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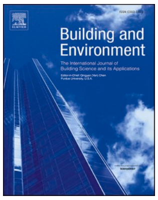

Modeling the influence of summer sea and estuarine breezes on heat stress in Lisbon (Portugal) using GRAMM-SCI

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ABSTRACT

In this study, the influence of the Tagus river and Atlantic Ocean breezes in a Mediterranean city (Lisbon) on outdoor thermal comfort was analyzed during the thermal summer days. Hourly wind fields were modeled using the GRAMM-SCI software, initialized with ERA5 reanalysis data. The Universal Thermal Climate Index (UTCI) was calculated for 80 weather stations across the city. Additionally, the UTCI anomalies (ΔUTCI) relative to a reference site (the airport weather station) were calculated during breeze and non-breeze events (typically N/NW winds). Results showed that sea breezes can reduce UTCI levels by up to 2,2° C during typical breeze days and up to 5,1° C during heatwave breeze events. The effect of these breezes on heat stress conditions is felt up to 4 km from the Tagus river, but especially on the areas up to 500 m. However, in 50 % of the cases where no thermal stress was recorded at the airport during breeze events, Lisbon's riverfront can be more uncomfortable (moderate heat stress) than the northern part of the city (from 2 to 8 km). Additionally, cooling effect of the breezes is only significant enough to cause a transition to a more comfortable UTCI class (especially from very strong to strong heat stress and from strong to moderate heat stress) during heatwaves (strong to very strong heat stress) and on areas up to 1,5 km from the estuary. The promotion of wind corridors is, therefore, crucial to insuring the progression of sea breezes in urban areas and to reduce heat stress.

1. Introduction

Sea and estuarine breezes are local wind systems driven by thermal differences that often develop during summer and interact with the urban environment, alleviating thermal stress in cities located near large water bodies. This natural ventilation occurs due to temperature differences between sea and land surfaces since the large heat capacity of water prevents its rapid heating during the day, while the urban surfaces and materials trap and absorb a significant amount of solar radiation [1–6].

Recently, research on the influence of sea breezes and their role in reducing air temperature and, especially the mitigation of Urban Heat Island effect (UHI) has been boosted across several coastal cities [7–12]. Ribeiro et al. [11] investigated the influence of sea breezes propagation on the development of urban boundary layer (UBL) in the Metropolitan Region of São Paulo Region (Brazil - Köppen classification of "Cfa", according to [13]). According to the authors, in both winter and summer, the passage of the sea breeze front disrupted the convective growth of the UBL and also the UHI circulation. The UHI further increased the thermal gradient (from 0,5 K to 2,0 K in summer and 1,0 to 2,5 K in winter), accelerating the sea breeze propagation [11]. Recently, Yang et al. [12] examined the day and nighttime differences in UHI, considering different local climate zones (LCZ- [14]) and sea breezes and concluded that this local ventilation system alleviated the UHI effect (linear correlation coefficient of −0,69 between them).

Nevertheless, the influence of sea breezes on heat stress is still poorly

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investigated. Papanastasiou et al. [15] studied the impact of these breezes on temperature, aerosol levels and on the inhabitants' thermal stress on the east coast of central Greece. The authors calculated three human biometeorological indices: Thom's discomfort index (RSI), Relative Strain Index (ESI) and Environmental Stress Index (ESI) on a breeze day and a non-breeze day during the summer of 2007. Lopes et al. [16] investigated the interactions between sea breezes and regional winds and their influence on heat stress in Funchal (Madeira island - Köppen classification of ”Csa”). The authors calculated Physiologically Equivalent Temperature (PET) for a sample of days during the summer of 2006. Later, Anjos et al. [17] explored the relationship between sea breeze fronts and PET in a mid-size city in northeastern Brazil (Sergipe - Köppen classification of ”Aw”). In a compact high-rise area of coastal Sydney (Australia - Köppen classification of ”Cfa”), He et al. [9] investigated the relationships between urban morphology, ventilation, UHI and outdoor human thermal comfort (PET). The study assessed precinct ventilation performance and its relationship with urban morphology, urban heat islands, and relative humidity, focusing on the role of sea breezes as a cooling mechanism in densely built environments. Recently, Wang et al. [18] studied the contrasting effects from urbanization and sea breezes on summer heat stress (Heat Index, wet-bulb temperature and Wet-bulb global temperature) over the Chicago metropolitan area (United States - Köppen classification of ”Dfa”).

The promotion and preservation of ventilation corridors/paths has been defended as one of the most effective indoors and outdoors heat mitigation and air quality strategies [19–22], promoting the so called “wind-sensitive” urban planning and design [9]. Palme et al. [23] evaluated the overheating risk of a small house in 4 South American cities (Guayaquil - Köppen classification of ”Aw”; Lima - Köppen classification of ”BWn”; Antofagasta - Köppen classification of ”BWh”; and Valparaíso - Köppen classification of ”Csb”) and the natural ventilation capacity to cool down residential buildings. The authors concluded that the UHI effect will reduce the capability of natural cross ventilation to evacuate heat in the order to 20–30 % in the cases of Valparaíso and Guayaquil. Hence, they suggested a better consideration of building dimensions and orientation, in order to increase the cross ventilation within the urban fabric, and the restriction of the height of buildings in the first coastlines, where sea breezes are more effective and can penetrate the urban tissue.

In Lisbon, the natural ventilation conditions have worsened over the past decades due to the aggressive expansion of the urban tissue [24]. As a consequence, the thermal environment and, particularly, the heat stress conditions were negatively affected on areas with high urban density levels such as the downtown area and the riverfront. Understanding and quantifying this impact will contribute to improving the efficiency of urban planning and design processes, thereby fostering the development of climate-resilient communities.

Hence, the main purpose of this research is to assess the influence of sea and estuarine breezes on an heat stress index, the Universal Thermal Climate Index (UTCI – a Fiala Energy Balance Model), in a Mediterranean coastal city, Lisbon (Portugal). This urban area has an increasingly hot and dry summer and current heat stress conditions are already unpleasant (strong heat stress during the hottest summer days – [25]), but will become extremely uncomfortable during this century (strong to very strong heat stress – [26]). More specifically, the goal is to answer the following questions:

- What is the maximum penetration area of sea breezes during the summer period (heatwave and non-heatwave events)?
- Considering the impacts upon the associated UTCI physiological stress scale, what is the intensity of the cooling effect of these breezes?

2. Materials and methods

2.1. Study area

Lisbon is a city covering 84 km^2 with approximately 547,000 inhabitants [27]. This urban area is situated on the western coast of the Iberian Peninsula, facing the Tagus Estuary(E, SE and S), and with the influence of the Atlantic Ocean at W (Fig. 1). The Tagus estuary is the biggest in Western Europe with an area between 300 and 350 km^2, depending on the tide levels. Although it can reach several tens of kilometers in width at its maximum extent, the estuary's mouth is very narrow, forming a "throat" where the air masses coming from the Atlantic Ocean are channeled inland.

Lisbon's geographic position favors a temperate climate (Köppen Geiger classification of “Csa”), with mild, rainy winters and a hot, dry summer season that has been extending into autumn. [29].

According to Lopes et al. [30] the number of summer days at Lisbon's peninsula will increase between 13 and 16 days by the middle of this century (2041–2070) according to RCPs 4.5. and 8.5, respectively, and between 14 and 27 by the end of the century (2071–2100).

The topographic scenery is characterized by the presence of four main valleys south and a large plateau north, even though altitude ranges only between sea level (at the riverfront area) and 226 m on the Monsanto forest hill, located on the western part of the city [31].

Regarding Lisbon's built environment, most of its urban fabric is considered a mid-rise continuum (about 69 % classified as low urban density, moderate aerodynamic roughness, low compacity and low volumetry – [32,33]), and the area occupied by high-rise buildings is proportionally smaller. According to Oliveira et al. [34], only 4 % of Lisbon's municipal territory corresponds to LCZs 1 (Compact high-rise) and 4 (Open-high-rise), while LCZs 2 (Compact midrise), 3 (Compact low-rise), 5 (Open midrise) and 6 (Open low-rise) represent 33 % of the area. Nevertheless, the city's expansion towards north caused a 30 % reduction of the surface summer wind speed until the eighties of the 20th century and it is estimated a 40 % reduction of wind speed above buildings if the aerodynamic roughness increases from 0,02 m to 1,5 m windward of the city [16].

Lisbon's annual wind regime is characterized by a high frequency of N and NW winds (“Nortada”) throughout the year. During summer, Nortada blows continuously on about 45 % of days [35]. On the other hand, sea breezes form on the Tagus estuary during the morning period and reach Lisbon's riverfront area, reducing air temperatures and improving heat stress. These breezes have been investigated in Lisbon since 1987 [21,26,35–37]. By utilizing a recently installed mesoscale meteorological network consisting of 80 weather stations, Reis et al. [26] analyzed sea and estuarine breezes during the thermal summer of 2022 and concluded that these local winds occur on about 37 % of days, mainly in July and August, usually start at 10:00AM and last about 6 h with average wind speeds of 3,4 m/s. Additionally, their influence on the reduction of air temperature is notable up to 4 km of the riverfront, but mostly on the first 500 m where the average maximum difference between breeze and Nortada days is about −1,7 °C [26].

2.2. Wind modeling in Lisbon: Gramm-Sci mesoscale model and validation of results

One of the determinant factors of outdoor heat stress is the surrounding atmospheric conditions that include air temperature, humidity, global radiation and wind. Hence, a comfortable thermal environment is extremely important to the enjoyment of public spaces [38]. In 2021, a mesoscale meteorological network with 80 weather stations was installed by the municipality of Lisbon.

However, only 2 stations have continuous wind speed and direction measurements, one located on the eastern part of the city, relatively close to the Tagus estuary (“Chelas”), and the other one located on the downtown riverfront area (“Santa Apolónia”). Chelas station was

Fig. 1. A: GRAMM-SCI (Graz Mesoscale Model-Scientific – [28]) wind prognostic modelling domains (domain 1 – dashed black line; domain 2 – solid black line; domain 3 – red area, referring to C); B: Tagus estuary; C: Lisbon's built environment and urban greenery. AWS – airport weather station. Chelas – meteorological station used as reference site by recent studies about the occurrence of breezes in Lisbon [26]. Tagus – Tagus river. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recently used for the identification of breeze events during the thermal summer of 2022 [26]. Since this wind data is insufficient to calculate heat stress conditions across the city with good precision, wind speed and direction were modeled utilizing the prognostic mesoscale model GRAMM-SCI for a sequence of Nortada and sea breeze days (Table 1).

Hence, this sequence incorporates 1 day with prevailing Nortada winds and 6 sea and estuarine days, considering that the last breeze day (08–07–2022) coincides with the beginning of an heatwave event, according to Excessive Heat Factor (EHF), a measure of heatwaves intensity based on three-day-averaged daily mean temperatures [39,40] recently calculated for Lisbon.

GRAMM-SCI is a new branch of the public and open source version of GRAMM 20.01 and is being developed by the Regional Government of Styria, Austria [28]. This non-hydrostatic mesoscale model is capable of

Table 1
Wind modeling in Lisbon: time span and general meteorological conditions.

Date	Wind classification[1]	Average air temperature (°C)[2]	ΔT(°C)[3]	Average wind speed (m/s)[2]
01–07–2022	Nortada	20,3	−3,9	6,3
02–07–2022	Breeze	21,9	−2,3	4,3
03–07–2022[4]	–	20,8	−3,4	3,4
04–07–2022	Breeze	20,2	−4,0	3,0
05–07–2022	Breeze	20,8	−3,4	3,7
06–07–2022	Breeze	22,5	−1,7	3,8
07–07–2022	Breeze	28,9	4,7	4,2
08–07–2022	Breeze	32,1	7,9	4,4

[1] Nortada and sea breeze days were previously classified by Reis et al. [26].

[2] 24 h average air temperature and wind speed were calculated from Lisbon's airport weather station (10m height).

[3] ΔT represents the deviation of average diurnal temperatures for the month of July 2022 (airport weather station).

[4] This day was not classified due to a lack of hourly wind direction records at the Chelas station.

calculating high-resolution meteorological wind fields in highly complex terrains by solving the Reynolds-Average-Navier-Stokes (RANS) equations as well as the prognostic equations for potential temperature, humidity, and cloud water content [41].

More information about these formulas can be found in Oettl [28].

GRAMM uses an eight-layer soil model for calculating the soil-heat flux, whereby the deep soil/water temperature is taken from ERA5. In the presence of forests, a drag law is applied in the conservation equation for the wind components [42], while the influence of built-up areas - as classified by the CORINE (2018) land cover categories used as input data - are taken into account by adjusting the albedo, emissivity, heat conductivity, and surface wetness [28].

The model incorporates ERA5 (ECMWF Reanalysis 5th generation) reanalysis data, a global climate dataset available since 1940 until today with a spatial resolution of 0.25°. Out of the thousands of atmospheric, ocean-wave and land-surface variables, GRAMM-SCI uses the three Cartesian wind components, air temperature, specific humidity, cloud water content, soil/water temperature, soil wetness, snow depth, as well as low, medium, and high cloud cover provided by ERA5 at certain pressure levels. Cloud and snow cover are used diagnostically to adjust the soil heat flux, albedo and radiation [28].

This mesoscale model has been tested and validated in the past years with robust results. For instance, Oettl [43], Oettl and Bergamin [42] simulated flow fields in highly complex alpine areas in Austria and Switzerland and concluded that GRAMMM-SCI was able to satisfactory reproduce thermally-driven mountain-wind systems as well as lake breezes and their interaction with synoptic-scale flows. GRAMM-SCI has also been evaluated in the frame of a model intercomparison study carried out by Giovanni et al. [44] focusing on thermally-driven winds in the Inn valley (Austria - Köppen classification of ”Cfb”). Recently, Maiwald et al. [45] characterized the GRAMM model performance in Heidelberg (Germany - Köppen classification of ”Cfb”) and found a good agreement between modelled and measured wind fields . According to the authors, wind speeds could be simulated with a root-mean square difference of about 1,0 m/s and a mean bias of about 0,6 m/s.

Additionally, GRAMM model demonstrates strong performance in urban environments due to its adaptability to complex terrains, computational efficiency, and ability to simulate mesoscale wind fields accurately. GRAMM effectively integrates detailed topography and land use data, enabling the generation of stable meteorological fields over large spatial domains and extended time periods, making it a computationally efficient solution for urban studies [46–48]. Its precomputed "catalogue approach" facilitates simulations of various synoptic wind and stability conditions, supporting time-series generation of wind fields and pollutant concentrations with reasonable accuracy [47,49]. Furthermore, GRAMM shows good agreement with observational data, achieving a root mean square difference of approximately 1 m/s for wind speeds, validating its use in challenging urban topographies [47,48]. However, the model has notable limitations. Its mesoscale resolution (100 m) does not capture fine-scale urban features, such as individual buildings or street canyons, requiring coupling with microscale models like GRAL for detailed dispersion analyses [46,47,49]. Additionally, GRAMM's vertical resolution near the ground is insufficient to fully resolve turbulence and mixing processes in urban canopy layers, impacting pollutant dispersion accuracy [48,49]. The model's reliance on steady-state assumptions may lead to inaccuracies in dynamic meteorological scenarios, such as rapidly changing wind patterns [46,49]. Finally, GRAMM's accuracy depends heavily on the quality of input data, with coarse or inconsistent meteorological data reducing its reliability, particularly in areas with limited observational coverage [46,47].

In this study, three nested model domains were set up following the modelling approaches as outlined in Oettl [43], Oettl and Bergamin [42] and Oettl and Reifeltshammer [28] (see Fig. 1; Tab 2): the first one is the largest and forced by ERA5 reanalysis (1h intervals and update on boundary conditions accordingly), in order to capture the regional synoptic flow; the second one is operated in nesting mode, while the third one is run in downscaling mode. Hence, the ERA5 results from the first model are used for initializing and setting the boundary conditions for the nested and downscaled subsequential models [28].

As for the input data, a Digital Surface Model (DSM) with 30 m horizontal resolution covering the entire domain area of the 1° model was combined with buildings information (height) provided by the Lisbon's municipality.

In order to cross and compare wind modelling results with the existing measurements in Lisbon, GRAMM wind fields were extracted for the location of Chelas station (see Fig. 1) and several statistical measures were computed and presented at Table 3.

The modelled wind speed is similar to measured one in minimum and mean values, while maximum values are overestimated by 1,6 m/s. According to the wind speed mean absolute error, the GRAMM model deviates by approximately 1,6 m/s and 38° when predicting wind speed and direction, respectively, compared to the observed records at Chelas station. However, the root mean squared error é quite higher (2,7 m/s and 50°) and might be explained by the coarser spatial resolution of GRAMM results (200 m), that reduce the complexity of the urban tissue, especially at Lisbon's riverside and downtown area (higher urban density levels).

The overestimation of wind speed by GRAMM is also illustrated in Figs. 2 and 3.This overestimation is more prominent at wind speeds between 3 and 6 m/s (Fig. 3). Nevertheless, according to Fig. 2, this mesoscale model effectively captures the high variability of wind speed throughout the entire period.

2.3. Heat stress estimation on breeze days

Several biometeorological indices have recently been employed to evaluate the influence of meteorological variables on heat stress conditions in urban areas. In this study, UTCI was selected and calculated with weather data from Lisbon's mesoscale meteorological network (air temperature and relative humidity) and GRAMM-SCI wind speed outputs (Table 4). More information about this network along with data

Table 2
GRAMM-SCI models description.

	1	2	3
Dimensions (km)	150 × 150	130 × 100	15 × 10
Height of the first model layer (m)	20	20	20
Horizontal resolution (m)	5000	1000	200
Maximum time step (s)	20	5	5
N° vertical layers	40	40	30
Vertical stretching factor	1,14	1,13	1,13
Model top (m)	26,861	20,294	20,294

Table 3
Wind speed and direction statistics according to GRAMM modelling results and Chelas weather station records.

	Wind speed (m/s)		Wind direction (°)	
	Chelas station	GRAMM results	Chelas station	GRAMM results
Minimum	0,3	0,2	–	–
Maximum	6,4	8,0	–	–
Mean	3,2	3,9	–	–
Standard-deviation	1,4	1,8	–	–
Range	6,2	7,7	–	–
Mean Absolute Error (MAE)	–	1,6	–	38
Root Mean Square Error (RMSE)	–	2,7	–	50

gaps during the thermal summer of 2022 can be found in Reis et al. [26].

This index is defined as the isothermal air temperature of the reference condition (air temperature equals Mean Radiant Temperature (MRT); 50 % relative humidity up to a constant water vapor pressure of 20 hPa; metabolic rate of 135 W/m^2) that would elicit in the same dynamic response (strain) of the physiological model as the actual environment been measured [50–52]. UTCI follows the concept of an equivalent ambient temperature (Table 5) and can be easily estimated with a regression equation that is based on a heat transfer model [53–55].

Ranges of physiological stress for UTCI calculation are based upon an internal heat production of 135 W, with the adaptive clothing model as stipulated by Havenith et al. [56].

MRT, required for the UTCI calculation, was estimated on Rayman Pro (v. 3.1 Beta – [57,58]), along with global radiation (W/m$^{2;}$ Table 4). RayMan calculates global radiation automatically based on the geographic coordinates and altitude provided for each point where UTCI was assessed, integrating direct, diffuse, and reflected solar radiation. The model uses solar geometry and atmospheric transmissivity as primary parameters [57,59]. Then, UTCI was calculated on Bioklima software (v. 2.6 – [60]).

2.4. *Influence of sea breezes on summer heat stress*

In order to quantify the influence of sea and estuarine breezes on human biometeorological conditions, hourly UTCI “anomalies” were estimated on each weather station of Lisbon’s mesoscale meteorological network utilizing as reference site, the airport weather station, (Fig. 1), according to the following equation:

$$\Delta UTCI = UTCI_{urb} - UTCI_{AWS} \text{where,} \tag{1}$$

ΔUTCI corresponds to hourly UTCI anomalies on each weather station;

$UTCI_{urb}$ is the hourly UTCI on each site and;

$UTCI_{AWS}$ is the hourly UTCI calculated for Lisbon’s airport weather station.

These ΔUTCI were ordered according to the distance to the riverfront area. Additionally, the ΔUTCI were isolated for heatwave breeze days in order to assess the influence on heat stress during extreme heat conditions.

3. Results and discussion

In Lisbon, sea and estuarine breezes during summer coming from the Tagus estuary and, at times, the Atlantic Ocean often lead to a decrease in air temperature and an increase in the moisture levels during the most thermally uncomfortable period of the day (10:00AM to 4:00PM) on the areas within 4 km from the river [26]. Since these breezes are frequent during days with no regional winds (these often alleviate heat stress across the city - [21]), its cooling effect might be reflected on human

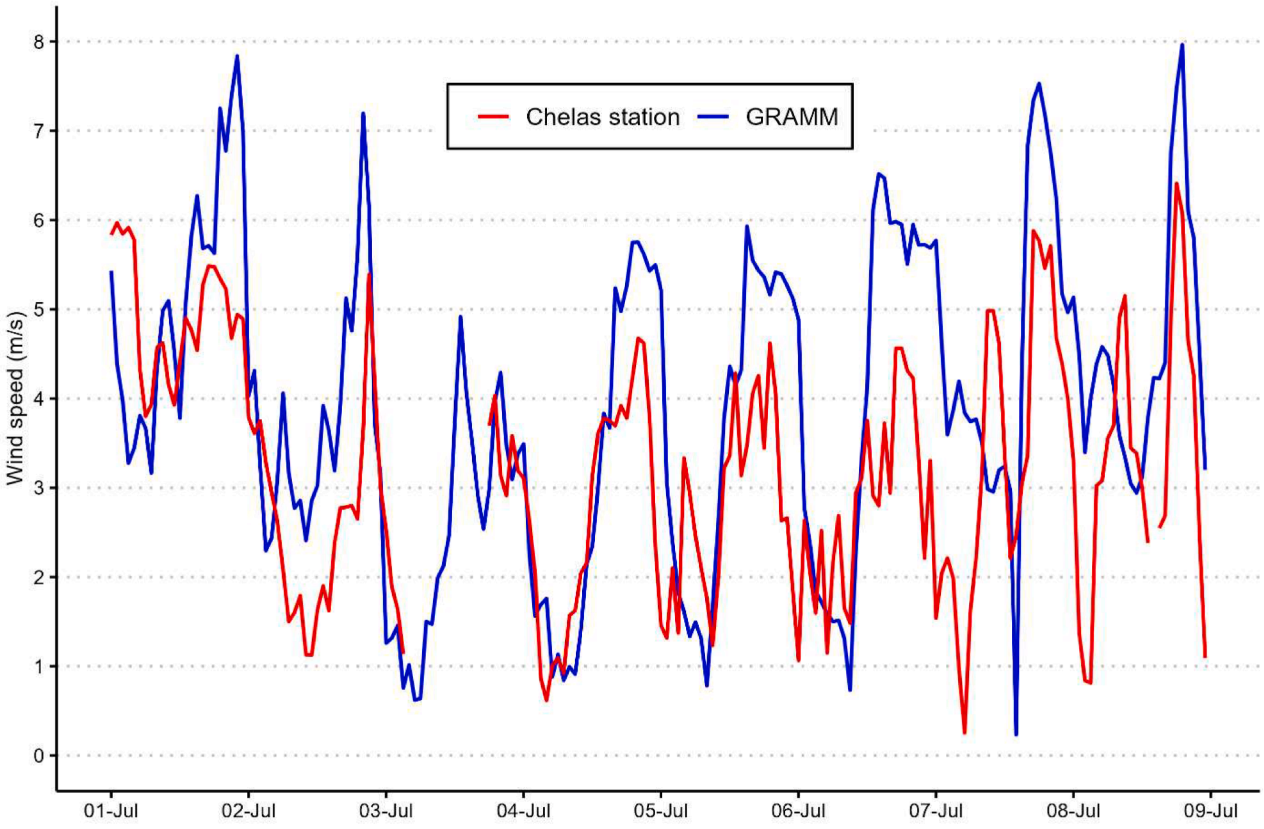

Fig. 2. Wind speed (m/s) registered at Chelas station vs modelled by GRAMM in July 2022.

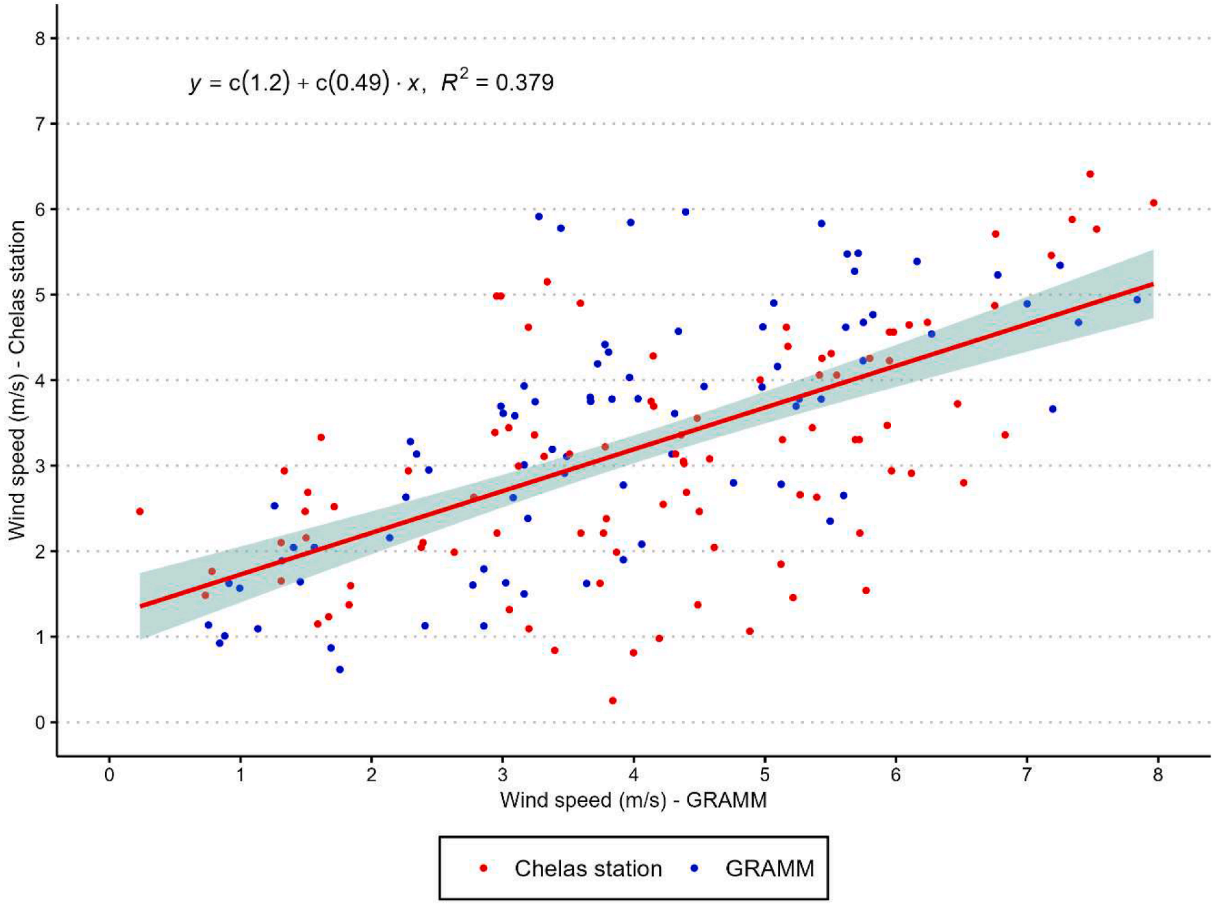

Fig. 3. Correlation between measured and modelled wind speeds at Chelas location (Lisbon – 2022).

Table 4
Input data and sources for UTCI calculation in Lisbon.

Input Hourly Data	Source
Air temperature	Lisbon mesoscale meteorological network
Relative Humidity	
Wind Speed	GRAMM-SCI model
Tmrt	Rayman

Table 5
UTCI assessment scale and grades of physiological stress.

UTCI (°C)[1]	Grades of physiological stress
<−40	extreme cold stress
−40,0 to −27,1	very strong cold stress
−27,0 to −13,1	strong cold stress
−13,0 to −0,1	moderate cold stress
0,0 to 8,9	slight cold stress
9,0 to 25,9	no thermal stress
26,0 to 31,9	moderate heat stress
32,0 to 37,9	strong heat stress
38,0 to 45,9	very strong heat stress
>46,0	extreme heat stress

[1] UTCI assessment scale was adapted from Brode et al. [53].

thermos-physiological comfort. Figs. 4–6 display the UTCI and modelled wind fields for Lisbon at three different times of a typical breeze day (4th July 2022): before the arrival of breeze with prevailing Nortada wind (7:00AM), during the breeze event (12:00PM) and after its cessation, with the return of Nortada (8:00PM).

During the early morning (7:00AM – Fig. 4), the difference between the water and the land surface temperature is still reduced since the majority of trapped radiation was released for the streets during the night. Hence, wind is blowing mostly from NW (Nortada) over the city with speeds of 3 m/s, on average. This explains the dichotomy between NW and SE, where the city historic center/downtown Lisbon close to the estuary and the eastern riverfront area register higher UTCI values (between 24 and 26 °C – no thermal stress) compared to the northern part (UTCI between 13 and 16 °C – no thermal stress).

With the arrival of the breeze, the heat stress pattern changes: the wind rotates to NE, then E and SE, and a few hours later to further S, SW and W (Fig. 5) with the channeling of breezes coming also from the Atlantic Ocean (average speeds of 3,1 m/s). Hence, the western part of the city, especially close to the river, registers a more thermally comfortable environment (UTCI between 23 and 25 °C – no thermal stress), in contrast to the eastern part of Lisbon, especially the NE area (UTCI above 32 °C – strong heat stress).

In Funchal city, Madeira island, Lopes et al. [16] found that during "hot days" (temperatures around 29/30 °C and PET above 38 °C at 12:00PM) no absolute comfort situation was observed inner city but near the shoreline the breeze was effective in reducing heat stress (suddenly reduction of 8 °C in PET during the breeze at the marina of Funchal).

By the end of the day, heat stress levels became acceptable near the shoreline, while the inner city remained "hot" probably because the ventilation is hampered by the built environment and the UHI may be intensified [16].

In Sidney (Australia), He et al. [9] demonstrated that precinct ventilation performance driven by sea breezes significantly enhanced outdoor thermal comfort by reducing relative humidity levels, even in compact high-rise environments. Recently, Wang et al. [18] showed that

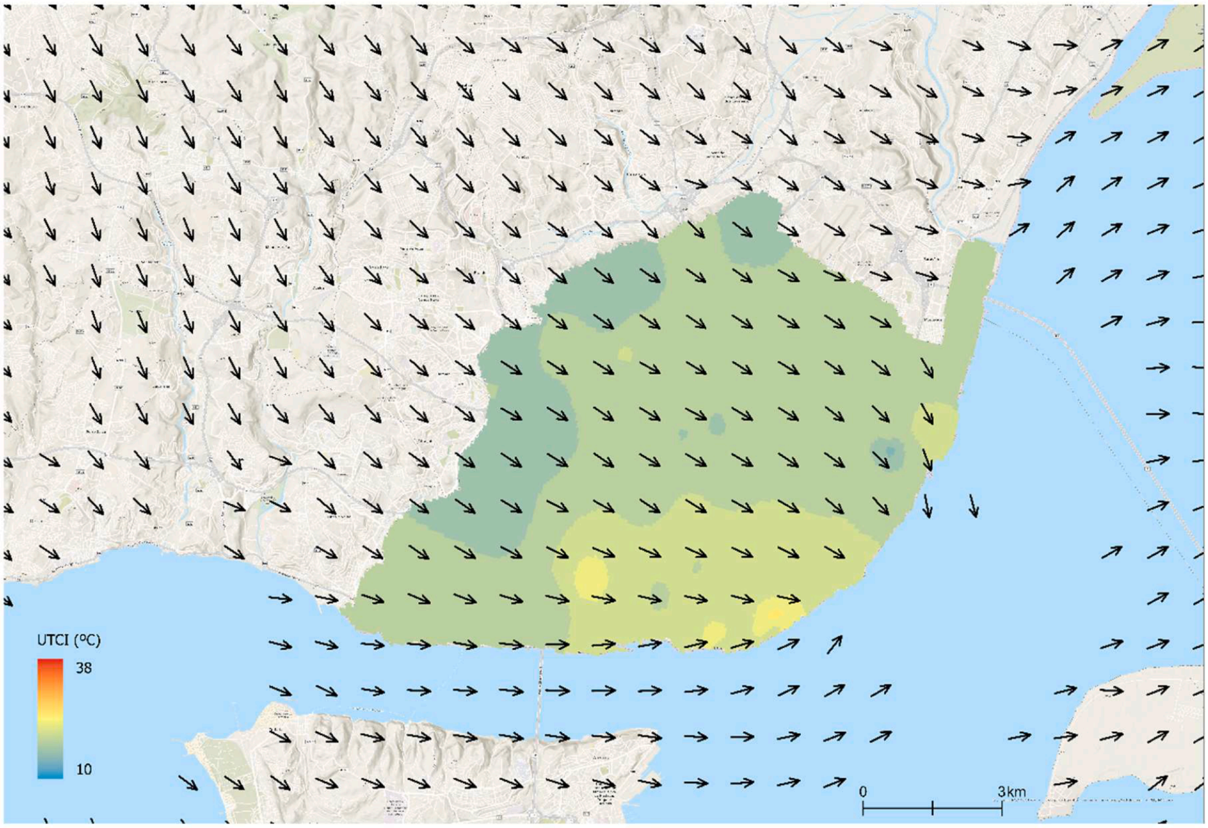

Fig. 4. UTCI and wind fields during a typical sea and estuarine breezes day (4th July 2022) in Lisbon at 7:00AM. The size of arrows represents wind intensity (m/s) and on areas with no arrows wind speed is below 1 m/s.

the lake Michigan breeze relieved heat stress in Chicago Metropolitan Area during afternoon (when the heat stress is the worst) and shortened the heat caution period by 1–3 h over inland urban grids and 3–4 h over coastal urban grids.

Differing from this common assumption that these breezes have a positive role in the reduction of air temperature and outdoor heat stress, Anjos et al. [17] found that mean air temperature and PET during breeze days in Sergipe, on the northeast coast of Brazil, were 2,0 and 3,8 °C higher, respectively, compared to non-breeze days in all LCZ sites.

Additionally, the highest PET of 40,0 °C (strong heat stress) was found on breeze days. Hence, according to the authors, the breeze's development could be an aggravating factor for increasing heat stress of the people living in the urban area since it potentialize the UHI (increase in mean solar radiation, by 84 Wm^2, and air temperature, by 1 °C, after the breeze passage).

At late afternoon (Fig. 6), the regional flow (Nortada) is restored (average wind speed of 5,4 m/s) along with the early morning heat stress pattern (dichotomy between N/NW and S/SE).

These UTCI patterns resemble the spatial distribution of average air temperature anomalies (ΔT_{urb}) during sea and estuarine breeze days recently disclosed by Reis et al. [26]. According to the authors, the air temperature differences between Lisbon's riverfront area and the airport weather station can be above 3 °C before the breeze arrival, up to −5 °C during the breeze event and above 5 °C after its cessation.

Even though the breeze effect on the amelioration of heat stress conditions during summer days in Lisbon is clear, it is important to quantify it and define its optimal influence area.

Fig. 7 displays hourly average ΔUTCI in Lisbon during sea breeze (heatwave and non-heatwave) and Nortada days according to the distance to the riverfront area. Above all, the breezes ΔUTCI daily cycle (non-heatwave and heatwave) assembles the one of UHI [61] and ΔT_{urb}, this latter previously described by Reis et al. [26].

During the night, the ΔUTCI is positive (2 to 3,4 °C higher on non-heatwave breeze days) due to the slow release of trapped heat into the urban canyons (UHI effect). As the night progresses and the day starts, a descent occurs that reaches its minimum (negative ΔUTCI) during typical breeze hours.

In areas up to 500 m from the riverfront, average ΔUTCI during breeze days (non-heatwave) drops to −2,2 °C at 1:00PM, and on extremely hot days with also a breeze system, drops to −5,1 °C at 2:00 PM. After that, it rises until late afternoon, reaching its maximum at 7:00PM on non-heatwave (up to 5,7 °C) and one hour later (up to 4,8 °C) on heatwave breeze days.

The ΔUTCI daily cycle like the ΔT_{urb}, is only noticeable on areas up to 4 km and the negative ΔUTCI during breeze hours faint from this distance onwards during heatwave and non-heatwave breeze days. In contrast, on typical Nortada days the ΔUTCI are always positive across the city, but especially on areas up to 500 m (between 3,7 °C and 7 °C). Hence, the N and NW winds are definitely being blocked as they approach the city and its cooling effect is not felt on Lisbon's usually hotspots (city historic center near the riverfront area).

Besides its maximum cooling extent, it is important to grasp whether these negative ΔUTCI during breeze events implicate a change to a more comfortable UTCI class. Fig. 8 represents the percentage of change of UTCI physiological stress class during breeze events (heatwave and non-heatwave) with reference to the airport weather station, according to the distance to Lisbon's riverfront area.

When considering the hours with no thermal stress (a) the percentage of change to uncomfortable physiological stress classes (in reference to no thermal stress) decreases from 50 % (in areas located up to 500 m to the riverside) to 0 % (in areas up to 2,5 km) and remains negligible throughout the rest of the city. Hence, on half of breeze hours with no thermal stress at the reference station, the riverfront area registers moderate heat stress., while on the northern half of Lisbon the human

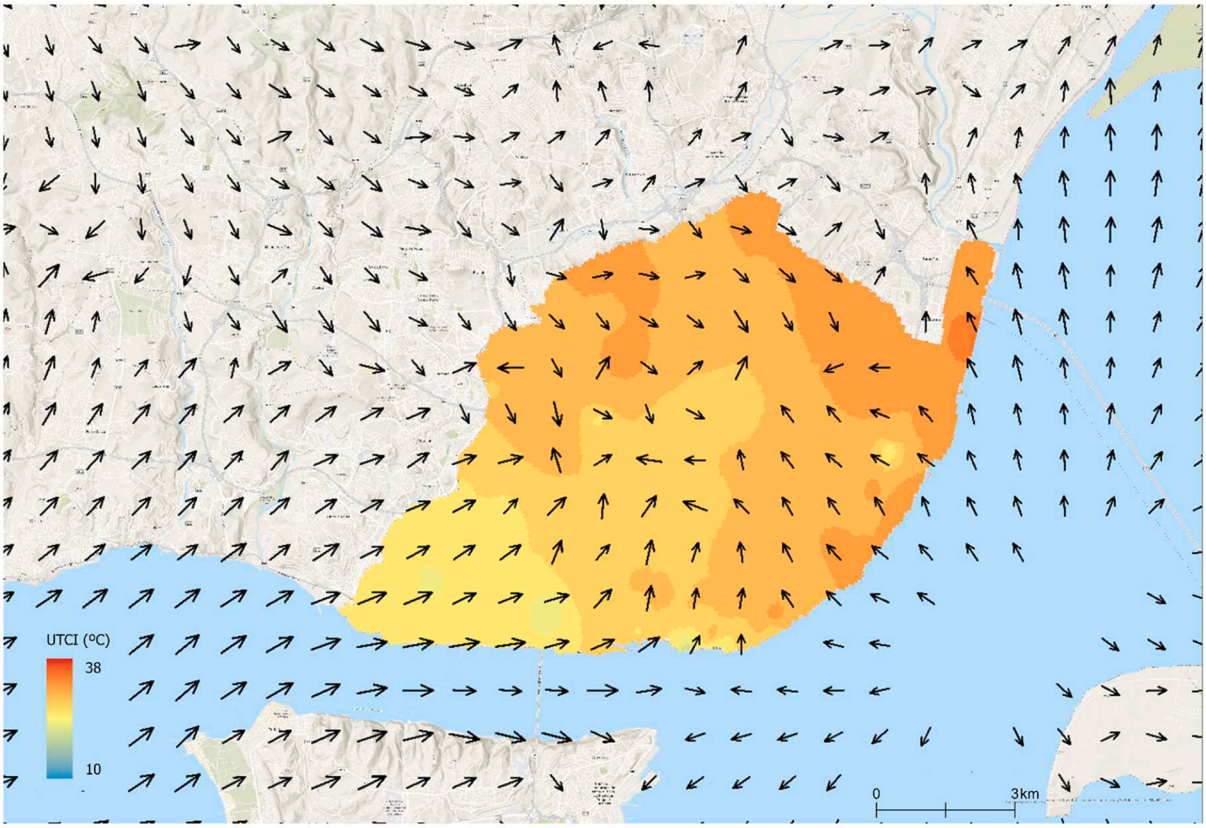

Fig. 5. UTCI and wind fields during a typical sea and estuarine breezes day (4th July 2022) in Lisbon at 12:00PM. The size of arrows represents wind intensity (m/s) and on areas with no arrows wind speed is below 1 m/s.

thermos-physiological comfort conditions are similar to the airport weather station. Considering the hours with moderate heat stress on the airport (b), on areas up to 500 m there is a decrease of 2 UTCI physiological stress classes (from moderate heat stress to slight cold stress) on about 1 % of breeze hours that vanishes on the remaining city area. Additionally, the percentage of decrease of 1 UTCI class ranges between 5 and 17 % across the city, with exception of areas between 6 and 7 km (0 %), while the percentage of situations in which the heat stress class remains unchanged ranges between 65 and 80 %. Furthermore, on areas up to 2,5 km the percentage of increase of 1 UTCI class (from moderate to strong heat stress) is higher (between 13 and 21 %) and it descends drastically between 2,5 and 4 km (8 to 9 %) due to the presence of a large urban green space, the Monsanto forest, and its cooling effect of the urban thermal environment. .

With regards to the strong and very strong heat stress classes (c and d), the scenario inverts. Firstly, considering the breeze hours with strong heat stress at the reference station, on areas up to 1,5 km the percentage of descend of one UTCI class (from strong to moderate heat stress) is actually higher than the percentage of situations in which the heat stress conditions remain the same as those at the airport, and it decreases with increasing distance to the Tagus estuary, such as the percentage of descend of two UTCI classes (from strong heat stress to no thermal stress): from 17 % on areas up to 500 m to 3 % 500 m to 3 % between 1 and 1,5 km and 0 % up to 2,5 km.

Between 2,5 and 4 km, on about 3 to 6 % of breeze hours there is a descend from strong heat stress to no thermal stress (this descend is actually higher than the one caused by the sea breeze cooling effect on the riverfront area) and on 48 % to 53 % a descend from strong to moderate heat stress (urban green space cooling effect).

Considering the scenarios with very strong heat stress at the reference station, that happened mostly on the heatwave breeze day (8th July) and on the day before (7th July), the transition to a more comfortable thermal environment (descend of 1 UTCI class) happens on 24 % of situations on areas up to 500 m, on 20 % between 500 m and 1 km, on 6 % between 1 and 1,5 km and then vanishes up to 3 to 4 km, where once again the presence of large urban green spaces (Monsanto forest) with densely tree covered areas (LCZ A) contributes to the reduction of outdoor thermal discomfort and, hence, to a descend of 1 and even 2 UTCI class on 7 % of breeze hours each. Therefore, on days with no thermal stress or only moderate heat stress at the reference station—conditions typical of about 64 % of the thermal summer in Lisbon [62], with daily average temperatures between 20 and 21 °C—the cooling potential of the breeze on Lisbon's riverfront is limited. This is because the likelihood of maintaining or even increasing the thermophysiological stress level is higher in these areas compared to locations farther from the Tagus Estuary.. However, during extreme heat conditions such as heatwaves, with heat stress conditions of strong to very strong heat stress, the breeze cooling effect is more pronounced within a restricted area close to the river (up to 1,5 km) where the percentage of descend of physiological stress class is substantially higher. In contrast, Papanastasiou et al. [15] analyzed several biometeorological indices on two Greek regions, an urban location in Volos, a city on the east coast of central Greece, and a suburban location on Velestino, a smaller city about 16 km to west of Volos. The authors found that during heatwaves, people living near the coast felt slightly more comfortable during daytime and less comfortable during nighttime than those living inland. However, the breeze development was not associated with significant thermal stress relief.

4. Conclusions

In this study the influence of sea and estuarine breezes on heat stress conditions (heatwave and non-heatwave) was accessed in Lisbon, Portugal. The breezes proved to be effective on the reduction of outdoor

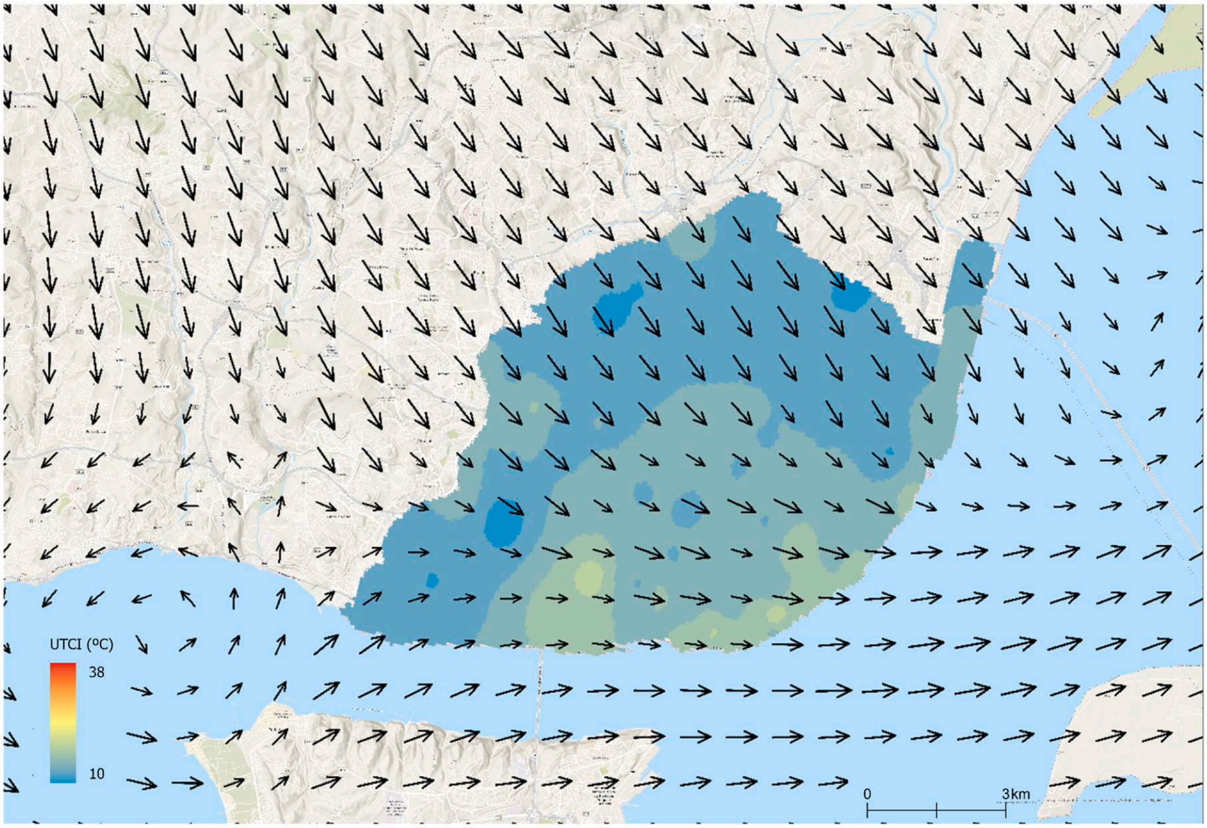

Fig. 6. UTCI and wind fields during a typical sea and estuarine breezes day (4th July 2022) in Lisbon at 8:00PM. The size of arrows represents wind intensity (m/s) and on areas with no arrows wind speed is below 1 m/s.

thermal discomfort on the areas up to 4 km from the Tagus river (negative ΔUTCI during breeze hours that reached −5,1 °C and −2,2 °C during breeze hours on heatwave and non-heatwave days, respectively). However, the improvement in heat stress conditions is only significant enough to induce a transition to a more comfortable UTCI physiological stress class during extreme heat events (from strong to very strong heat stress) and within areas up to 1.5 km from the estuary.

This study represents an exploratory analysis of how sea breezes behave in the city of Lisbon, focusing on their progression and impact on heat stress. One of the main limitations of the GRAMM-SCI model is its coarse spatial resolution, which in this case is 200 m, which restricts its ability to evaluate the influence of buildings and vegetation on small-scale wind fields. Therefore, future research on the influence of the built environment on breeze progression should include microscale flow field simulations with GRAL (e.g. [46,63]). GRAL, which is based on computational fluid dynamics, computes the flow around obstacles (buildings and vegetation) with high spatial resolution ($\leq$ 5 m), enabling a more detailed analysis of urban morphological and vegetative characteristics, such as the LCZs. Combining these parameters with the distance to the riverfront would allow for a more comprehensive understanding of the interactions between sea breezes and urban morphology, providing clearer guidance for urban planning and design.

Furthermore, the period of analysis was restricted to a few breeze days due to high computational power and time constraints, which may not represent the full spectrum of the effect of these breezes on local wind systems and human thermo-physiological comfort throughout the thermal summer.

Nevertheless, this study offers valuable insights into the cooling effects of local ventilation patterns, such as breeze systems, on s heat stress conditions. These findings are essential for microscale urban planning regulation, particularly in the context of future climate projections that predict the deterioration of local weather conditions in southern European/Mediterranean cities. The methodology presented in this study contributes to risk identification processes and may assist in the development of heat/health warning systems, laying the groundwork for future high-resolution analyses.

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CRediT authorship contribution statement

Cláudia Reis: Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dietmar Oettl:** Writing – review & editing, Software, Formal analysis. **António Lopes:** Writing – review & editing, Validation, Supervision, Software, Project administration, Methodology, Formal analysis. **A. Santos Nouri:** Writing – review & editing, Supervision, Formal analysis. **João Vasconcelos:** Writing – review & editing, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal

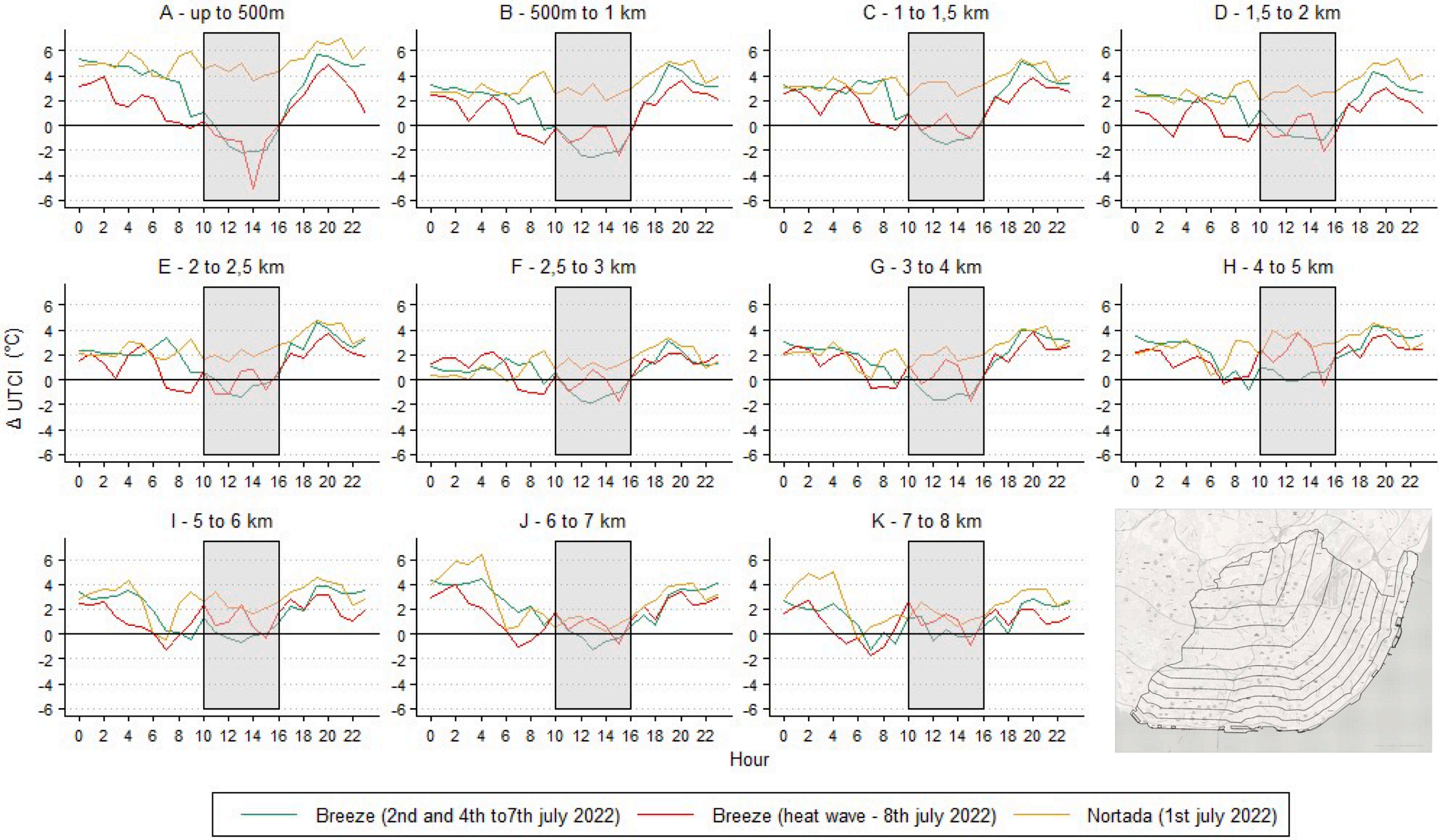

Fig. 7. Hourly average UTCI anomalies (ΔUTCI) in Lisbon during sea and estuarine breezes (heatwave and non-heatwave) and Nortada days according to the distance to the riverfront area. Grey areas represent typical breeze hours according to Reis et al. [26]. Linear distances to the riverfront are depicted on the grey map.

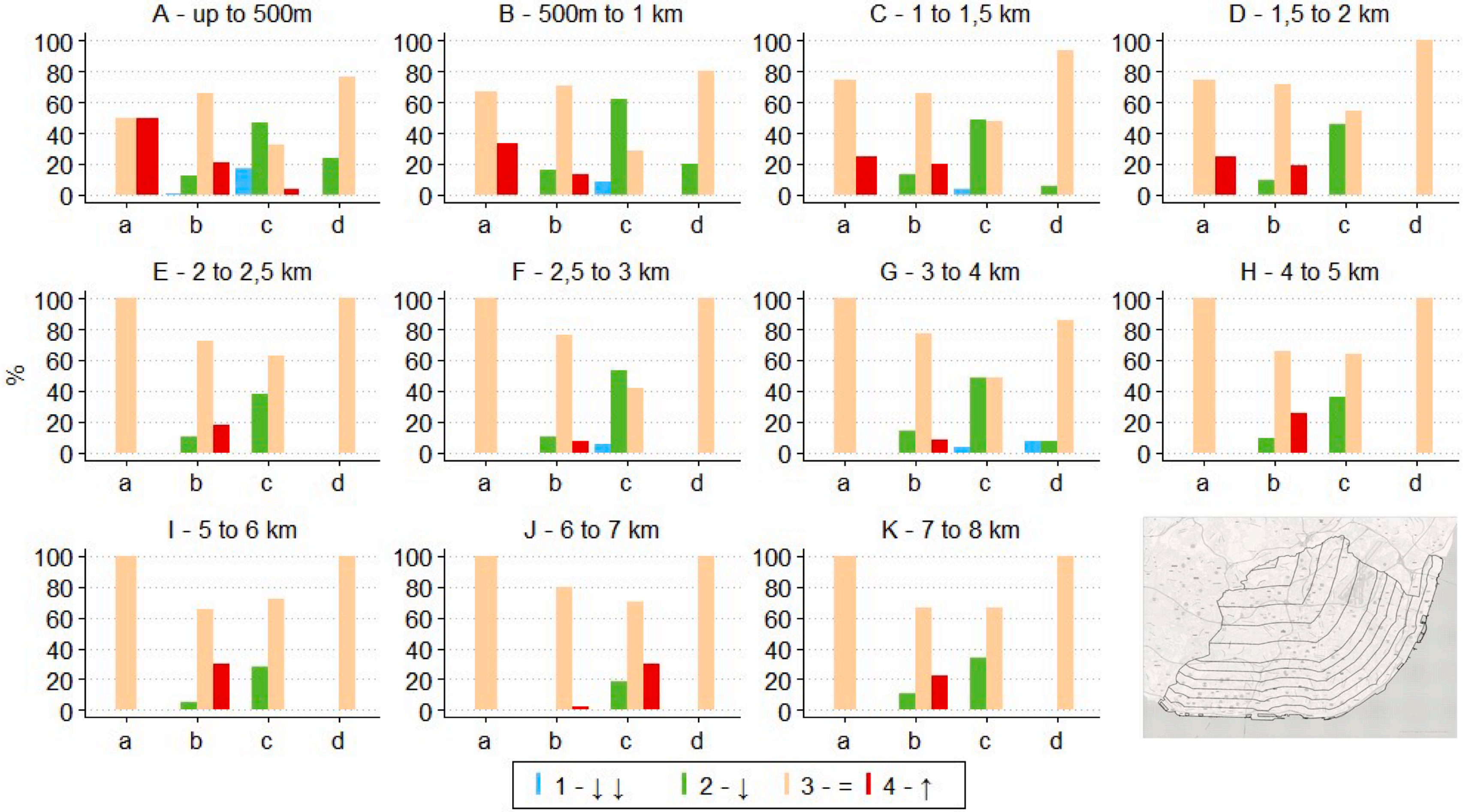

Fig. 8. Percentage of UTCI physiological stress class change on breeze hours in relation to Lisbon's airport weather station, according to the distance to the riverfront area: blue bars indicate a descent of 2 classes, green a descent of 1 class, beige indicates no change of UTCI physiological stress class and red indicates an increase to a more uncomfortable UTCI class. UTCI physiological stress classes: a – no thermal stress; b - moderate heat stress; c – strong heat stress and; d – very strong heat stress. Linear distances to the riverfront are depicted on the grey map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relationships which may be considered as potential competing interests: Claudia Reis reports financial support was provided by Foundation for Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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