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Research Article

Unveiling the Thermo-Hygrometric Influence of Summer Sea and Estuarine Breezes (SEBs) in Lisbon (Portugal)

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Local wind, such as sea breezes, play a crucial role in cooling coastal cities. This study presents new insights about the thermo-hygrometric influence of the Tagus and Atlantic Ocean breezes (sea and estuarine breezes [SEBs]) in Lisbon's urban climate (Portugal). SEB events were identified in the summer of 2022 according to a wind rotation criterion: the interruption of prevailing North and Northwest (Nortada) winds during the morning, the wind shift to Northeast/East/Southeast and, sometimes, to further South/Southwest/West (rotation between 22.6° and 292.5°) and the return of the regional flow at late afternoon. Additionally, air temperature and absolute humidity anomalies ($\Delta T/\mathrm{Ha}_{\mathrm{urb}}$) were calculated according to the distance to the riverfront area. Results show that SEB occurred on 37 (31%) out of 120 days, mainly in July (43%) and August (32%), between, on average, 10:00 AM and 4:00 PM, and average wind speeds of 3.4 m/s. According to the daily thermo-hygrometric cycle, the areas up to 4 km of the Tagus estuary were, on average, cooler than northern Lisbon during SEB events, especially the areas up to 500 m (average ΔT_{urb} reached −1.7°C). Additionally, there was a significant increase in the moisture content during SEB hours across the city but especially close to the riverfront area: the areas up to 500 m registered, on average, $\Delta \mathrm{Ha}_{\mathrm{urb}}$ of 4.2 g/m^3 on SEB events (12:00 PM) against 2.1 g/m^3 during typical Nortada days. This research is a starting point for a future delimitation and preservation of SEB penetration zones in Lisbon to address outdoor thermal discomfort during summer.

Keywords: air temperature; humidity; Lisbon; local wind systems; sea breezes; urban climate

1. Introduction

The proximity of large water bodies such as lakes, rivers, and oceans has been historically an attraction factor for the establishment of densely populated settlements [1]. Today's megacities like New York, Tokyo, Shanghai, Rio de Janeiro, Cairo, and Sidney are perfect examples of these human preferences motivated by strategic reasons (trade, transportation, communication, tourism, access to resources, etc.).

Sea, lake, and estuarine breezes (herein after called "sea and estuarine breezes" or SEBs) are a mesoscale atmospheric phenomenon in which local wind systems are initiated by temperature and, consequently, atmospheric pressure differences between the water surface and the adjacent land areas [2–5]. This happens because as the sun rises, the land's surface warms more quickly than the water's surface. This effect is particularly pronounced in urban areas, which trap a significant amount of solar radiation. The differential heating creates a horizontal pressure gradient from the water (ocean, river, or sea) to the land. Consequently, an inland flow of cooler and moister air occurs [6–11]. SEB replace temporarily the regional wind systems and can increase the humidity levels and reduce air temperatures in coastal urban areas, alleviating the urban heat island (UHI) effect (difference between the air temperature inside an urban area and the corresponding temperature in the countryside—[9]) and the thermo-physiological discomfort associated with strong heat conditions [12–18]. This is especially relevant considering that SEBs are more frequent during the summer season [7, 13, 19, 20]. According to Khan and Simpson [21], Simpson et al. [22], and Ma et al. [23], the UHI effect may promote an early onset by several hours and intensification of the SEB. On the other side, the urban structure with a generally increased surface roughness may weaken the intensity of these thermally induced wind systems. Hence, the SEB's duration, penetration, and effectiveness in the improvement of the urban environment depend on an array of local and regional environmental factors such as geographical (topography, coastal morphology, hydrology) and meteorological conditions (atmospheric stability, synoptic circulation), land surface properties and urban form [16, 24].

SEBs have been extensively studied in coastal cities of the Mediterranean region, such as Alicante, located in the Levant region of Spain [12, 20, 25, 26]. The authors examined its atmospheric features, main characteristics (onset time, mean wind speed and direction, time of cessation, duration, mean wind path, etc.), and degrees of persistence and developed a multi-year climatology of the SEB using a semi-hourly wind speed and direction database. The results showed that the SEB in Alicante usually occurs between 12 and 13:00h UTC (Coordinated Universal Time), coming mostly from E during spring and summer, and their intensity range from 3.6 to 11.6 m/s, but the mean wind speed at the time of the passage of the SEB fronts is quite low (2.07 m/s—[12]). Additionally, Azorín-Molina and Martín-Vide [25] found that the high levels of persistence of the SEB in Alicante during summer are related to the synoptic regional conditions (weak surface pressure gradient, anticyclonic circulation, intense solar radiation, and clear skies) and topographic features (relatively flat terrain close to the coast—[20]).

However, the effect of SEB on the local climate of coastal cities from the Iberian Atlantic coast, such as Lisbon, located in the vicinity of the Tagus estuary and the Atlantic Ocean, is still insufficiently known, especially considering its cooling potential. In the 1980s, Alcoforado produced a preliminary analysis about the occurrence of Tagus breezes in Lisbon during summer using hourly wind, temperature, and relative humidity data between 1959 and 1977 [27]. Later on, these SEBs were further characterized (frequency of occurrence, penetration pattern, regional wind thresholds, SEB triggering conditions, etc.) and modeled [7, 28]. In 2010, Baltazar conducted several mobile measurements (wind, temperature, and humidity) in Lisbon in order to define the mean penetration area of SEB. Despite that, the full spectrum of the influence of SEB in Lisbon's local climate, considering the recent urban expansion, has yet to be examined. Moreover, according to [20] and Peng et al. [29], an important aspect of the sea-breeze is the extent to which it penetrates inland and its influence on the thermal and hygrometric features of inland areas. Recently, several urban climate guidelines were established for Lisbon, in which the preservation of the wind paths is crucial [30]. Thus, there is also a need for a deep understanding of SEB causes and penetration patterns [7].

Therefore, the purpose of this investigation is to characterize the thermo-hygrometric influence of the Tagus breezes using a mesoscale meteorological network of 80 weather stations recently installed in Lisbon covering the full range of land cover and land use schemes (local climate zones or "LCZ"—[31]).

2. Study Area

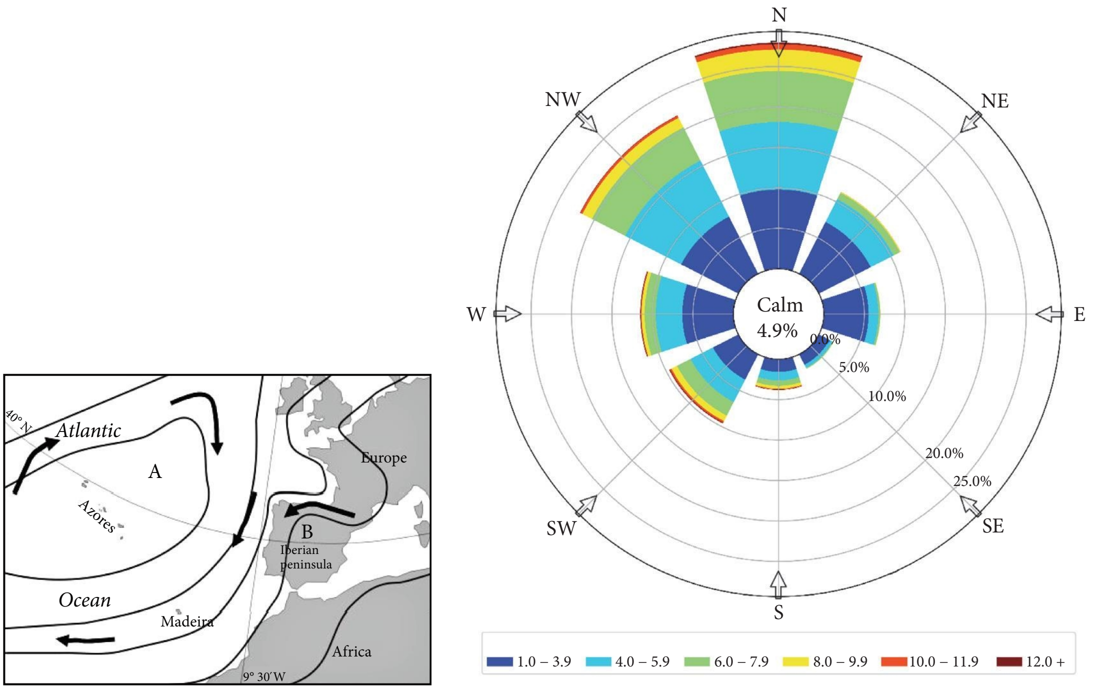
Lisbon, Portugal (38° 43′N; 9° 9′W—Figure 1), is a coastal city with a temperate climate (Köppen Geiger classification of "Csa," according to [32]), positioned on the southwestern extremity of the Iberian Peninsula. The combined influence of the proximity of two large water bodies (the Tagus estuary and the Atlantic Ocean) shaped its local climatology characterized by hot and dry summers and moderate and humid winters, even though several hills stand between this urban area and the ocean: Sintra hill at 30 km West with 500 m; at Northwest, Carregueira hill; at South, Almada hills on the opposite margin of the Tagus estuary and the Monsanto forest hill (about 200 m) already inside the Lisbon's western urban area [27]. Often named the "city of the seven hills," Lisbon's unique topography includes four main valleys in the South and a large plateau in the North, considering that there are no major changes in elevation and the maximum altitude is only 226 m at the Monsanto hill [33, 34].

Lisbon's wind regime is characterized by a high frequency of North and Northwest flows ("Nortada") on a yearly basis (Figure 2), even though there is a large seasonal variability [30, 34]. During winter, North and Northeast winds occur on 27% of days, while Southwest and South winds are prevalent on 29% of days [36]. This may be explained by the occurrence of Southwest perturbations and the Northeast and East trajectory of cold and dry air masses. From March onward, Northwest and North winds become more frequent [30]. In summer, Nortada occurs on 70% of days during the afternoon, with average wind speeds above 4.2 m/s on 27% of these days. On 45% of the summer days, it blows continuously all day [27].

These North and Northwest winds are associated with a strong surface pressure gradient generated between the Azores anticyclone and a thermal low above the Iberian Peninsula [34, 35]. Still, in summer, cool, and humid SEB coming from the Tagus estuary and/or the Atlantic Ocean interrupt the daytime temperature increase, mainly on the riverfront area and along the streets perpendicular to the Tagus estuary, promoting a more thermally comfortable urban environment in those areas [27, 34, 37]. According to previous studies, these SEBs occur on 30% of summer days when the Nortada flow is weak, especially in August, and are associated with the interruption of this regional flow and a rotation in the directional component of wind [7, 27, 28, 33–35]. Additionally, the unusual shape of the Tagus

(B)

Figure 1: (A) Geographic map of Lisbon and (B) Lisbon's mesoscale meteorological network. Chelas station (no. 50) is highlighted. AWS, airport weather station. See Table S1 with the identification of each measuring site.



(A) (B)

Figure 2: (A) Surface synoptic circulation favorable for the occurrence of North winds in Portugal (A—anticyclone; B—depression; bold arrows—flow direction; adapted from Alcoforado et al. [35]) and (B) windrose plot for Lisbon (airport weather station/AWS—see Figure 1), between 3rd January 1931 and 20th December 2023.

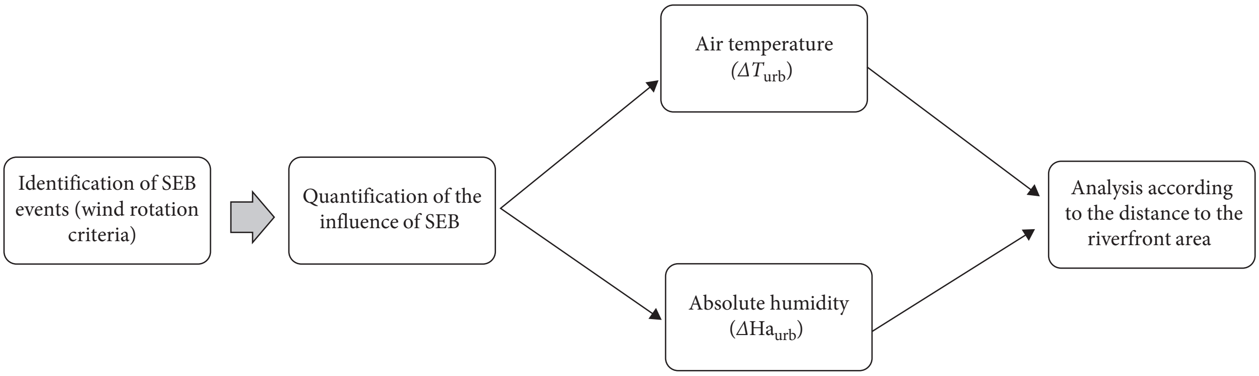


Figure 3: Analysis of the thermo-hygrometric influence of sea breezes in Lisbon's summer climate: scheme. SEB, sea and estuarine breeze.

estuary surrounding this city, with an area of over 300 km^2, promotes the channeling of maritime air masses coming from the Atlantic Ocean through a very narrow "throat" at the estuary's mouth. In the late afternoon, Nortada is reestablished with an increase in wind speed and air temperature and a decrease in the moisture content [27]. On non-SEB days with the prevailing Nortada regime, the riverfront area of Lisbon is generally hotter due to the shelter effect favored by the recent urban expansion to the north [7, 34].

3. Materials and Methods

This study focuses on the influence of local winds, such as those coming from the Atlantic Ocean and the Tagus estuary, on Lisbon's summer climate conditions. Hence, the methodology adopted can be divided into three main phases (Figure 3): the identification of SEB events based on several mandatory wind rotation criteria, followed by the calculation of air temperature and absolute humidity anomalies ($\Delta T/\mathrm{Ha}_{\mathrm{urb}}$) to a reference station and the analysis of those differences according to the distance to the riverfront area.

3.1. SEB Identification Method

3.1.1. Mesoscale Meteorological Network. In this study, SEB events were analyzed with a mesoscale network of 80 stations installed across Lisbon in 2021 (Figure 1). The sensors are mainly located on illumination pols at approximately 3.5 m

Table 1: Meteorological network in Lisbon: number of stations per LCZ.

LCZ[a]	**No. of stations**
1 (compact high-rise)	1 (2%)
2 (compact midrise)	16 (20%)
3 (compact low-rise)	8 (10%)
123 (compact mix-rise)	1 (2%)
4 (open high-rise)	1 (2%)
5 (open midrise)	3 (4%)
6 (open low-rise)	7 (9%)
8 (large low-rise)	17 (21%)
10 (heavy industry)	1 (2%)
A (dense trees)	3 (4%)
B (scattered trees)	5 (2%)
C (bush/shrub)	1 (2%)
D (low plants)	7 (9%)
E (bare rock or paved)	9 (11%)

Abbreviation: LCZ, local climate zones.

[a] LCZ refers to local climate zones created by Stewart and Oke (2012) and recently updated for Lisbon by Oliveira et al. [38, 39]. In this case, LCZ is representative within a 100 m range.

height, measuring air quality, traffic, and meteorological parameters (atmospheric pressure, relative humidity, wind, precipitation, air temperature, global and ultraviolet [UV] radiation) every 15 min. In the case of temperature, wireless thermometers were installed with a precision of ±0.5°C and a resolution of 0.1°C. Hourly means are calculated and provided. Tables S2–S8 present a detailed characterization of every measuring site (geographical location, urban morphology parameters, and data gaps). Table 1 represents the distribution of meteorological stations in Lisbon according to the LCZ scheme.

Air temperature (°C) and relative humidity (%) records are available for all measuring sites, but wind speed and direction are only registered in two locations (ID 7—*Santa Apolónia*; ID 50—*Chelas*). For the identification of SEB events, only *Chelas* station was used as a reference due to its geographical proximity to *Cabo Ruivo* weather station, previously used by Alcoforado [27] and *Cabeço das Rolas* weather station used by Vasconcelos [7] in previous studies about Lisbon's SEB, but also due to its proximity to the riverfront area and low urban density (Table S5). This station is located on a relatively open area (LCZ 8) about 1 km from the riverside, particularly a street orientated with the prevailing Nortada regime in Lisbon (from Northwest to Southeast), with low urban density (average building height of 9 m) and several trees. Wind records at *Santa Apolónia* station were neglected due to its position inside of a high urban-density canyon. Additionally, these local wind systems were only analyzed during the thermal summer of 2022 (11th June to 8th October—[40]) since it is the first complete summer with data from this meteorological network. This thermal summer season refers to a new seasonal division recently designed for Lisbon based on the annual cycle of maximum and minimum temperatures [40].

3.1.2. Identification Criteria and Thermo-Hygrometric Influence. In previous studies, the main identification criteria usually included the analysis of wind speed and direction patterns, land-sea temperature and pressure gradients, synoptic conditions, and physical processes associated with these local wind systems (Azorín—molina and Martín-Vide 2006) [12, 13, 26, 41–43]. In a study about the degree of persistence in the SEB in Alicante (Spain), Azorín-Molina and Martín-Vide [25] used the change in wind direction (approximately between 120° and 180°) and speed (over 1.5 m/s) during the day as the criterion to assure that the synoptic regional conditions were stable and the difference between the land-sea temperature was positive. Later, in a study about the influence of summer SEB on thermal comfort in Funchal (Madeira island), Lopes et al. [13] considered two criteria: the change in wind direction (sea-land) after sunrise, necessarily oppositive to the general wind on top of the mountain (Pico do Areeiro) and the identification of a thermal difference of 1°C between a station on Funchal marine (Pontinha) and a Museum, inside of the city.

In the case of Lisbon, the previous identification of SEB events encompassed an analysis of the daily wind directional rotation component [7]. Thus, SEB occurred when the wind regional circulation is shut down [27]. The SEB identification criteria considered in this study were adapted from Vasconcelos [7], who considered an SEB when all the following conditions were observed:

1. During the night and early morning, the surface wind blows usually from North and Northwest;
2. A few hours after the sunrise, it rotates to East or South during the midday and the early afternoon;
3. At the end of the day/late afternoon, the wind returns back to the North and Northwest.

Only 93 (77.5%) out of 120 thermal summer days (11th June to 8th October) were classified according to these criteria due to a lack of wind data at *Chelas* station. However, about 96% of the missing wind records at this station are concentrated in September (between 5th and 28th). Hence, hourly wind direction records between 22.6° (Northeast) and 292.5° (West) registered at this weather station on days with the above-mentioned conditions were considered SEB events. In contrast, the days whose first two criteria are met but there is no wind shift back to North or Northwest at the end of the day were not considered SEB days, although on some, the SEB might appear. Additionally, days where North and Northwest winds are prevalent of most hours of the day were classified as typical Nortada days. Figure 4 shows an example of a typical SEB day in Lisbon.

In addition to the diurnal changes of wind speed and direction, SEB events are accompanied by a temperature drop and a humidity rise [5, 6, 15]. According to Alcoforado [27], SEB can be analyzed from their effects, namely the air temperature and humidity differences ("anomalies") to a reference site. As a result, the thermo-hygrometric influence of SEB in Lisbon's climate was examined in this study. For

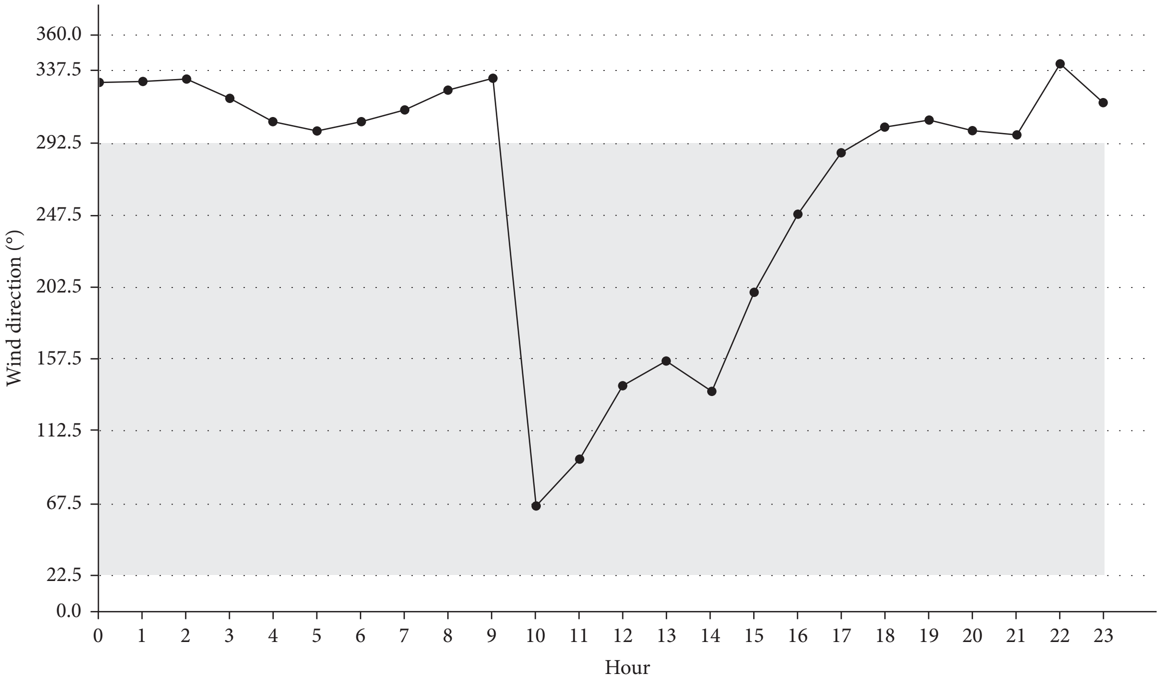


FIGURE 4: Wind rotation at *Chelas* weather station on 2nd July 2022. The shaded area indicates typical wind directions during SEB events. SEB, sea and estuarine breeze.

every measuring site of the mesoscale meteorological network, hourly air temperature ($\varDelta T_{\mathrm{urb}}$) and specific humidity ($\varDelta \mathrm{Ha}_{\mathrm{urb}}$) anomalies were calculated according to the following equation:

$$\varDelta T/\mathrm{Ha}_{\mathrm{urb}} = T/\mathrm{Ha}_{\mathrm{urb}} - T/\mathrm{Ha}_{\mathrm{aws}}, \tag{1}$$

where $\varDelta T/\mathrm{Ha}_{\mathrm{urb}}$ refers to hourly mean air temperature (T—°C) or absolute humidity (Ha—$\mathrm{g/m^3}$) anomaly; $T/\mathrm{Ha}_{\mathrm{urb}}$ refers to hourly air temperature (T—°C) or absolute humidity (Ha—$\mathrm{g/m^3}$) records on each of the 80 measuring sites and $T/\mathrm{Ha}_{\mathrm{aws}}$ refers to hourly air temperature (T—°C) or absolute humidity (Ha—$\mathrm{g/m^3}$) records from the Lisbon's airport weather station (AWS).

Considering the hygrometric component, absolute humidity was calculated using air temperature and relative humidity records for every measuring site, according to Vaisala [44] equation:

$$A = C \cdot Pw/T(\mathrm{g/m^3}), \tag{2}$$

where C refers to the constant 2.16679 gK/J, Pw refers to the vapor pressure in Pa, and T is the air temperature in K.

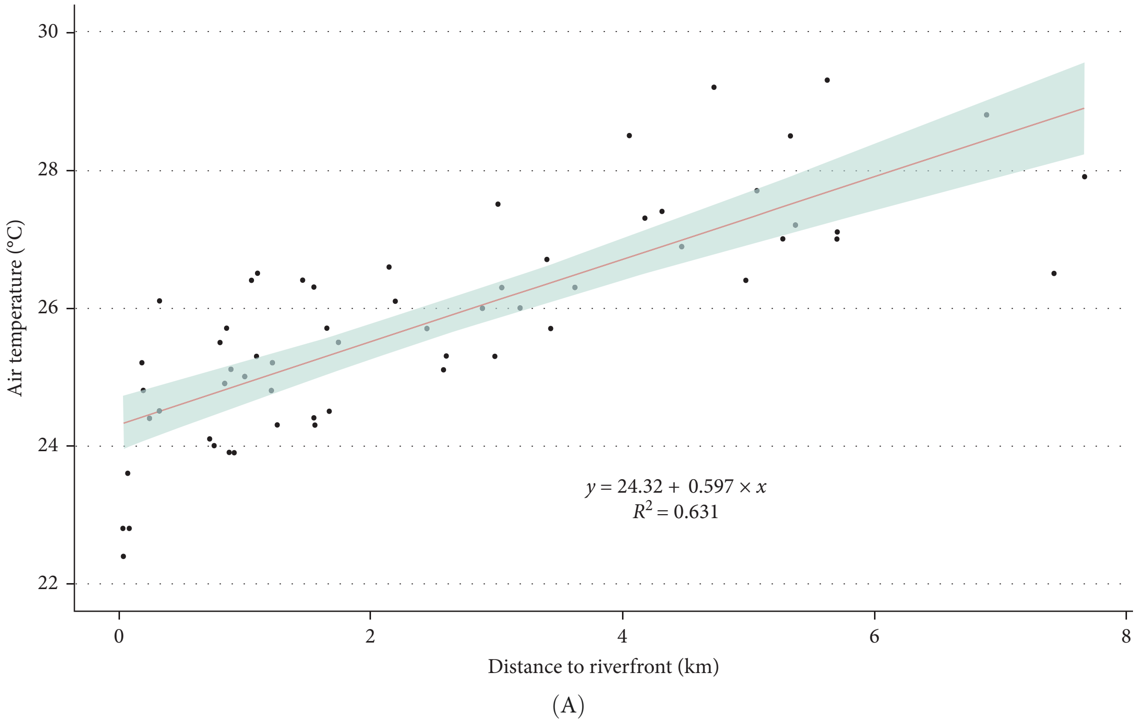
Since the thermo-hygrometric influence of SEBs shows a direct relationship with the inland penetration (Figure 5), all measurement locations were aggregated according to the distance to the riverside (Table 2), and the hourly average $\varDelta T/\mathrm{Ha}_{\mathrm{urb}}$ was calculated according to these distances for the Nortada and SEB days. In the case of air temperature, the determination coefficient shows that about 63% of the variation in air temperature in Lisbon during breeze days can be explained by the distance to the riverfront. Additionally, according to Figure 5A, there is a linear increase with the distance from Lisbon's riverside, averaging 0.6°C per kilometer. In contrast, the relationship between distance from the riverside and absolute humidity is stronger (the proximity/distance to the riverfront explains about 87% of the variation of humidity during breeze days) and resembles a logarithmic pattern: humidity levels drop sharply up to around 500 m (from 19 to $15\,\mathrm{g/m^3}$). Beyond this point, the humidity decreases more slowly, by about $3\,\mathrm{g/m^3}$, up to 7 km from the riverside.

3.2. Local Weather Types (LWTs).

SEBs are triggered by thermal differences between the land and the water surface on a particular set of meteorological conditions. According to Lopes et al. [13] and Jia et al. [3], SEBs occur mostly on clear days with strong atmospheric stability and no significant synoptic wind. Particularly in Lisbon, they are associated with the occurrence of high air temperatures and no regional flow, which are favorable conditions for strong thermo-physiological discomfort associated with heat [7]. On the other hand, on days with continuous strong winds, SEBs are not easily detected [34].

In this study, daily meteorological conditions whose SEB events occurred were classified according to different LWTs recently produced for Lisbon by Reis et al. [40, 45]. These summer LWTs include:

- Mild, cloudy, and humid days with light rain and moderate NW winds;
- Mild, sunny, and humid days with moderate NW and N winds;



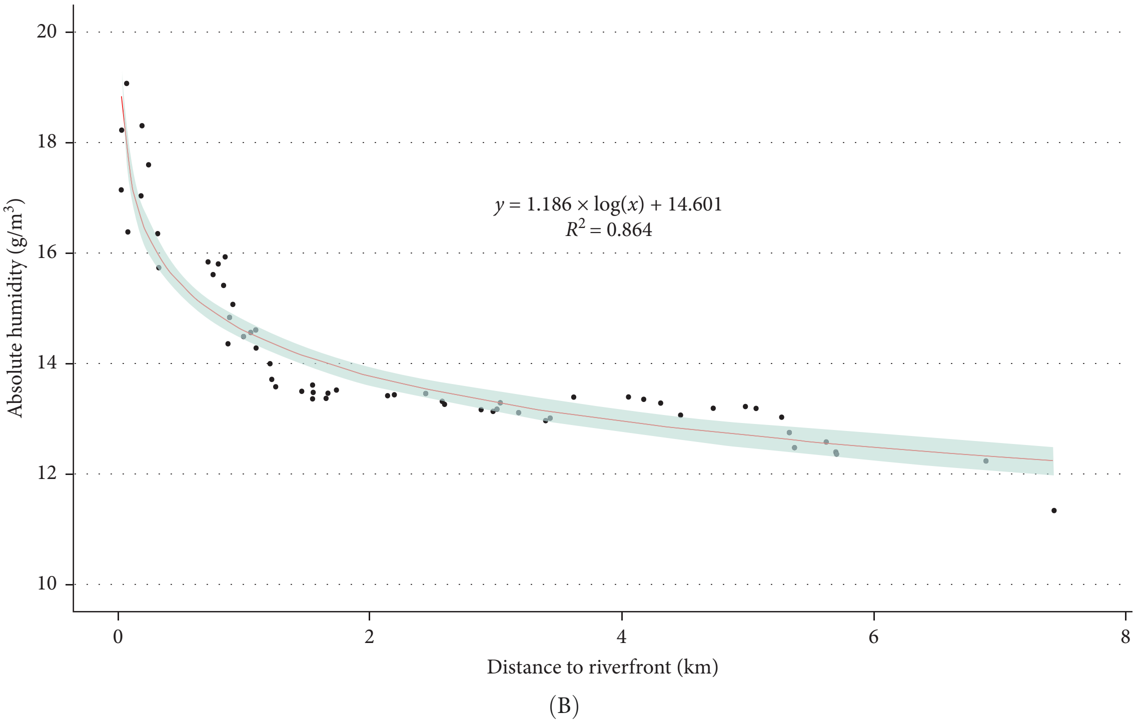


FIGURE 5: Direct relationship between air temperature (A), absolute humidity (B), and distance to Lisbon's riverfront area during breeze days (average conditions—2022).

TABLE 2: Distribution of meteorological stations in Lisbon according to the distance to the riverfront.

Distance to riverfront	No. of stations
0–500 m	11
500 m–1 km	11
1 –1.5 km	8
1.5–2 km	9
2–2.5 km	5
2.5–3 km	4
3 km–4 km	8
4–5 km	10
5–6 km	9
6–7 km	3
7–8 km	2

- Mild, sunny, and humid days with strong N winds;
- Hot, sunny, and humid days with moderate N winds and;
- Very hot, sunny, and humid days with moderate N winds.

For that, daily air temperature, specific humidity, total precipitation, wind speed and direction, and cloud cover data from the AWS (Figure 1) and ERA5 and ERA5-Land reanalysis were compared with average meteorological conditions of each LWT presented by Reis et al. [45] and, then, the frequency of SEB events per LWT was calculated.

4. Results and Discussion

4.1. SEB Events in Lisbon. This section presents the results about the occurrence of SEB in Lisbon during the summer of 2022, their distribution per months (Figure 6), LWTs (Figure 7), and their wind speed thresholds (Figures 8 and 9).

SEB in Lisbon occurred on 37 days (31%), with a total of 258 h, while typical Nortada days were registered on 29 days (24%). However, 29 (24%) out of 120 thermal summer days were not classified (missing wind records), and 25 days (21%) revealed different wind conditions, which include regional South and West fluxes (18%) and variable winds (3%). Vasconcelos [7] registered a total of 112 SEB days in Lisbon between the summers of 2002–2004 (15th June to 15th September), with 460 SEB hours.

Figure 6 displays the frequency of SEB, Nortada, other circulation, and unclassified days per month.

SEB occurred mostly in July (16 out of 37 days—43%) and August (12 days—32%). However, it should be noted that 26 out of 30 September days were not classified, and in June and October, only 20 and 8 days, respectively, belong to the thermal summer season. In previous studies, Vasconcelos [7] registered a higher occurrence of SEB events in August (30%), followed by June (25%).

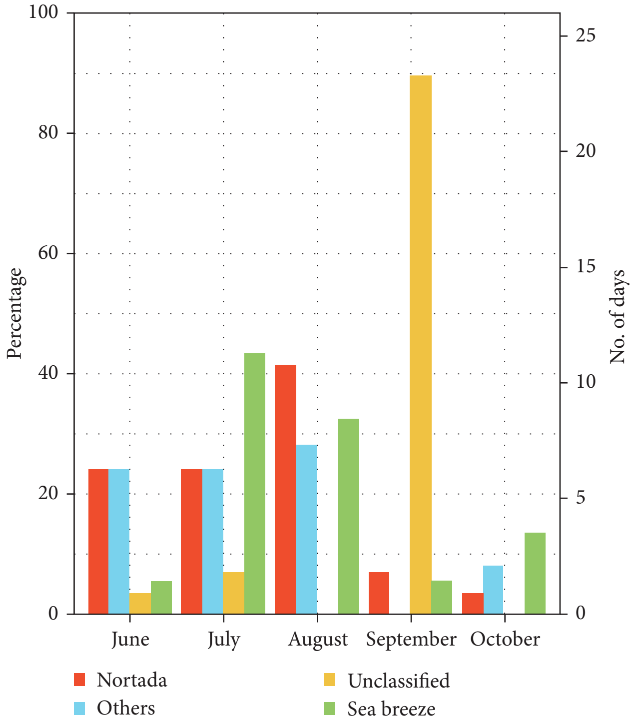


FIGURE 6: Frequency of occurrence of SEBs, Nortada, others, and unclassified days per month in Lisbon (2022). SEBs, sea and estuarine breezes.

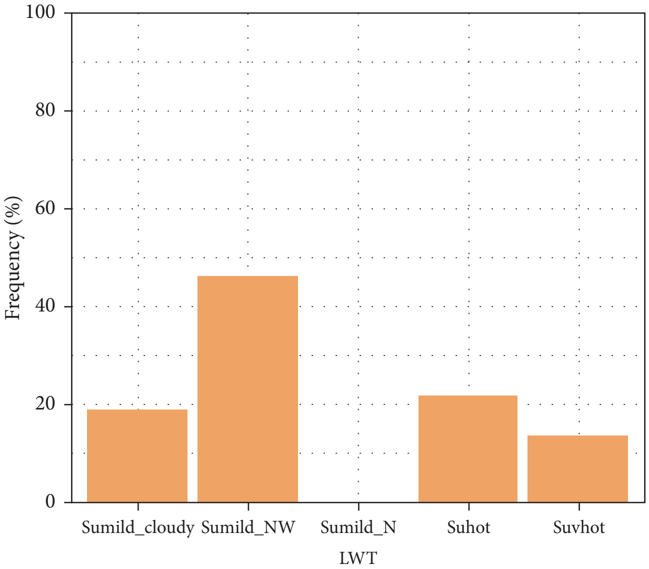


FIGURE 7: Frequency of SEBs by LWTs in Lisbon (2022). This set of meteorological conditions was recently summarized by Reis et al. [40, 45]. LWTs, local weather types; SEBs, sea and estuarine breezes.

On average, SEBs started at 10:00 AM, lasted 6 h, and were replaced by the regional flow (Nortada) at approximately 4:00 PM. However, SEB that rotated only to East (Northeast/East and, sometimes, Southeast) lasted, on average, 3 h, while SEB that rotated to East and, then, to South and West lasted 8 h. Alcoforado [27] identified three different SEB regimes: on 8% of days wind blows from the East in the early afternoon, then rotates to the Southeast and, sometimes, South; on 11% of days, North and Northeast

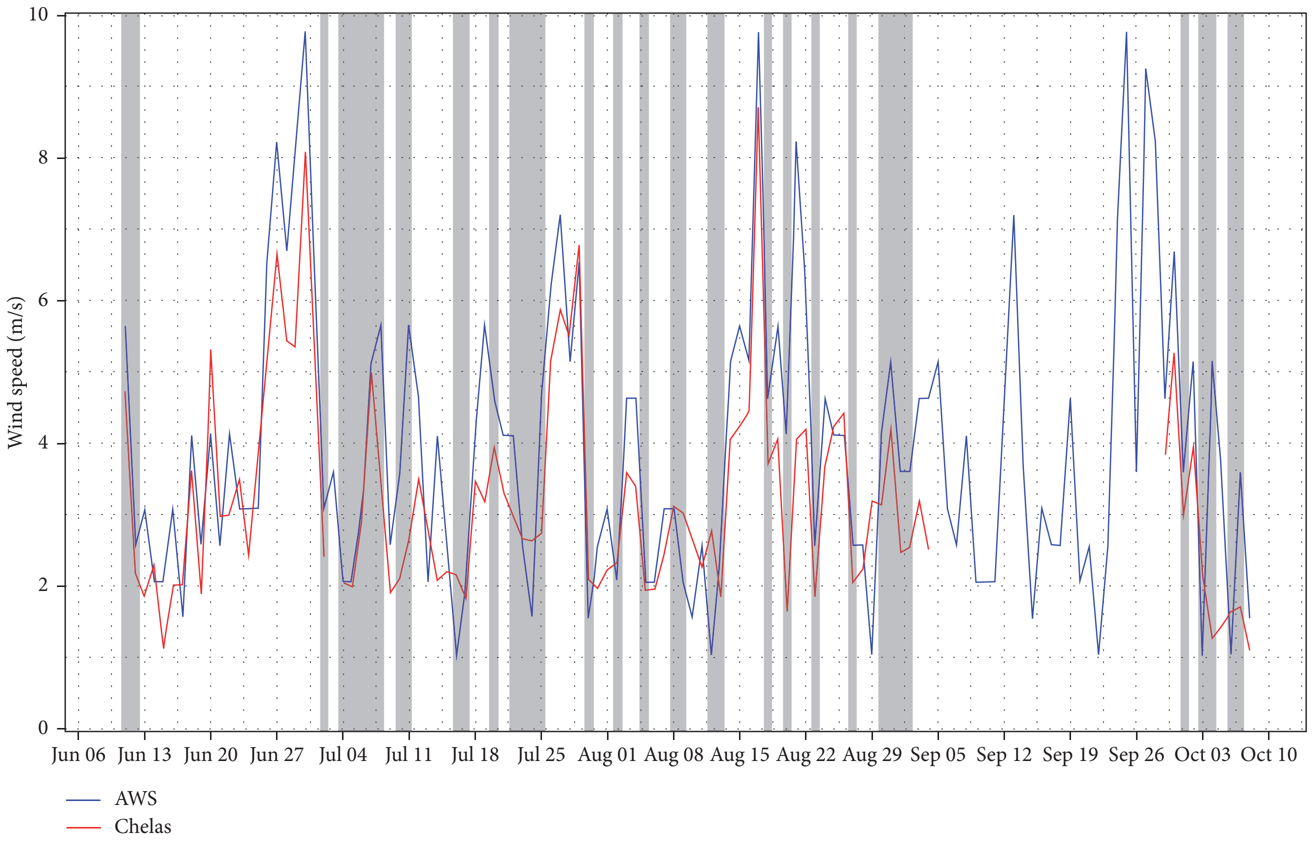


FIGURE 8: Wind speed (m/s) at 10:00 AM during the thermal summer of 2022, recorded at *Chelas* and Lisbon's AWS. Light gray areas highlight SEB events. AWS, airport weather station; SEB, sea and estuarine breeze.

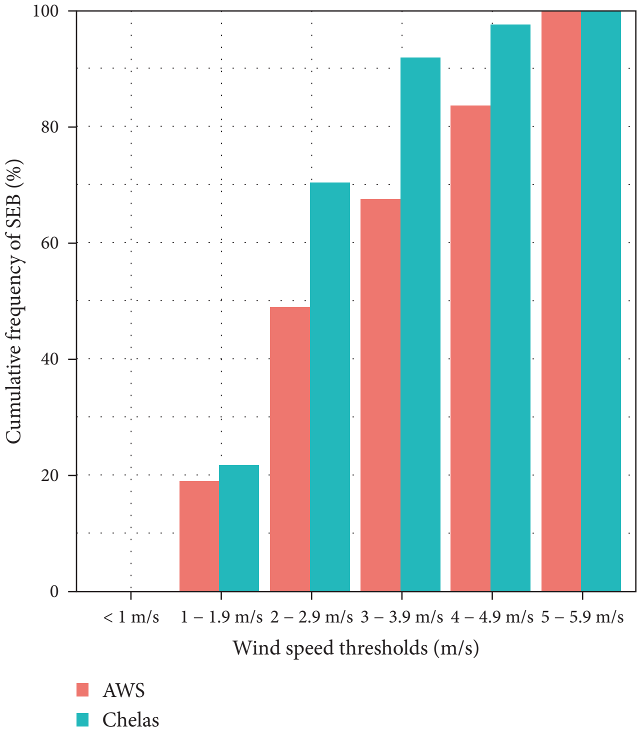


FIGURE 9: Cumulative percentage of SEB events per wind classes at *Chelas* and Lisbon's AWS (2022). AWS, airport weather station; SEB, sea and estuarine breeze.

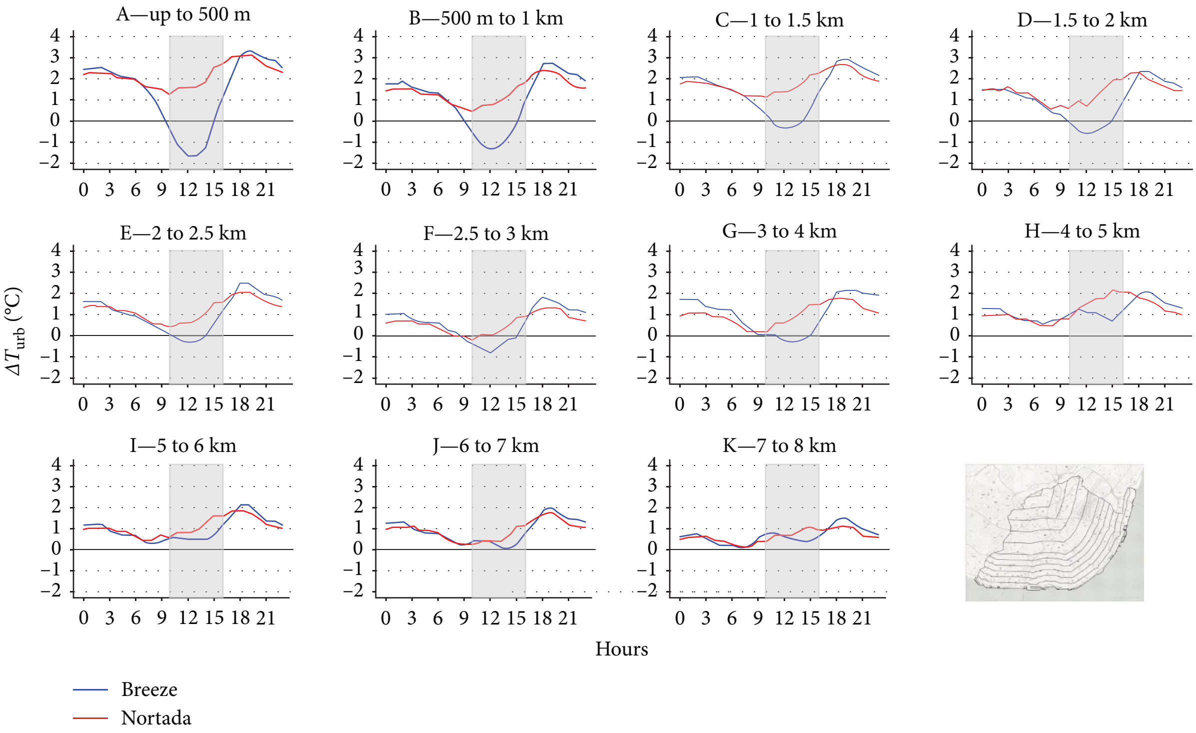


Figure 10: Hourly average air temperature anomalies (ΔT_{urb}) on SEB days and Nortada days according to the distance to the riverfront area (2022). Dark gray areas highlight the average breeze period (10:00 AM–4:00 PM). Linear distances to Lisbon's riverfront are depicted on the map. SEB, sea and estuarine breeze.

winds rotate toward the Southeast and; and the remaining 11% of days, SEB can rotate from North, East or Southeast to Southwest and West in the late afternoon. In 2006, Vasconcelos detected a 56% occurrence of East/Southeast/South/Southeast SEB regimes, followed by a 34% occurrence of East/Southeast and a 10% occurrence of Northeast/East SEB. According to the author, the SEB penetration ability depends on these different SEB regimes, and the rotation pattern East/Southeast/South/Southwest usually persists for a longer period with a more pronounced cooling effect (lower temperatures and higher humidity levels) that can be partially explained by a possible penetration of Atlantic Ocean breezes.

Figure 7 displays the frequency of SEB events by LWT.

Almost 50% of the SEB events occurred during mild, sunny, and humid days with moderate Northwest and North winds (Sumild_NW), which are also the most frequent meteorological conditions during the thermal summer (26.1%—[45]), followed by hot, sunny and humid days with moderate North winds (Suhot—22%) and mild, cloudy, and humid days with light rain and moderate Northwest winds (Sumild_cloudy—19%). On these three LWTs, daily average wind speed ranges between 4.5 and 4.8 m/s [45]. On the other hand, no SEB event was identified on mild, sunny, and humid days with strong North winds (SumildN), with daily average wind speeds of 7.5 m/s [40]. Hence, there might be a wind speed threshold that inhibits the development of SEB. Figure 8 displays wind speed (m/s) at 10:00 AM (identified as the most frequent onset time of the SEB according to this study and Vasconcelos [7] during summer recorded at both *Chelas* and the AWS. All SEB occurred with wind speeds below 6 m/s at the AWS (on average, 3.4 m/s) and up to 5 m/s at *Chelas* station (on average, 2.9 m/s).

Figure 9 exhibits the cumulative percentage of SEB per wind classes (m/s) at both weather stations. Almost 50% of the SEB events occurred with regional winds below 3 m/s (AWS) and this percentage increases to 70% at *Chelas*. Considering regional winds below 4 m/s, this percentage increases to 68%, while in *Chelas* increases to 92%. These findings are consistent with Vasconcelos [7] work, who also recorded a cumulative frequency of 50% for SEB events with regional winds equal to or less than 3 m/s and a frequency of 78% for winds equal to or less than 4 m/s.

4.2. SEBs Thermo-Hygrometric Patterns.

In this section, the influence of SEB on air temperature (Figures 10 and 11) and absolute humidity (Figure 12) in Lisbon is presented and discussed, considering the distance to the riverfront area.

Figure 10 displays the average daily cycle of ΔT_{urb} on Nortada and SEB days according to the distance to Lisbon's riverfront area. Upon first look, there is a distinct daily thermal pattern similar to the daily UHI cycle, and this pattern is more pronounced on SEB days. In Lisbon, the UHI daily cycle was described by Oliveira et al. [46], who defined six stages, and analyzed by Reis et al. [45] according to different LWT:

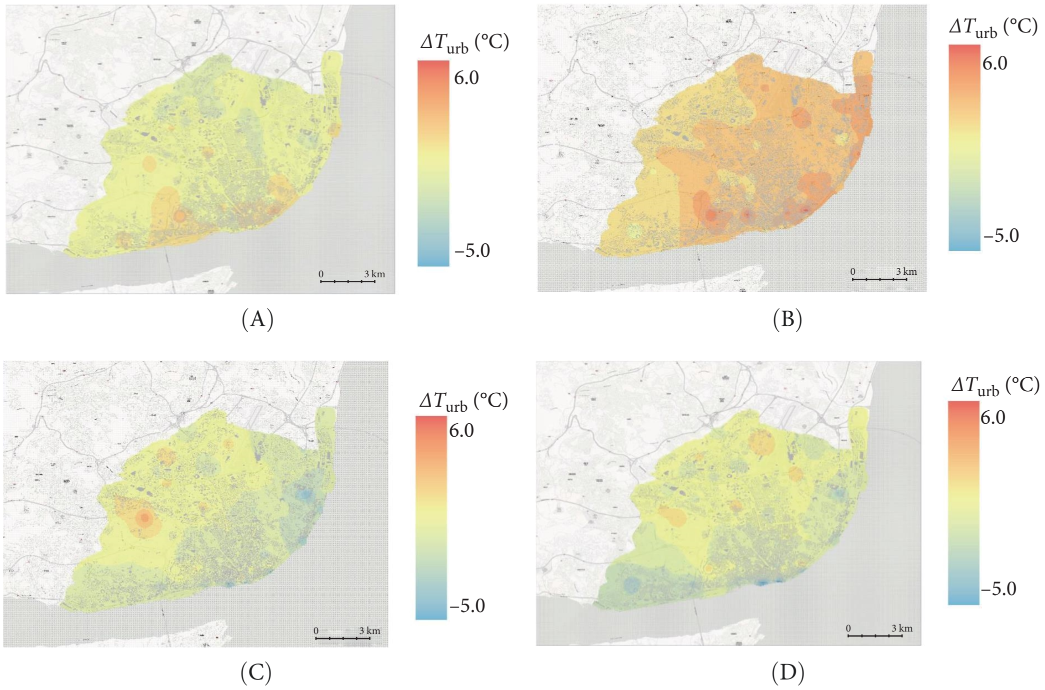


Figure 11: Hourly average air temperature anomalies (ΔT_{urb}) during SEB events in Lisbon (2022): (A) at 8:00 AM (Nortada), (B) at 11:00 AM (breeze), (C) at 2:00 PM (breeze), and (D) at 6:00 PM (Nortada). SEB, sea and estuarine breeze.

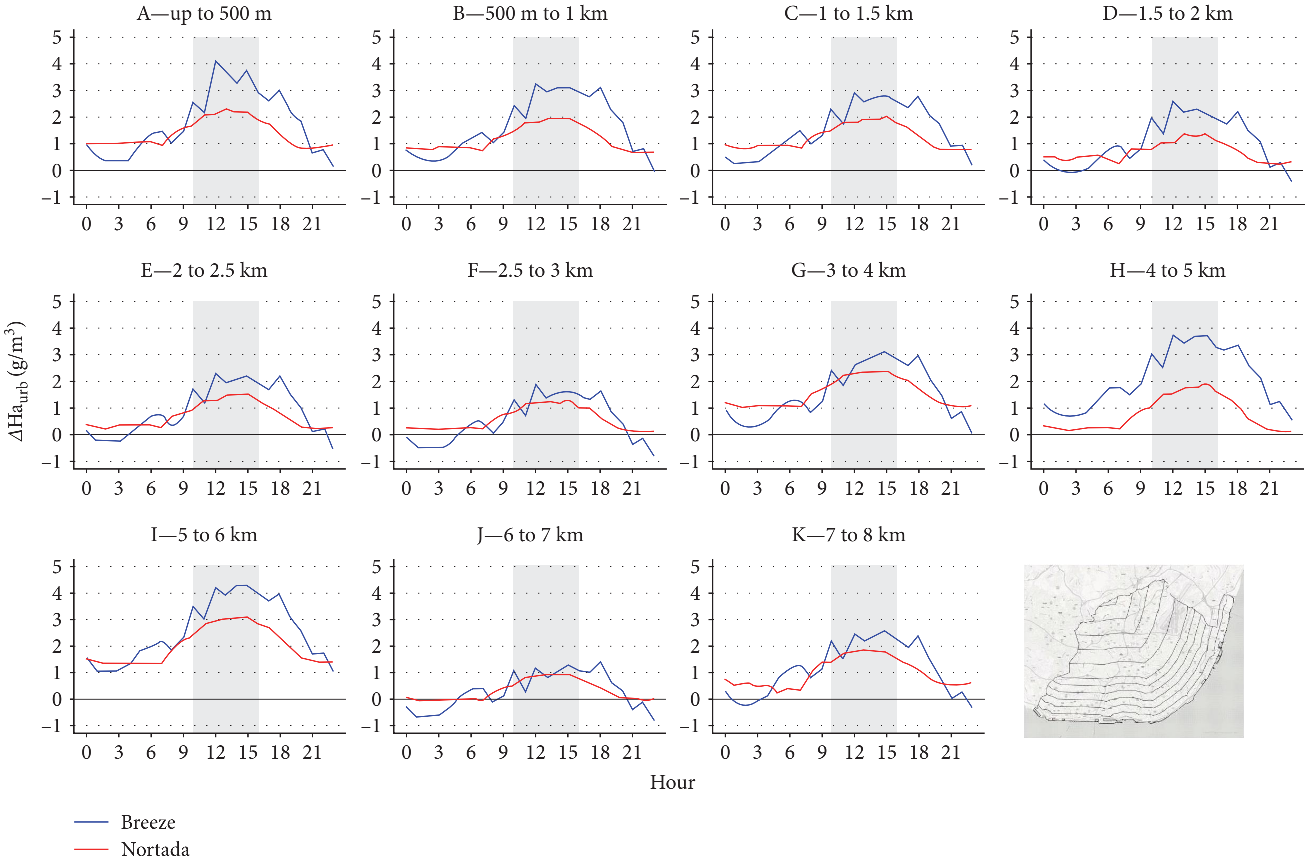


Figure 12: Hourly average absolute humidity anomalies (ΔHa_{urb}) on SEB days and Nortada days according to the distance to the riverfront area (2022). Dark gray areas highlight the average breeze period (10:00 AM–4:00 PM). Linear distances to Lisbon's riverfront are depicted on the map. SEB, sea and estuarine breeze.

- During the nighttime period, the UHI effect is positive and stable. Likewise, on both Nortada and SEB days, the nighttime ΔT_{urb} is positive and more pronounced close to the riverfront area. For instance, the areas up to 500 m registered a ΔT_{urb} of 3.0°C at 9:00 PM during SEB events and of 2.6°C during Nortada days, while the areas from 7 to 8 km registered an average ΔT_{urb} of 1.0 and 0.7°C during SEB and Nortada days, respectively; as the sun rises, there is an abrupt decrease of the UHI intensity with minimum values between 10:00 AM and 11:00 AM (typical SEB onset time).

This sharp decrease is also observed on the ΔT_{urb} during SEB events but only in areas up to 4 km, while during Nortada periods, the differences between diurnal and nocturnal ΔT_{urb} are less pronounced, regardless of the distance to the riverfront area. For instance, on areas up to 500 m, from 6:00 to 10:00 AM during SEB days, the ΔT_{urb} decreases 2.0°C and becomes negative (from 2.0 to −0.5°C), while on Nortada days, during the same period, the descent is of only 0.6°C (from 1.9 to 1.3°C).

- The average minimum ΔT_{urb} during SEB days is registered between 11:00 AM and 2:00 PM. Additionally, up to 4 km, on SEB days, the average ΔT_{urb} is negative during the typical SEB duration period, which indicates the southern half of Lisbon is cooler than the AWS (located on the northern part of the city);
- From 1:00 PM forth, the UHI intensity increases strongly and reaches its maximum in late afternoon/early evening (7:00–8:00 PM). The same signature is observed on average ΔT_{urb} during SEB days and up to 4 km from the riverfront area.
- For instance, up to 500 m, the ΔT_{urb} increases 5°C, on average, from 1:00 PM to 7:00 PM (from −1.7 to 3.3°C), while on the same period, this increase is of only 1.0°C on the northern borders of Lisbon (7–8 km). Considering Nortada days, there is an increase of 1.5°C (from 1.6 to 3.0°C) in areas up to 500 m and an increase of 0.5°C in areas between 7 and 8 km.

Hence, during SEB events, the areas closest to the Tagus estuary (up to 500 m) can be, on average, 1.7°C cooler than the northern part of Lisbon, while during Nortada days are usually 1.6°C hotter. In contrast, from 4 km onward, the ΔT_{urb} are consistently positive on both SEB and non-SEB days, although during the SEB hours, they are slightly lower.

Vasconcelos [7] only compared the thermo-hygrometric pattern on SEB days between two locations, a previous weather station located in the eastern part of Lisbon (relatively close to current station no. 80—Expo) and a weather station located on the northern part of the city (School of Arts and Humanities, University of Lisbon) but depicted a similar daily cycle. The author found that on non-SEB days, the difference between the two locations was weak (usually below 0.5°C), while on SEB days, the riverfront area was, on average, 3.5°C cooler than the N of Lisbon. In a study about the role of SEB on temperature, comfort, and pollution levels during heat wave events in several Greek regions, Papanastasiou et al. [47] found that the SEB development caused a decrease of approximately 4°C from maximum temperature during the summer of 2007. Recently, Zhou et al. [24, 43] proposed and tested in Adelaide (Australia) a method to quantify the cumulative cooling ability of SEB events and its inland penetration distance. Their results showed that it takes 67 min on average for the SEB cooling fronts to penetrate inside the metropolitan area of Adelaide, and its mean cooling penetration distance ranges between 29 and 42 km along the prevailing wind path. Additionally, during the penetration process, the SEB cooling capacity decreased at a rate of 0.7 and 0.9°/h/km from coast to inland on an average SEB day and a hot SEB day, respectively [24]. The multiple linear regression analysis performed by the authors indicated that the distance from the coast and elevation at the onshore point together explain 88% of the spatial variability of the temporally average SEB cooling capacity in the study area.

Figure 11 presents the spatialization (linear interpolation) of the average ΔT_{urb} during SEB days: during the morning period (8:00 AM) with prevailing Nortada winds, throughout the SEB event (11:00 AM and 2:00 PM) and in the late afternoon (6:00 PM). Short after the sunrise (8:00 AM), the warmest urban canyons are concentrated in the downtown districts of Lisbon [48], close to the riverfront area due to the barrier effect of prevailing Nortada winds caused by the city's expansion toward the North.

However, this scenario is inverted immediately after the arrival of the SEB (11:00 AM), and the rise gradual rise of air temperatures is partially slowed down on the southern half of Lisbon, especially the eastern riverfront area (since North/Northwest winds rotate first to Northeast/East/Southeast). If these local wind systems rotate further to South/Southwest/West, which happened on 59% of SEB days, the cooling effect is even more pronounced on the western riverfront area of the city because of the most probable channeling of SEB from the Atlantic Ocean into the Tagus estuary.

Finally, at 6:00 PM, shortly after the SEB average cessation time (4:00 PM), the ΔT_{urb} resembles the one during the morning before the SEB event, but with even more pronounced positive differences to the AWS due to high absorption of solar radiation during the daytime period by urban surfaces whose heat is about to be released to the streets (UHI effect).

Regarding the hygrometric component, Figure 12 shows the $\Delta \mathrm{Ha}_{\mathrm{urb}}$ also according to the distance to the riverfront area. The daily cycle of $\Delta \mathrm{Ha}_{\mathrm{urb}}$ seems to be the opposite of that of UHI and ΔT_{urb}: despite the average differences being always positive during the night (except during SEB days for areas between 1.5 and 3 km and 6–8 km), the minimum values are registered during this period and, as the sun rises, the moisture content increases drastically, especially on the closest areas to the Tagus estuary (up to 1 km) and on areas between 4 and 6 km. Hence, maximum ΔT_{urb} is recorded during the typical SEB hours. Additionally, the difference between ΔT_{urb} during SEB and Nortada days, mainly between 10:00 AM and 4:00 PM, is positive, and it decreases as the distance to the riverfront area increases. Thus, during

SEB days, the areas up to 500 m can be, on average, 4.2 g/m^3 more humid than the AWS, while during Nortada days, this positive difference falls to half. In contrast, for instance, on areas between 6 and 7 km, the average maximum $\Delta \mathrm{Ha}_{\mathrm{urb}}$ on SEB and Nortada days is only 1.2 and 0.8 g/m^3, respectively. However, the decrease of the hygrometric differences SEB/Nortada with the increase of distance to the Tagus river is not linear. Actually, the average maximum hourly $\Delta \mathrm{Ha}_{\mathrm{urb}}$ is registered on areas between 5 and 6 km during SEB days at 2:00 PM (4.3 g/m^3). Moreover, there is an increase in the moisture content of air masses, especially in areas between 5 and 6 km, followed by areas between 4 and 5 and 3 and 4 km, which happens on both Nortada and SEB days.

This might be explained by the proximity of some weather stations to medium and large urban green spaces, particularly the Monsanto Forest Hill on the western part of Lisbon (station no. 25—*Parque Ecológico*, between 4 and 5 km), the Gulbenkian's Garden at the city center (station no. 37—*Praça de Espanha*, between 3 and 4 km), and two green parks at north of the city, close to stations no. 53 (*Rua Alferes Malheiro*, between 3 and 4 km) and 73 (*Rua Lúcio Azevedo*, between 5 and 6 km).

The urban green spaces cooling effect, mostly known as the Park Cool Island (PCI) effect, has been extensively studied in several cities due to its contribution to the improvement of the local climate conditions, especially outdoor thermal comfort [9].

Thus, during the SEB days, there is a significant increase in the moisture content of air masses, especially in the areas close to the Tagus river. Previously, Vasconcelos [7] compared the hygrometric profile in terms of relative humidity on SEB and non-SEB days in two locations (riverfront area vs. north Lisbon). The author's results showed that the eastern riverfront area of Lisbon was always more humid than the northern part of Lisbon. However, on SEB days, the riverfront area registered an increase of more than 25% in moisture content compared to the station located in the School of Arts and Humanities.

In an attempt to clarify the influence range of sea breezes in Sendai (Japan) using a Weather Research and Forecasting (WRF) model, Peng et al. [29] concluded that the effect of sea breezes on temperature was only concentrated within 5 km of the coast and this cooling effect was not significant in urban and inland areas. However, in terms of moderating the temperature rise, the authors found an effect within 7 km from the coast. Additionally, in terms of humidity, the effect of sea breezes occurred approximately 1 h later than the effect of temperature and reached the inland area. In Lisbon, the sea breezes effect on both temperature and humidity is quite concentrated on the riverside, probably due to the prevalence of high urban density areas that partially block the progression of the local winds.

5. Conclusions

This study assessed the influence of SEB events on air temperature and humidity summer patterns in Lisbon using a large meteorological network recently installed across the city. The SEB events were defined according to a wind rotation criterion from a weather station located in the eastern area of the city (relatively close to the Tagus river—no. 50 *Chelas*), and the daily average $\Delta T/\mathrm{Ha}_{\mathrm{urb}}$ were analyzed according to the distance to the riverfront area. Results showed that SEB occurred on 37 thermal summer days (31%), mainly in July and August (43% and 32%, respectively), with average winds of 3.4 m/s registered at the AWS. These local wind systems lasted, on average, 6 h (from 10:00 AM until 4:00 PM), but if the wind rotated further to S/SW/W, the average duration time increased to 8 h due to the channeling of Atlantic Ocean air masses into the estuary. Additionally, SEBs occurred in different meteorological conditions, from mild to very hot days, except for summer days with strong North winds (daily average wind speeds of 7.5 m/s).

Concerning the daily thermo-hygrometric cycle, the areas up to 4 km from the estuary were always cooler than the northern part of the city during SEB events (negative ΔT_{urb}), especially the areas up to 500 m that registered an average ΔT_{urb} of −1.7°C at 1:00 PM during SEB days and 1.6°C on typical Nortada days. In contrast, from 4 km onward, the ΔT_{urb} is consistently positive on both SEB and non-SEB days, and the SEB cooling effect is almost nonexistent. Also, a significant increase in the moisture content was registered, mostly close to the riverfront area: the areas up to 500 m were, on average, 4.2 g/m^3 more humid than the AWS, while during Nortada days the $\Delta \mathrm{Ha}_{\mathrm{urb}}$ was of only +2.1 g/m^3.

Nevertheless, it is important to mention the possible underestimation of SEB events, mainly because the days in which the Nortada flow is replaced with East/South/West winds but there is no return of the regional wind at late afternoon were not considered. Moreover, this large mesoscale meteorological network is only functioning since the midsummer of 2021, so the amount of data to consolidate these findings is low, and there are significant air temperature and relative humidity data gaps on several weather stations. Still, the identification of SEB events was solely based on a single weather station (*Chelas*) located in the eastern part of the city whose results, despite corroborating previous studies in Lisbon, might be biased. Future work is needed to validate these findings, especially the estuarine maximum penetration areas which are crucial for the preservation of wind corridors. Hence, this original thermo-hygrometric study is a starting point to a subsequent assessment of the SEBs influence on outdoor thermal comfort levels across Lisbon, a valuable information for urban planning and design, especially considering the expansion of the city and the development of new urban canyons.

Data Availability Statement

The data that support the findings of this study are available from Lisbon City Hall. Restrictions apply to the availability of these data, which were used under license for this study. Data are available at https://www.lisboa.pt/cidade/ambiente/alteracoes-climaticas upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. (*Supporting Information*) Lisbon's mesoscale meteorological network (ID and designations—Table S1; location, altitude, urban morphology parameters and data gaps—Tables S2–S8).

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