1700-1800 UTC. Deeper cloud development with a local Cb cap was observed along the front in the center-right of the picture (the upper part of the Cb anvil is clearly fibrous or striated). Shower and thunderstorm occurred over the Prebetic mountain ranges.

Fig. 2b. *Cumulus mediocris, cumulus congestus* and *cumulonimbus capillatus incus* developed in the SBCZ over the Prebetic system mountains at 1520 UTC on August 29, 2004

Figure 2c corresponds to the formation of *Stratocumulus stratiformis* (Sc str) clouds over the highest peaks of the Salinas mountains on April 13, 2006 (1815 UTC). This is the most distinctive cloud formation and provides the observers with valuable information concerning the arrival of sea breezes inland. The formation of Sc str clouds is caused by the rising and cooling of turbulent moist sea air over the highest slopes of the Prebetic system mountains at the end of the day. This is the result of continuous observations from the VC station over three years. *Stratocumulus*

Fig. 2c. *Stratocumulus stratiformis* clouds at the top of the Salinas mountain range (south-west of the Prebetic mountain ranges in Alicante) at 1815 UTC on April 13, 2006.

cumulogenitus or *cumulonimbogenitus* can be also observed in the skies in the late evening, when the sinking motion occurs on the landward side of the cell. Table II shows the occurrence of Sc str clouds over the Salinas mountains. September (17 days, i.e., 38.6%) and May (9 days, i.e., 20.5%) represent the months with highest frequency, whereas Sc str clouds do not form in January, November and December, a phenomenon which results from reduced inland propagation of sea breezes. In most Sc str formations, we observed dense fog banks of Stratus nebulosus (St neb) and dew during the early next morning, covering the inland topographical depressions. Figure 2d illustrates the formation of a dense fog bank in the surroundings of the VC station (Villena pool) on February 20, 2001 (0730 UTC).

Table II. Monthly number (n_i) and probability (P_1) of Stratocumulus stratiformis observed at the top of the Salinas mountains (from the VC station) over a 3-yr observation period (2003-2005)

	Jan		Feb		Mar		Apr		May		Jun	
	n_i	P_1	n_i	P_1	n_i	P_1	n_i	P_1	n_i	P_1	n_i	P_1
2003	0	0.0	1	6.7	2	13.3	1	6.7	1	6.7	1	6.7
2004	0	0.0	0	0.0	2	9.5	2	9.5	6	28.6	2	9.5
2005	0	0.0	0	0.0	0	0.0	1	12.5	2	25.0	0	0.0
Total	0	0.0	1	2.3	4	9.1	4	9.1	9	20.5	3	6.8
	Jul		Aug		Sep		Oct		Nov		Dec	
	n_i	P_1	n_i	P_1	n_i	P_1	n_i	P_1	n_i	P_1	n_i	P_1
2003	0	0.0	0	0.0	7	46.7	2	13.3	0	0.0	0	0.0
2004	2	9.5	0	0.0	7	33.3	0	0.0	0	0.0	0	0.0
2005	1	12.5	1	12.5	3	37.5	0	0.0	0	0.0	0	0.0
Total	3	6.8	1	2.3	17	38.6	2	4.5	0	0.0	0	0.0

Fig. 2d. *Stratus nebulosus* (dense fog bank) covering the Villena pool in inland areas of the province of Alicante at 0730 UTC on February 20, 2001.

The primary effect of sea breezes on cloud patterns can be clearly identified in the visible satellite images shown in Figure 3, which represents an example of the cloud formation at the CIBL (Fig. 3a) and at the SBCZ (Fig. 3b) in the southeast of the IP.

a) b)

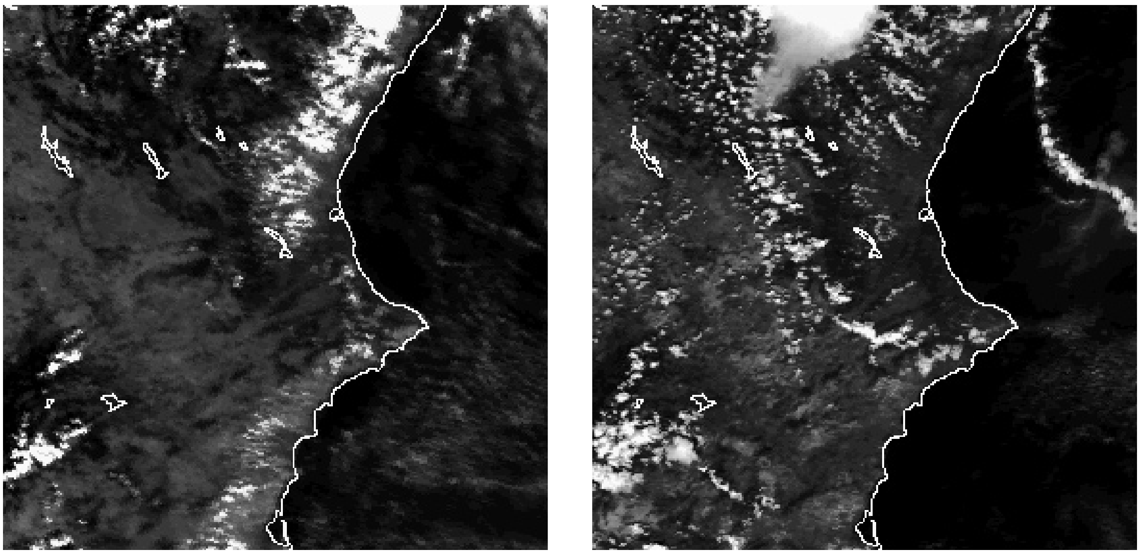


Fig. 3. NOAA-AVHRR satellite images showing a) St fra, Cu fra and Cu hum clouds within the marine air mass (CIBL) on the coastal plain of the province of Alicante (NOAA-17 visible channel, $R_{0.9}$ μ ; at 1134 UTC on August 30th, 2004), and b) Cu med, Cu con and Cb cap clouds at the leading edge of sea breezes (SBCZ) over the Prebetic mountain ranges in Alicante (NOAA-16 visible channel, $R_{0.9}$ μ ; at 1420 UTC on August 29, 2004)

The secondary impacts of sea breezes on cloud genera are a) high-level (*Cirrus, Ci, Cirrocumulus*, Cc, and *Cirrostratus*, Cs, in form of an anvil originating from Cb), b) medium-level (*Altocumulus*, Ac, and *Altostratus*, As) and c) low-level (St, Sc, and *Nimbostratus*, Ns) clouds formed by the spreading or flattening of thunderstorm clouds at the sea breeze front (mother-clouds, i.e., *Cumulogenitus* or *Cumulonimbogenitus*), progressively invading the skies above the coast. These clouds are generally steered toward the coast (Rubin and Duncan, 1989).

Consequently, sea breezes may make a contribution on cloud development as a local and regional forcing. Stratiform and convective clouds dominate under stable and unstable atmospheric conditions, respectively.

3.2 Total cloud cover

Table III summarizes some statistics of the TCC for each category. Mean TCC is 3.4 oktas for the 6-yr study period (AD). The mean fractional coverage of the sky is greater for the NSB days (4.6 oktas; i.e., 33.0% > AD mean value of 3.4 oktas) than the SB (2.1 oktas; i.e., 40.1% < AD) and the PSB (2.8 oktas; i.e., 18.4% < AD) categories. The overall feature is that the TCC on the SB and the PSB days is lower than TCC on days with no development of local winds at all. The NSB days usually correspond to non anticyclonic weather types, moderate to strong large-scale flows, and particularly cloudy skies and few hours of sunshine. On the NSB days, the forcing for the formation of the temperature gradient across the shore (ΔT; separation of the cool, moist marine air from the warm, dry air form the inland valley; Schroeder *et al.*, 1967; Johnson and O'Brien, 1973) is absent and sea breezes are cancelled. The NSB days have higher cloud cover than the AD, SB and PSB categories throughout the whole year (Fig. 4). The minimum values for mean monthly TCC in June, July and August support the high level of occurrence and persistence of sea breezes in the Bay of Alicante (Azorin-Molina and Martín-Vide, 2007). The mean monthly TCC values for the SB days are lower than the PSB days because the latter category groups more sea breeze episodes under partially cloudy conditions. Also from Figure 4 it is possible to identify that respect to the AD category, the SB days, and to a lesser degree the PSB days, present monthly negative differences with extreme negative values in winter and minimum ones from April until September. This is due to the fact that, for the sea breezes to develop in winter months, clear-sky conditions are needed; in addition, no SBCZ are discernible in the winter sea breezes. In contrast, clouds in the CIBL and in the SBCZ are frequent in the SB and the PSB categories from April to September. The *t*-test confirms an annual significant difference at the 95% level ($\alpha = 0.05$) in mean TCC values among the four categories, and especially on a month-to-month basis between the SB and the NSB days (significant at the 99% level; $\alpha = 0.01$).

Table III. Statistic of the total cloud cover for the AD, the NSB, the SB and the PSB categories during the 6-yr study period (2000-2005).

Cloud genera	Min	1st Quartil	Mean	Median	3rd Quartil	Max
AD	0.0	1.3	3.4	3.3	5.3	8.0
NSB	0.0	3.0	4.6	4.7	6.3	8.0
SB	0.0	0.7	2.1	1.7	3.0	4.7
PSB	0.0	1.0	2.8	2.7	4.3	7.3

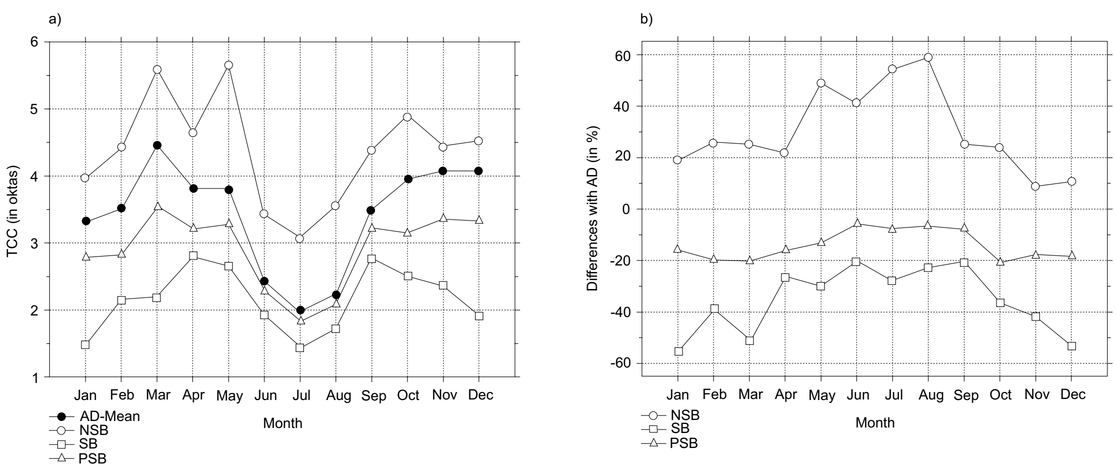


Fig. 4. Mean monthly TCC for the AD, the NSB, the SB and the PSB categories (left panel) and differences with AD (right panel) for the 6-yr study period (2000-2005).

Figure 5 shows the evolution of mean monthly diurnal TCC for the SB (Fig. 5a) and the NSB (Fig. 5b) categories. Sea breeze events display a significant ($\alpha = 0.05$) diurnal TCC evolution, as mean monthly TCC values gradually increase from morning (07h UTC) until evening (18 h UTC), particularly in April, May and June. This diurnal TCC evolution is associated with the daily sea breeze cycle as well as with convection in the form of forced lift occurring along the SBCZ throughout the day. The evolution of diurnal TCC is not displayed in July due to the sinking motion under the dominant Azores high pressure system and the dominance of mainly clear skies. This is a distinctive feature in mid and high-latitudes during summertime, and has been shown in cloud climate studies (Karlsson, 2003; Azorin-Molina, 2007). November also has a significant ($\alpha = 0.05$) diurnal TCC evolution, but in an unexpected inverse sense probably caused by low St clouds (Fig. 8a), which tend to break up early in the afternoon.

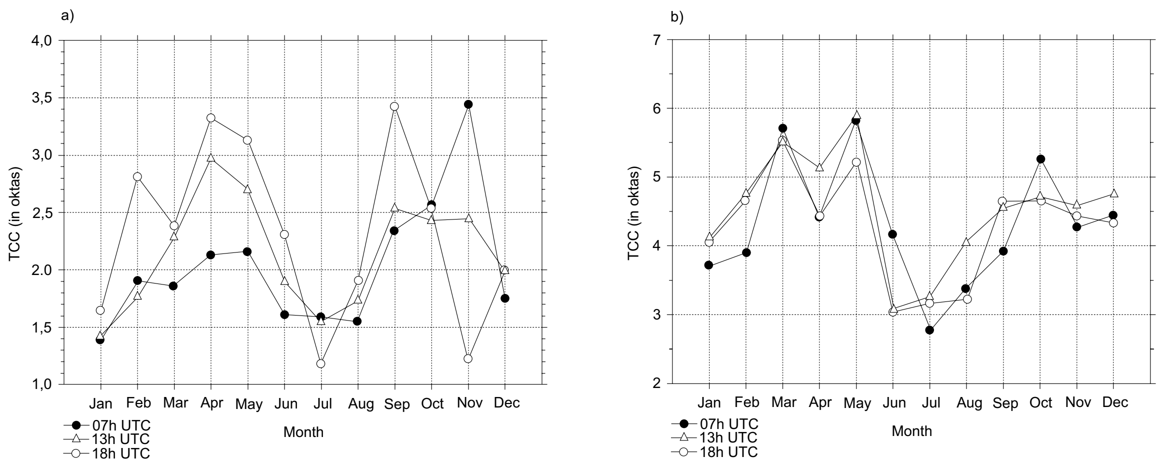


Fig. 5. Monthly mean diurnal TCC evolution for a) the SB category and b) the NSB category during the 6-yr study period (2000-2005).

3.3 Cloud frequency in the CIBL and in the SBCZ

Table IV summarizes the frequency distribution of cloud genera for the four categories during the 6-yr study period (2000-2005). The statistical results demonstrate the empirical hypothesis (see Section 3.1) of the primary impact of sea breezes on low-level (St; NSB 3.7%, SB 4.4% and PSB 4.3%) and vertical development (Cu; NSB 13.7%, SB 17.1% and PSB 14.4%) clouds. The chi-square test (χ^2) verifies significant differences ($\alpha = 0.05$) on the St and Cu cloud types between the SB and the NSB days. The St clouds increase on SB days in the CIBL by the inflow of moist air supplied by onshore winds at the lower levels. The Cu clouds also show an increase due to the convergence of sea breezes and synoptic winds in the SBCZ, where there is deep convection caused by currents of rising air (updrafts). Cb clouds frequencies (SB 1.2% and PSB 1.7%) in the SBCZ were also revealed during the observational field campaigns, but their differences are not significantly different of NSB (1.4%). This is probably due to the fact that the surface cloud observation point at the CJ coastal station cannot completely monitor Cb clouds formed far inland. Moreover, Cb clouds have a similar frequency for the AD (1.5%) and NSB (1.4%) categories. As has been shown before, banks of Sc clouds associated with sea breezes (SB 17.1% and PSB 16.4%) are typically seen at the top of many coastal and inland mountain ranges at the end of the day. When sea breezes collide with mountain slopes air rises, and often condenses and forms Sc clouds (Fig. 2c).

Table IV. Frequency (%) of the 10 cloud genera for the AD, the NSB, the SB and the PSB categories during the 6-yr study period (2000-2005). Frequencies were calculated in relation to all genera observed for each category.

Cloud Genera	AD	NSB	SB	PSB
Ci	24.0	17.1	33.6	29.8
Cc	0.8	0.8	1.0	0.9
Cs	8.2	6.5	9.7	9.7
As	9.1	12.7	2.1	6.1
Ac	20.2	24.4	13.8	16.6
St	4.0	3.7	4.4	4.3
Sc	17.7	19.1	17.1	16.4
Ns	0.3	0.6	0.1	0.1
Cu	14.1	13.7	17.1	14.4
Cb	1.5	1.4	1.2	1.7

Regarding the high level clouds, Figure 6a shows the mean monthly frequency of the high-cloud family for the AD, the NSB, the SB and the PSB categories. The relative frequency of the high-cloud genera is greater for the SB (Ci 33.6%; Cc 1.0%; Cs 9.7%) and the PSB (Ci 29.8%; Cc 0.9%; Cs 9.7%) than for the AD (Ci 24.0%; Cc 0.8%; Cs 8.2%) and the NSB (Ci 17.1%; Cc 0.8%; Cs 6.5%) during the whole year. The differences between SB and NSB days are statistically significant for a significance level $\alpha = 0.05$ for the Ci and Cs genera. This may be explained by the already mentioned secondary effect of sea breezes, i.e. the formation of cirriform clouds on the top of Cb triggered by the convergence at the sea breeze front. In addition, sea breeze episodes are associated with stable weather types and mostly clear skies and therefore clouds at high levels can be observed in sea breeze days. Moreover, the high-cloud genera do not disturb the development of sea breezes. Note in Figure 6a that the frequency of high clouds for the NSB episodes is too low because clouds at low and medium levels may prevent the observation of high clouds in the troposphere, as well as the initiation of sea breezes.

On the other hand, Figure 6b shows the mean monthly frequency of the medium-level cloud family for the four categories. The relative frequency of medium-cloud genera is lower for the SB (As 2.1%; Ac 13.8%) and the PSB (As 6.1%; Ac 16.6%) than the AD (As 9.1%; Ac 20.2%) and the NSB (As 12.7%; Ac 24.4%) throughout the year. The differences between SB and NSB events are also statistically significant ($\alpha = 0.05$) for both genera. Ac and the As clouds interfere with solar radiation and heating, reduce the land-sea air ΔT and tend to interrupt the development of local sea breezes, therefore their greater frequencies in NSB is logical. Finally, low Ns clouds are not associated with sea breezes, except for those originating in thunderstorms in the SBCZ. The frequency of the four categories is as follows: SB (0.1%), PSB (0.1%), AD (0.3%) and NSB (0.6%). The differences between the SB and the NSB days are statistically significant ($\alpha = 0.05$), which confirms the fact that this cloud genera is not associated with sea breeze development.

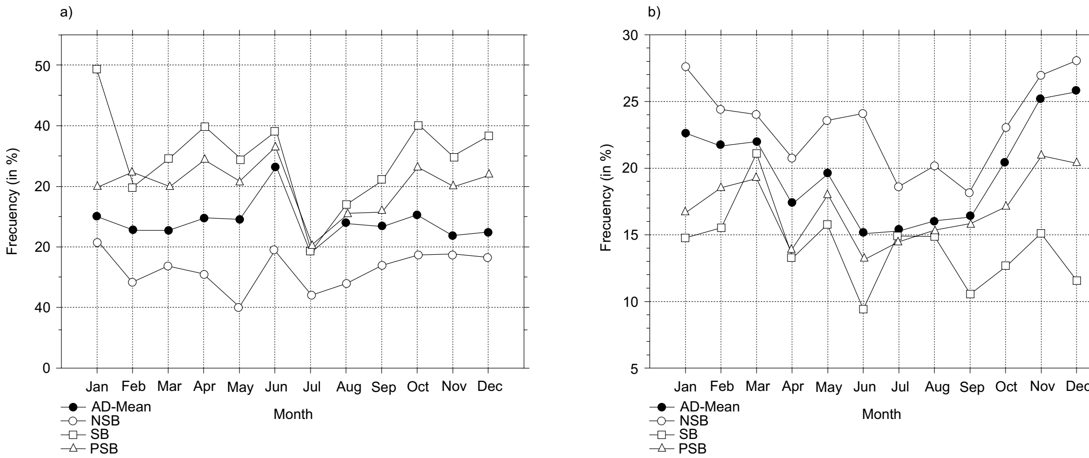
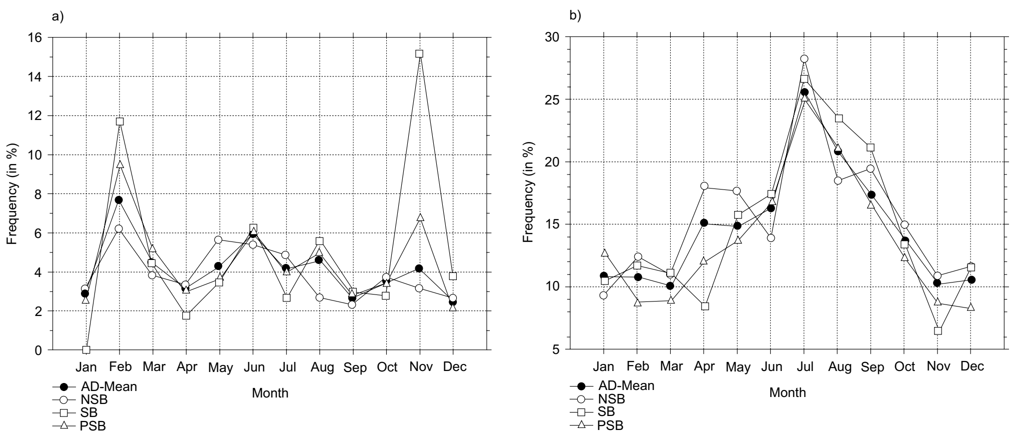


Fig. 6. Mean monthly frequency of a) high clouds and b) medium clouds for the four categories during the 6-yr study period (2000-2005).

3.4. Monthly frequency and diurnal evolution of St, Cu and Cb clouds

Figure 7 shows the mean monthly frequency of St (a), Cu (b) and Cb (c) clouds for the four categories during the 6-yr study period. Sea breeze flows influence the formation of St clouds in



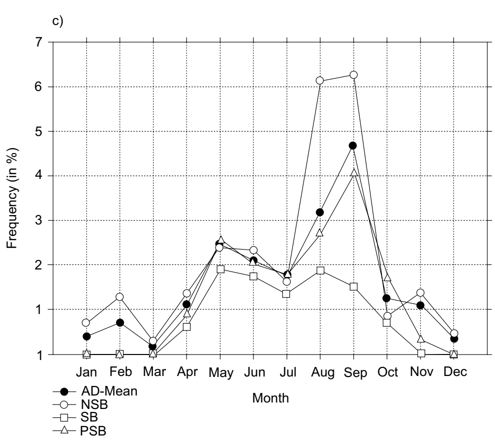
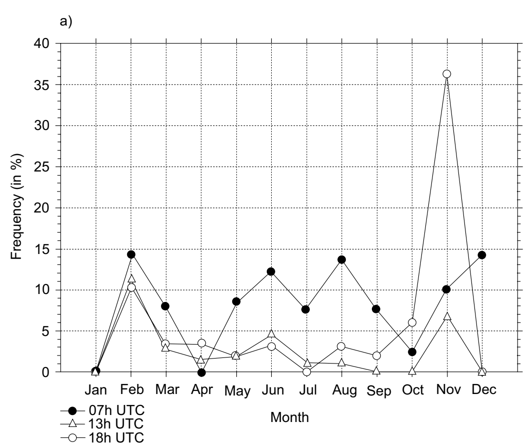
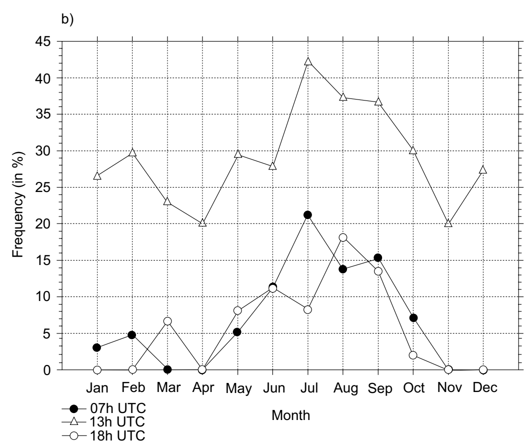


Fig. 7. Mean monthly frequency of a) St, b) Cu, and c) Cb clouds for the four categories during the 6-yr study period (2000-2005)

the CIBL during summertime (June and August) and particularly in February and November (Fig. 7a). These high monthly frequency values for the St clouds are hypothetically due to the moist sea breeze air that becomes cooled and contributes to low stratus formation in the late afternoon and evening. Sea breezes can provide the moisture to help form Cu clouds in the SBCZ, particularly in July, August and September (Fig. 7b). Between April and November, Cb clouds develop as a result of both sea breezes and the thermal convective period at mid latitudes. The higher relative frequency of Cb clouds occurs in August and September under the NSB category in relation to unstable weather types (Fig. 7c). However, SB and PSB have the ability to develop Cb at the SBCZ in the Prebetic mountain ranges in Alicante.

Figure 8 displays the mean monthly frequency of St (Fig. 8a), Cu (Fig. 8b) and Cb (Fig. 8c) clouds for the SB category at 07, 13 and 18 h UTC for the 6-yr study period (2000-2005), i.e., diurnal cloud evolution. St clouds are more frequent at 07 h UTC. The only exception to this behavior is the clear evening maximum for November. The inflows of moisture driven by sea breezes generate the formation of fragments of clouds at 13 and 18 h UTC (St fra). The mean monthly frequency of the diurnal evolution of Cu clouds for SB days is much higher at 13h UTC than 07 and 18 h UTC during the whole year, mainly in the colder season (Fig. 8b). Cb clouds can be observed at 13 and 18 h UTC on SB days, except for June and July, when they also form at 07 h UTC. A strong





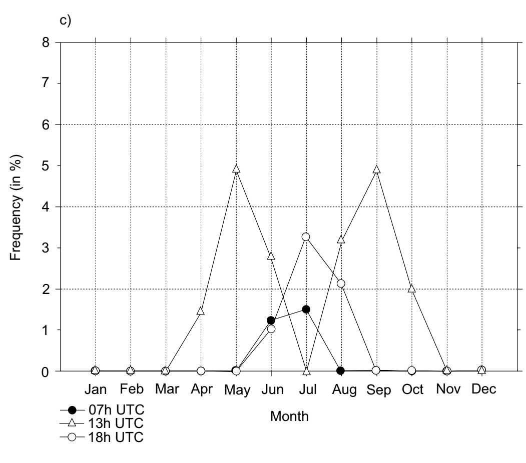


Fig. 8. Mean monthly frequency of the diurnal evolution for (a) St, (b) Cu, and (c) Cb clouds for the SB category during the 6-yr study period (2000-2005)

diurnal cycle of Cb clouds was detected in Figure 8c: a) Cb clouds are more frequent at 13h UTC and disappear at 18 h UTC in spring (April and May) and at the end of summer (September and October); b) There is a delay in Cb development during the summertime, particularly in July, when development is at its maximum at 18 h UTC.

4. Conclusions

We conducted a detailed climatological-observational study of the impact of sea breezes on cloud development in the convective internal boundary layer and in the sea breeze convergence zone for the southeast of the Iberian Peninsula: province of Alicante. This empirical study presents the following major findings:

a) The main result is that sea breezes have a primary effect on low (St) and convective (Cu) cloud genera, which was statistically verified by the chi-square ($\chi 2$) test at the 95% (α = 0.05) significance level. Sea breezes provide the moisture to help form distinctive St clouds in the CIBL and Cu clouds in the SBCZ, particularly from April to October. St clouds are more frequent at 07 h UTC (probably due to banks of fog, particularly in February and November), whereas Cu clouds tend to develop at 13 h UTC.

b) The fractional cover of the sky on sea breeze days is lower than TCC measured in non sea breeze events and all days for the 6-yr study period. The t-test confirms an annual significant difference at the 95% level ($\alpha = 0.05$) in the mean values of TCC among the four categories, particularly on a month-to-month basis, between sea breeze days and non sea breeze days at the 99% ($\alpha = 0.01$) significance level. Sea breeze episodes show a significant ($\alpha = 0.05$) evolution of diurnal TCC, as mean monthly values gradually increase from 07 h UTC until 18 h UTC, particularly in April, May and June. We detected the evolution of non-diurnal TCC for the non sea breeze days.

c) We also observed Cb clouds in the SBCZ (higher relative frequencies occur in May and September) in the observational field campaigns, but their differences are not statistically significant for a significance level of $\alpha = 0.05$. Cb clouds can be observed at 13 and 18 h UTC. These convergence lines can be very intense and develop large banks of clouds, causing rain and even severe thunderstorms in inland zones. The convection is not deep enough on the coast for clouds to develop due to the advection of cool sea air by the low-level sea breeze circulation. Banks of Sc clouds associated with sea breezes are typically seen on the top of many coastal and inland mountain ranges at the end of the day. We also detected a secondary effect on high clouds (Ci, Cc and Cs), but also on medium and low level clouds in relation to thunderstorm clouds in the SBCZ.

As a result of the climatic-environmental impacts of sea breezes and clouds, the results presented in this study are of great scientific interest and provide a good basis for other future research projects. For instance, orographic fog occurrence (Stratocumulus clouds) associated with sea breezes determine water collection potential over the mountain ranges near the Mediterranean coast (Estrela *et al.*, 2008). On the other hand, clouds associated to sea breeze development may have an impact on the photochemistry that drives ozone formation; these effects of clouds should be taken into account in photochemical models used for air quality assessment.

Although the major findings of the present study are site-specific, they should be similar for other coastal locations. However, cloud formation associated with sea breezes is also influenced by geographical-physical, meteorological, hydrological and oceanic factors (Carnesoltas, 2002; Azorin-Molina and Chen, 2008). Therefore, there is a need for further research to compare surface cloud observations from coastal and inland stations throughout the Iberian Mediterranean area and on the Balearic Islands, as well as in other areas, in order to validate these initials results.

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