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# 1 A practical approach to the evaluation of 2 local urban overheating– a coastal city 3 case-study

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## 8 **Abstract**

9 In response to urbanization and global warming, which amplify heatwave effects and might  
10 lead to urban heat stress, this paper proposes a practical approach to characterize the local  
11 microclimate at the neighborhood scale. In this approach, the local urban climate is described  
12 using suitable indicators, to support the ecodistrict design process or refurbishment.  
13 Experimental and numerical results illustrate the approach in a case study of a French coastal  
14 city, La Rochelle. In the first step, we set up urban and rural weather stations to characterize  
15 the local urban climate over a summer period and to identify local temperature differences.  
16 The measurements highlighted a daytime urban cooling effect due to the local sea breeze.  
17 While the Urban Weather Generator (UWG) simulation tool used for this study does not  
18 capture coastal effects, the results were consistent with the urban heat island (UHI)  
19 measurements. We proposed two indicators to quantify the local climate modifications: local  
20 UHI and overheating intensity. The parameters of the adaptation strategies were assessed  
21 through a sensitivity analysis for these two indicators. For this case-study, we identified  
22 vegetation cover, building height and road albedo as key parameters that can be used to  
23 mitigate local overheating.

## 24 **1 Introduction**

25 In recent decades, the expansion of cities and environmental constraints [1] have resulted in  
26 increasing challenges for urban planning, district renovation and building energy design.  
27 Urban heat islands (UHI) are closely tied to the complex interactions between the urban  
28 canopy, buildings (envelope and system waste heat), and the occupants [2,3]. In this context,  
29 and to adapt to increasing temperatures due to climate change, the decision process requires  
30 practical quantitative tools, and indicators to compare urban strategies and building design  
31 adaptations. In this paper, we combined an experimental and numerical approach to propose  
32 easy to interpret quantitative indicators. The results can be used to adapt the urban fabric to  
33 future UHIs and future urban heatwaves. Indeed, the occurrence of heatwaves will increase  
34 during the 21<sup>st</sup> century, and studies have shown that the UHI effect is amplified during hot  
35 days and nights in dense cities [4,5]. Our approach is illustrated through a case study of a  
36 coastal city (La Rochelle, France), which shows similarities with other coastal studies [6–8].  
37 Indeed, under some conditions, the sea breeze may attenuate high daytime temperatures in  
38 summer.

39 On hot days, in the urban context, critical periods of thermal discomfort [9,10] or thermal  
40 stress [11] may occur. During the 2003 European heatwave [12], the UHI amplified the  
41 intense exposure to the heatwave and led to increased mortality, especially among vulnerable  
42 people. Seventy thousand deaths were correlated with the heatwave in Europe, and 15,000 in  
43 France, where the highest excessive mortality rate was recorded in Paris [13]. Laaidi *et al.*  
44 [14] showed that abnormally elevated night temperatures (26 °C on the warmest day of the  
45 heatwave at 6 am in Paris) were due to the UHI, and had a strong impact on the health of  
46 occupants in buildings. Old residential free-floating Parisian buildings are not adapted to heat,  
47 and the reduced cooling effect of the urban fabric at night could explain these elevated  
48 nighttime temperatures. In a recent study, an ecodistrict (i.e., an urban area with a reduced

49 carbon footprint and a sustainable design [15,16]) in Paris was modelled under a future  
50 intense heatwave around the mid-century, and the results indicated that the urban  
51 neighborhood would be subject to heat stress [17]. This reinforces the need to adapt the urban  
52 fabric to climate change and implement effective mitigation strategies.

53 In this study, we focused on both exposure to overheating and microclimate modification due  
54 to the local UHI. Exposure to overheating (defined in section 2.4.1) is specifically related to  
55 summer thermal discomfort and potential heat stress within inhabited spaces. Although the  
56 proposed indicators are based on common UHI and overheating definitions, this approach  
57 quantifies the exposure in more detail, with two time-integrated quantitative indicators that  
58 account for both exposure duration and intensity. Unlike purely numerical or spatially  
59 averaged studies, our aim was to highlight the practical benefits and limitations of this  
60 approach, based on the very local differences that can be captured experimentally by these  
61 indicators, so that they can be used in adaptation strategy simulation and the decision-making  
62 process.

63 On the one hand, we installed two urban weather stations within a specific local climate zone  
64 (LCZ) [18] to highlight and quantify very local urban effects, since urban simulation tools  
65 usually take into account the spatially averaged local climate (LCZ scale). Our analysis is  
66 specifically supported by data recorded during a 10-day heatwave.

67 On the other hand, we used the spatially broader modelling approach with the numerical  
68 Urban Weather Generator (UWG) model [19,20]. This approach is useful for experimenting  
69 with various strategies to mitigate overheating, and with future weather conditions. Recent  
70 studies using this model [21–25] demonstrated its potential to assess UHI, thermal discomfort  
71 and health issues [26]. The neighborhood architecture may also benefit from this approach,  
72 which takes into consideration different urban contexts using a modified weather file [27].

73 The UHI parameters are well-known [28–31], and we analyzed the improvement in radiative  
74 properties such as increased albedo (e.g., cool roofs) and the implementation of evaporative  
75 cooling (e.g., green roofs) to decrease solar heat gain on the building fabric. Susca *et al.* [32]  
76 reported a 2°C difference between sparse and well-vegetated areas in New-York. Bonafoni *et*  
77 *al.* [33] and Taha *et al.* [34], investigated the benefits of increased albedo on urban climate  
78 and air-conditioning cooling loads. In Montreal [35], cool roofs on commercial buildings  
79 could save up to 11% of cooling energy consumption. Various other advanced techniques are  
80 under development to mitigate urban heat with surface modifications [36,37].

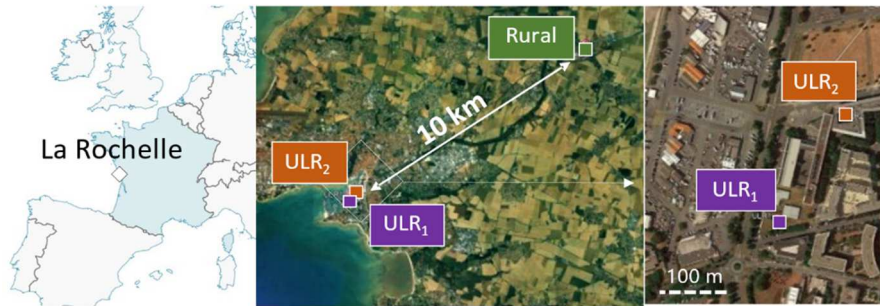
81 Through a sensitivity analysis, we analyzed the potential of these passive cooling solutions to  
82 mitigate urban heat and summer overheating. For this purpose, we used the defined  
83 quantitative indicators as objective functions. This method can be applied to other cities,  
84 which might identify different key solutions, depending on the location. This method is  
85 therefore positioned upstream of the decision-making process, and could be useful for the  
86 implementation of strategies at the building and the urban area design stage, and in identifying  
87 the main parameters responsible for urban overheating that could then be adjusted to achieve  
88 better climate adaptation.

## 89 **2 Methodology**

### 90 2.1 Case study and methodology overview

91 The neighborhood studied is located in La Rochelle, a city on the southwest coast of France.  
92 A total of three weather stations were installed. The two urban stations (ULR<sub>1</sub> and ULR<sub>2</sub>)  
93 were set up in the university urban neighborhood located very close to the sea (500 m), and  
94 the rural station is about 10 km inland (Figure 1). Several studies suggest methods and  
95 guidelines to properly install and analyze data in an urban area [38–40] such as the  
96 positioning of the reference station, different methods to calculate UHI, and in particular the  
97 positioning of the weather stations. The two weather stations were installed close to each

98 other (approximately 200 m) to (i) estimate local overheating and UHI, and (ii) highlight the  
 99 local differences due to urban heterogeneity within the same LCZ zone.



100

101

Figure 1: La Rochelle case study and weather station location

102

According to the Köppen classification [41], La Rochelle (latitude 46°2' North, longitude

103

1°1' West) is considered a temperate oceanic climate. Even though the two urban weather

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stations are located in the same neighborhood, they have different surroundings. The ULR<sub>1</sub>

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station was set up between buildings (dense urban context), while the ULR<sub>2</sub> station is in a

106

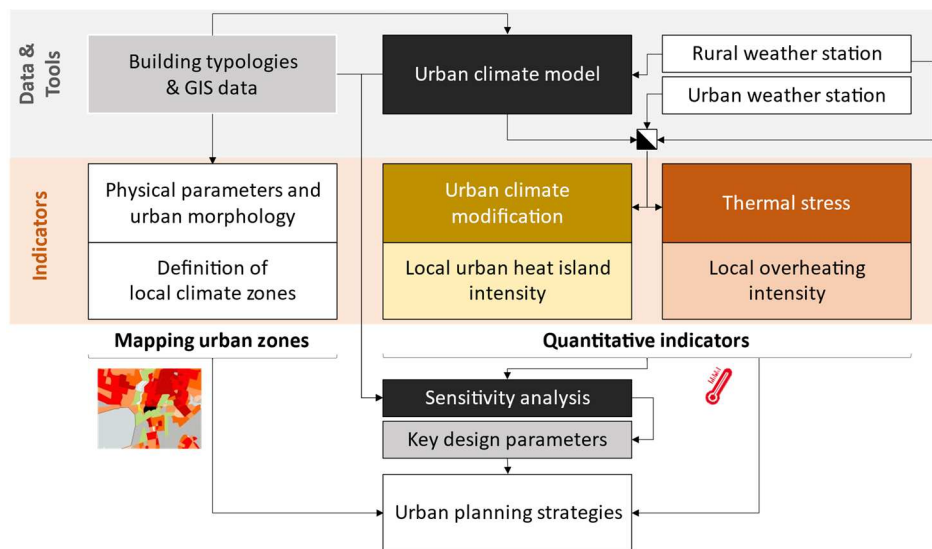
clear field with few nearby obstacles. The period under study was a 10-day heatwave that

107

occurred between the 20<sup>th</sup> and 30<sup>th</sup> July in the summer of 2019.

108

The proposed methodology is illustrated in Figure 2.



109

110

Figure 2: Overview of the proposed methodology

111 The methodology used in this research can be split into four parts: (i) Information on building  
112 typologies and GIS data was collected for two reasons: First, to map the urban area into  
113 LCZs, which are of interest to urban planners in understanding UHI risk and hot spots [42–  
114 44]. They are then used as input data for the urban climate model (UWG); (ii) The urban  
115 model is used to complement the meteorological stations (rural and urban) in order to  
116 understand and analyze the change in the local climate in the city; (iii) In order to facilitate the  
117 analysis of the data, two quantitative indicators were defined and calculated using the above.  
118 The first indicator quantifies the intensity of the local urban heat island, which is related to  
119 urban climate change, while the second calculates the intensity of local overheating, which  
120 provides information on outdoor heat stress during heatwaves; (iv) Finally, the urban climate  
121 model was used to perform a sensitivity analysis of the different design parameters during  
122 urban planning, to determine the main mitigation and adaptation strategies for the coastal city  
123 under study. The overall goal was that the practical indicators enable the stakeholders to  
124 address overheating issues in a holistic approach that takes into account the related health  
125 impacts, energy poverty and social disparity in the population.

## 126 2.2 Mapping urban zones

127 Stewart and Oke [18] defined the LCZ classification from urban parameters. These LCZ  
128 parameters include the urban morphology and thermophysical characteristics of urban zones.

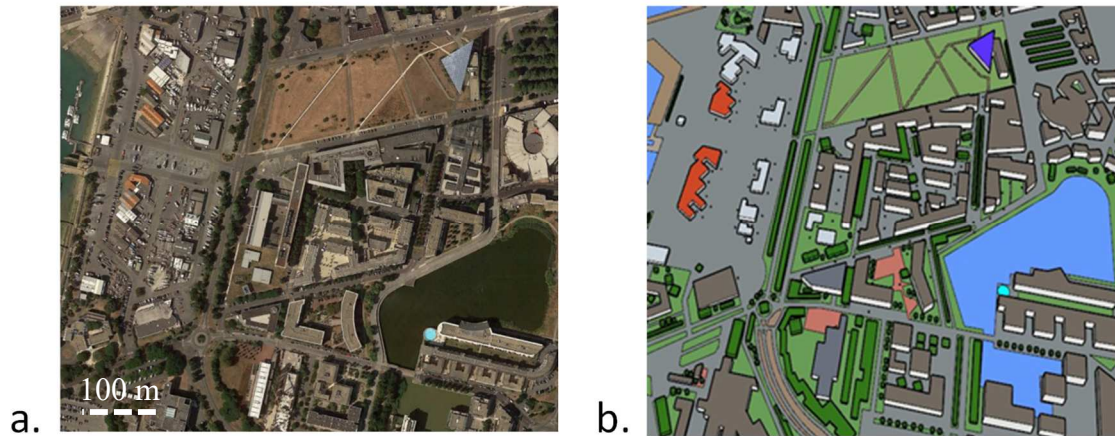
129 Long *et al.* [45] classified the LCZ for 42 French urban areas and highlighted a significant  
130 link to UHI intensity, defined here as the temperature difference between urbanized and non-  
131 urbanized temperature for the same location. These results were obtained from numerical  
132 simulations at a spatial resolution of 250 m using the Town Energy Balance (TEB) model  
133 coupled to the Méso-NH atmospheric model. In the MUSTARDijon project [46], the  
134 reliability of this LCZ classification was experimentally studied, including the establishment  
135 of a network of 47 meteorological sensors [46]. The authors compared both LCZ and Urban

136 Climate Zone (UCZ) classifications [47,48] with a 150 m grid resolution. These results  
137 showed that LCZ is the most applicable mapping method for the thermal clustering of urban  
138 areas.

139 The LCZ classification is based on the average values of morphological urban parameters, as  
140 defined by Oke [18]. We extracted most of the morphological urban and building data  
141 required for LCZ identification from the detailed BD TOPO database in France (database  
142 from IGN, <http://professionnels.ign.fr/bdtopo>), and from OpenStreetmap [49]. Collecting  
143 precise data on green areas and identifying trees was more challenging. To tackle this  
144 problem, Haala and Brenner [50] proposed an imagery data methodology for urban areas. We  
145 defined the main building typologies from local surveys and the TABULA project database  
146 (<http://webtool.building-typology.eu/>). The definition of thermal properties at this urban zone  
147 scale requires simplifications, especially given the strong variation in surface properties, such  
148 as the albedo. For anthropogenic heat release in the district, we used the typical value from  
149 the literature of about 8 W/m<sup>2</sup>, which was measured in Toulouse, a city located in southwest  
150 France [51,52].

151 According to the classification available online ([mapuce.orbisgis.org](http://mapuce.orbisgis.org)), La Rochelle is  
152 characterized by low and mid-rise buildings. Most of the downtown buildings are low-rise  
153 residential constructions (height 3 to 6 m), while some suburban constructions are higher. We  
154 studied an urban area located around the university (Figure 3a,b), close to the city center.





155

156

Figure 3: Aerial view (a), and digital model (b) for the neighborhood studied in La Rochelle.

157

We delimited the area of the case-study neighborhood within a 200 m radius (Figure 3a) to

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extract morphological data from the BDTPOPO database (GIS). No available database was

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available to determine green areas accurately and to provide all the necessary parameters. We

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therefore built a digital model enhanced with simple vegetation modelling (Figure 3b).

161

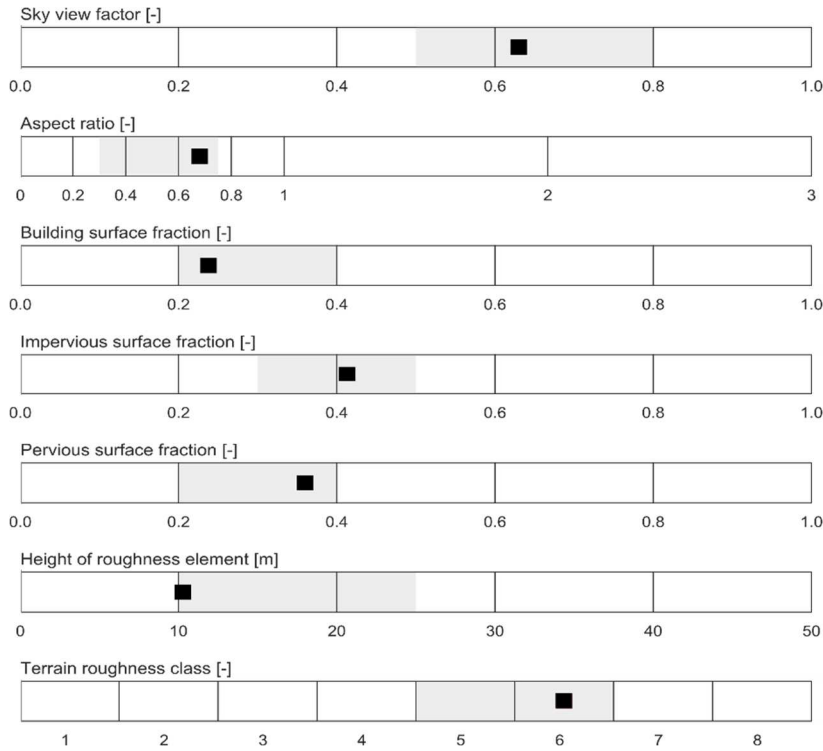
Finally, the case-study of the university neighborhood (Figure 3a,b) was determined as LCZ

162

type 5. The main parameters computed for this case-study and their variation range for LCZ 5

163

are presented in Figure 4.



164

165

Figure 4: Range values for LCZ 5 and parameters calculated according to Oke [18]

166

We computed for this urban area a plan-area density of 27 %, defined as the ratio of building

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plan area to total plan area (%) [53], and an average building height of 11.6 m. This first step

168

characterizes an LCZ and the associated neighborhood UHI risk. Due to the lack of available

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data and tools to quantify several urban parameters, this estimation may have significant

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uncertainties. For example, green areas vary throughout the year, which was not taken into

171

account in the model, and this may impact the pervious surface fraction. Leconte [54] recently

172

highlighted similar limitations.

## 173 2.3 Measurement and urban model

### 174 2.3.1 Weather station technology

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We collected weather data from the urban and rural weather stations (Figure 1) over the

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summer period from June 1 to September 1, 2019. The rural station, located in a residential

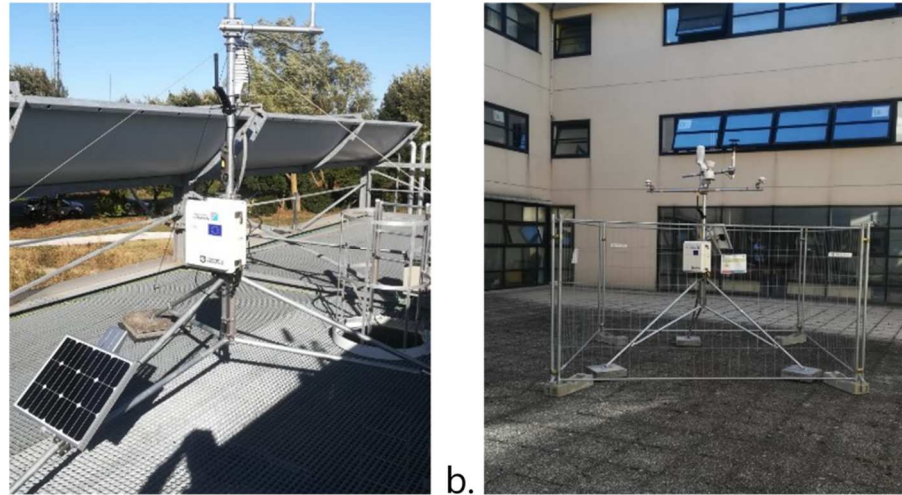
177

area in the northeast of La Rochelle, served as a reference station and is approximately 10 km

178

away from urban areas. Both urban weather stations (ULR<sub>1</sub> and ULR<sub>2</sub>) in La Rochelle are in

179 the LCZ type 5 defined in the previous section. These urban weather stations are close to the  
 180 sea (500 m approximately). The ULR<sub>1</sub> station is in an open field surrounded by trees and  
 181 grass, while the ULR<sub>2</sub> station is located in the courtyard of a building (Figure 5a); ULR<sub>2</sub> is  
 182 therefore shadier than ULR<sub>1</sub> (Figure 5b).



183 a. 184 b. Figure 5: ULR<sub>1</sub> (a) and ULR<sub>2</sub> (b) weather stations

185 The weather stations are composed of Campbell Scientific dataloggers and sensors (Table 1).  
 186 The air temperature and humidity sensors were positioned at a height of 2 m.

187 Table 1 : Weather parameters and sensors for weather stations

Parameter	Sensor	Uncertainty
Air temperature [°C]	Rototronic© thermocouple HC2A-S3	0.1 °C
Relative humidity [%]	Rototronic© humidity sensors HC2A-S3	1%
Solar irradiance [W/m <sup>2</sup> ]	Kipp and Zonen© pyranometer CMP 3	2.6 %
Longwave irradiance [W/m <sup>2</sup> ]	Kipp and Zonen© pyrgeometer CMP 3	6.2 %
Wind direction	Windsonic© ultrasonic wind sensor WINDSONIC-LC Gill 2-D	-
Wind speed	Met One Instruments© wind anemometer 014A	-
Rainfall	Campbell© Kalyx-RG	-

188  
 189 The suppliers provided the uncertainty of the solar shortwave and longwave sensors (Table 1).  
 190 We performed a specific calibration for the relative humidity and the air temperature sensors.  
 191 For the temperature, all the sensors were calibrated using a Fluke 7321 calibration bath that  
 192 guarantees a 0.1 °C uncertainty between sensors. Similarly, humidity sensors were calibrated  
 193 using LiCl and NaCl salts. Concerning other values, simultaneous recordings from all weather

194 stations demonstrated that the instruments provided the same output values for the same input  
195 conditions.

### 196 2.3.2 Urban model

197 In order to complement the experimental analysis and further evaluate different passive  
198 cooling strategies, the UWG model was used [19]. This model predicts the effects of the local  
199 UHI for a specific urban zone. The physical UWG model is divided into four sub-models: (i)  
200 a rural station model for heat flux calculation at a rural site; (ii) a vertical diffusion model for  
201 vertical air profiles at the rural site; (iii) an urban boundary layer model for the calculation of  
202 air temperature above the urban canyon; and (iv) a representative street canyon model to  
203 compute the urban canopy and building energy sensible heat fluxes. Each sub-model is  
204 represented by one node, and the street canyon model evaluates the average temperature  
205 modification in an urban neighborhood. The model output is an urban weather file with  
206 modified values of urban air temperature and relative humidity from a rural weather file.

207 The required input weather data, from the measurements at the rural weather station, include  
208 ambient dry bulb temperature [ $^{\circ}\text{C}$ ], relative humidity [%], wind direction [ $^{\circ}$ ] and speed [m/s],  
209 and rainfall [mm]. The horizontal direct and diffuse solar irradiances [ $\text{W}/\text{m}^2$ ] were calculated  
210 using the horizontal global solar irradiance measurements and the python pvlib library [55].  
211 Finally, the direct normal irradiance and the solar position were estimated with the DISC  
212 algorithm [56] and the PyEphem package [57].

213 The UWG model calculates the local UHI and overheating from a rural weather file. The  
214 model was validated in the cities of Toulouse (France), Basel (Switzerland) [58], Rome and  
215 Antofagasta (Italy) [20]. Furthermore, a study of the 2003 urban heatwave in downtown Paris  
216 (France) gave a good correlation between UWG simulations and the measured temperatures  
217 [7].

## 218 2.4 Urban planning strategies

### 219 2.4.1 Quantitative indicators

220 While no clear standard is available for urban planners, a large variety of tools and guidelines  
221 are available to policy makers, such as in the US [59] and France [60], especially to answer  
222 community requests relative to urban overheating issues. However, the spatial and temporal  
223 results obtained from numerical simulations and measurements are too precise, and therefore  
224 inappropriate to efficiently support stakeholders' decision-making. Martilli *et al.* [61] pointed  
225 out the importance of looking at thermal stress in preference to UHI intensity as way to  
226 propose heat mitigation strategies for urban stakeholders. While UHI intensity is useful  
227 complementary information that quantifies the anthropogenic contribution to local climate  
228 modification, the change in urban overheating in inhabited areas, especially during heatwaves,  
229 is also a crucial indicator. We therefore propose to convert the detailed scientific data into two  
230 easy-to-use indicators, initially to help fill the gap between the detailed evaluation and the  
231 decision process:

- 232 • UHI exposure at the neighborhood scale, related to local microclimate warming;
- 233 • Neighborhood overheating related to heat thermal discomfort.

234 UHI has been quantified using different indicators in many research articles. Schwarz *et al.*  
235 [62] discussed the relevance of eleven different surface UHI indicators, and noted a weak  
236 correlations among them. UHI intensity is typically quantified by air or surface temperature  
237 difference at a specific time-step between urban and reference rural weather stations [63–65]  
238 (Eq. (1)). We decided to take into account UHI intensity rather than UHI exposure ( $\text{UHI}_{\text{exp}}$   
239 [ $^{\circ}\text{C}\cdot\text{h}$ ], (Eq. (2)), which is a sum of positive differences between urban ( $T_{\text{urb},t}$ ) and rural ( $T_{\text{rur},t}$ )  
240 air temperatures.

$$\text{uhi}(t) = (T_{\text{urb},t} - T_{\text{rur},t})_{T_{\text{urb},t} > T_{\text{rur},t}} \quad (1)$$

$$\text{UHI}_{\text{exp}} = \sum_{t=0}^{n\Delta t} \text{uhi}(t) \times \Delta t \quad (2)$$

241 This cumulative intensity of UHI highlights the warming effect without the overstatements  
 242 induced by maximum intensities at some specific periods.

243 The rural reference definition impacts UHI intensity [66], and was studied by Vogel and  
 244 Afshari in the context of a coastal city [67]. They suggested different approaches:

- 245     ▪ The first approach is to locate both the reference rural and the urban weather stations  
 246         at the same distance from the coast, as during sea-breeze events the coastal effect is  
 247         also examined;
- 248     ▪ In the second approach, the reference is a virtual rural station located in an urban area  
 249         without the city effects, which can be obtained only from simulations;
- 250     ▪ The third approach analyses an upstream rural reference station (related to wind  
 251         direction), which gives similar results to the virtual reference method at nighttime.

252 In our approach, we used an inland reference rural weather station. Due to its location (see  
 253 Figure 1), this reference is upstream during land breeze events. In contrast, during sea breeze  
 254 events, the upstream reference station would be located in the sea, which is not relevant for  
 255 our study since our aim was to characterize inhabited areas. Given that the purpose of this  
 256 study was to determine the risk of an urban heat island for the inhabitants, we defined a rural  
 257 station that could serve as a reference when the wind was inland (wind from the east). In this  
 258 case, the city does not benefit from the refreshing marine breeze. Therefore, the positioning of  
 259 the rural station makes it possible to evaluate the most unfavorable case concerning the risk of  
 260 heat thermal discomfort.

261 For exposure to overheating, we adapted the Cooling Degree Hours indicator. This indicator,  
 262 originally defined for the building energy sector, is also used to characterize local urban

263 climate [68]. Outdoor overheating affects both indoor and outdoor thermal comfort. We did  
 264 not use thermal discomfort indexes (e.g., PMV, PET, or UTCI) due to the variety of locations  
 265 and activities, and the vulnerability of urban inhabitants. As residents are usually indoors at  
 266 night, the calculation of outdoor thermal discomfort is not relevant here. However, urban  
 267 overheating during nighttime may be critical and lead to significant heat-related health  
 268 impacts on the population.

269 The proposed overheating intensity was defined as the temperature difference between the air  
 270 temperature ( $T_{urb,t}$ ) and a threshold temperature ( $T_{overheat}$ ). This temperature threshold was set  
 271 at 26 °C during daytime, which is the cooling set-point for conditioned buildings as defined  
 272 by the French thermal regulation [69]. Since nighttime-overheating exposure is more sensitive  
 273 to the urban heat island, we also adopted a nighttime threshold of 21°C, a reference defined  
 274 by the Heat Health Warning System heatwave for the city of La Rochelle. At each time step,  
 275 the overheating intensity  $oh(t)$  was quantified by the positive temperature difference between  
 276 the outdoor air temperature and the threshold temperature, Eq. (3). Overheating exposure  
 277  $OH_{exp}$ , Eq. (4) is defined as the sum of the overheating intensities.

$$oh(t) = (T_{urb,t} - T_{overheat})_{T_{urb,t} > T_{overheat}} \quad (3)$$

$$OH_{exp} = \sum_{t=0}^{n\Delta t} oh(t) \times \Delta t \quad (4)$$

278

#### 279 2.4.2 Sensitivity analysis

280 In construction or renovation projects, the neighborhood adaptation strategies and design must  
 281 be analyzed through a multi-criteria analysis, which often lacks quantitative criteria and  
 282 objective levers of action. In order to further guide adaptation strategies, sensitivity analysis  
 283 (SA) helps to improve the understanding of model interactions and to identify the most  
 284 relevant urban parameters in order to mitigate outdoor overheating and local UHI. The Morris  
 285 method [70] has been used frequently in building design [71–73]. This method, also called the

286 elementary effects method, is a screening method used to estimate the elementary effects of  
287 the input parameters roughly corresponding to a first-order partial derivative. For each  
288 parameter studied, the Morris method evaluates the absolute average of the effects ( $\mu^*$ )  
289 corresponding to the mean effect of the parameter, as well as the standard deviation of these  
290 effects ( $\sigma$ ), which represents its interactions with the others parameters of interest (the  
291 sampling method is based on an iterative variation of the parameters). All parameters are then  
292 represented in the ( $\sigma$ - $\mu^*$ ) plan for the analysis of the results. We used a grid-jump of 6 (level  
293 of partition of the inputs domain) which was qualitatively estimated as sufficient to explore  
294 the domain of the parameter space.

295 The first step was to define the possible design parameters for the neighborhood studied and  
296 their bounds. In the literature, the morphological parameters have often been identified as  
297 prominent for UHI; however, in a refurbishment context, these parameters cannot be modified  
298 significantly. Other mitigation strategies have proven to be successful, such as an increase in  
299 cool and green surfaces, and a reduction of anthropogenic heat. We assessed the influence of  
300 five parameters, given fixed bounds: (i) road albedo (0.05 to 0.65); (ii) wall albedo (0.05 to  
301 0.85); (iii) anthropogenic heat (2 to 20 W/m<sup>2</sup>); (iv) building height (7 to 13 m); and (v)  
302 vegetation cover (0 to 85 %). We varied the building height to determine if adding one or two  
303 floors to a building would impact the UHI intensity or overheating. Anthropogenic heat was  
304 modulated following the default UWG weekly and daily schedule for urban traffic.

305 For the Morris method used here [70], we used a 100-trajectory sample , which corresponds to  
306 500 simulations with the specified parameters and their discretization steps (we used a grid-  
307 jump = 6). However, the SA approach is inconsistent for correlated parameters such as  
308 vegetation cover and the average albedo of urban surfaces. To tackle this problem, we first  
309 analyzed the albedo impact as a UHI mitigation strategy, given both the impact of the average

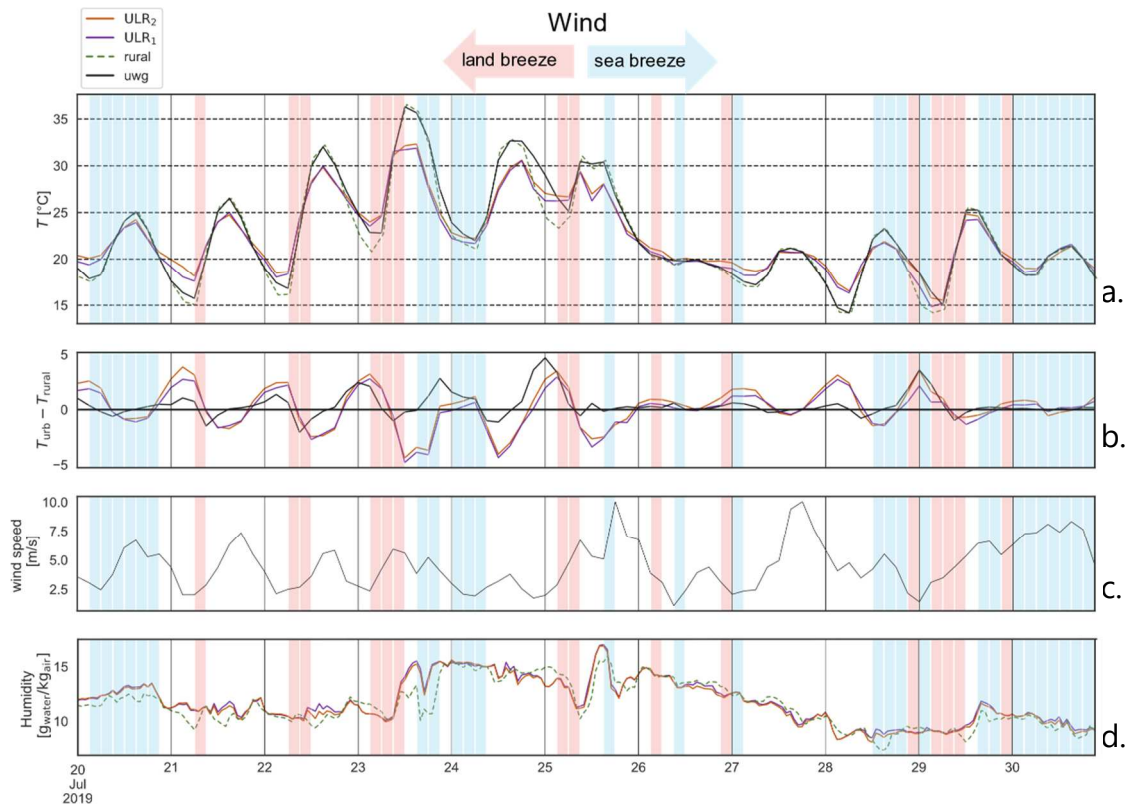


310 albedo for both roofs and walls. In the second step, we assessed the influence of vegetation  
311 cover, without albedo modifications for non-vegetated surfaces.

## 312 **3 Results**

### 313 3.1 Local microclimate – urban and coastal effect

314 This section presents and analyses the measurements made during the heatwave, from the 20<sup>th</sup>  
315 to the 30<sup>th</sup> July 2019. Figure 6 presents from top to bottom: air temperature, the temperature  
316 difference between the urban and rural stations, wind speed, and specific humidity. We  
317 compared the modelled temperatures (UWG) to the measurements, and we discuss the  
318 reliability of the model for our case study. It seems that the direction of the wind coming  
319 either from the sea or from the land affected the results, which is explained below. To  
320 understand the influence of the wind, the sea breeze periods (NNW 337° to SSW 202°) are  
321 highlighted in Figure 6 in blue, and the land breeze periods in red (NNE 22.5° to SSE 157.5°).



323

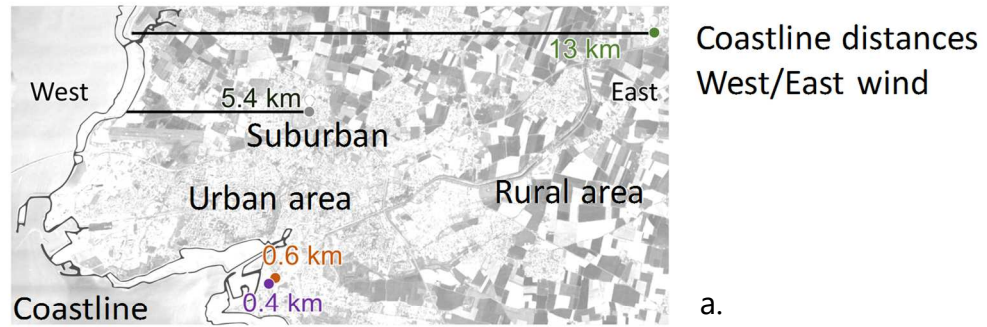
324 Figure 6: (a) Air temperature at the rural weather station for both urban weather stations during heatwave days in  
 325 La Rochelle and predicted by the UWG model (b) Temperature differences between rural/urban areas both  
 326 measured and predicted by the UWG model (c) Wind speed (d) Measured humidity

327 In Figure 6a, the urban heat island is recognizable during nighttime, where higher  
 328 temperatures were recorded at both urban stations (ULR1 and ULR2) than at the rural station.  
 329 A maximum of 4°C temperature difference was recorded during this period. The predicted  
 330 urban night temperatures (UWG) were higher than the rural measurements but lower in  
 331 comparison to the urban measurements. During the day the phenomenon was reversed, and  
 332 the measured temperatures in the urban area were lower than in the countryside, as illustrated  
 333 on Figure 6b. From July 20<sup>th</sup> to July 25<sup>th</sup>, the temperature difference between urban and rural  
 334 areas was positive during nighttime and negative during daytime, up to almost 5°C cooler on  
 335 the warmest days, July 23 and 24. The daily amplitude between temperature minima and  
 336 maxima in the local neighborhood was, therefore, greatly reduced compared to the  
 337 countryside.

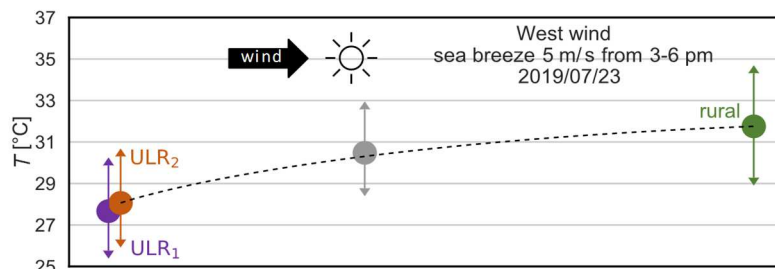
338 Daytime temperatures obtained from the UWG model were consistent with the rural weather  
339 station records. The model confirmed this trend during the night, but overestimated the  
340 temperature during daytime, especially on July 22<sup>nd</sup>, 23<sup>rd</sup> and 24<sup>th</sup>. To explore this divergence,  
341 we analyzed the wind direction and intensity (Figure 6c). The sea breeze was more likely to  
342 occur at the end of the day. With evaporation effects, this sea breeze contributed to a decrease  
343 in the temperature of the urban area. These local mass flows due to the sea were not modelled  
344 by the UWG model, which contributed to the observed divergences during daytime. Other  
345 studies using the UWG model observed an overestimation of the heat island during the day  
346 [74]. This overestimation may come from a poor assessment of the urban limit layer height,  
347 which is a challenging parameter to estimate. An improvement in the vertical model has been  
348 proposed recently [75].

349 This divergence was further investigated by analyzing the difference in absolute humidity  
350 between urban and rural areas, as represented in Figure 6d. During sea breeze events, the  
351 absolute humidity increased in the urban area, which contributed to the decrease in  
352 temperatures (Figure 6d, see evenings on July 20<sup>th</sup>, 23<sup>rd</sup>, 25<sup>th</sup>, 28<sup>th</sup> and 29<sup>th</sup>). The phenomenon  
353 rarely occurred during land breeze events.

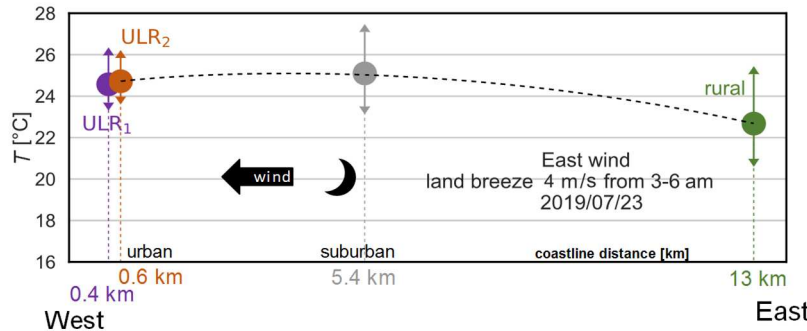
354 The influence of wind direction is more specifically addressed in Figure 7, during the hottest  
355 day of the heatwave under study (July 23<sup>rd</sup>).



a.



b.



c.

356

357 Figure 7: Day and night temperature distribution for 4 urban, suburban and rural weather stations, during the  
358 hottest day of the heatwave (July 23<sup>rd</sup>, 2019)

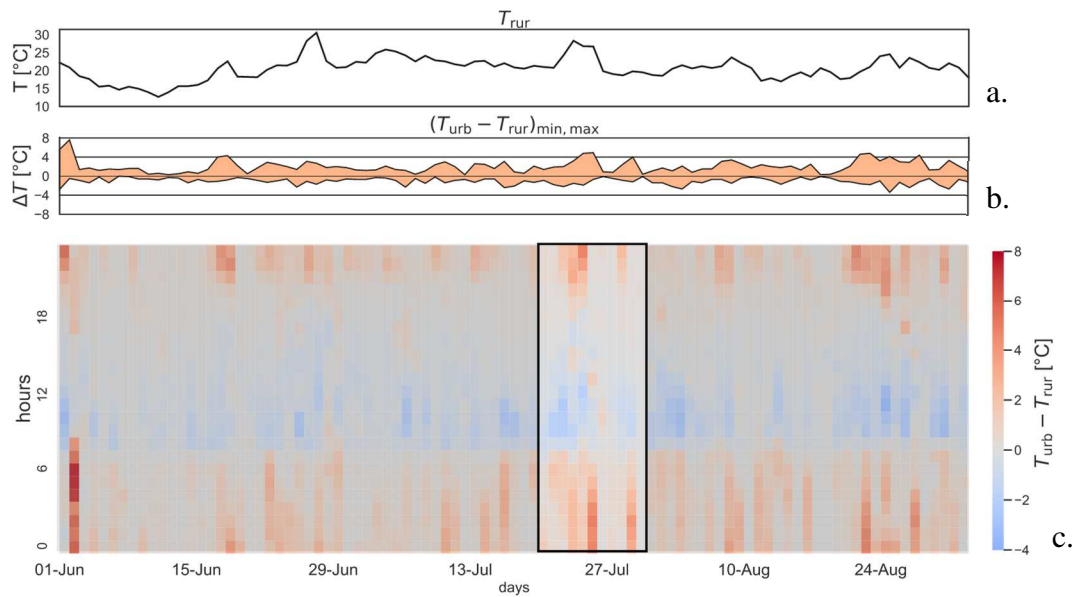
359 The coastline distance (Figure 7a) was defined for each weather station as the distance from  
360 the sea along the wind direction (from east and from west). The temperature values for  
361 specific periods of the day are represented for urban, suburban and rural areas, given the  
362 coastline distance (Figure 7b-c). At 5.4 km from the coastline (grey point), an additional  
363 suburban weather station was available in an industrial area north of La Rochelle (Figure 7a),  
364 identified as an LCZ 8. In Figure 7b, the temperatures were averaged over the three-hour  
365 interval in the afternoon, 3 PM to 6 PM, identified as a sea breeze event from the wind  
366 direction records. The arrows represent the minimum and maximum temperature intervals for  
367 this period. For the three-hour night period, from 3AM to 6 AM (Figure 7c), we observed a

368 land breeze event. During this night period, the air temperature decreased with the coastline  
369 distance from the urban, to the suburban, and to the rural stations. An average difference of  
370 2°C was observed between the urban and rural areas during the night. The suburban air  
371 temperature increased slightly due to the stronger local UHI effect and the reduced sea  
372 cooling effect, reinforced by the absence of a sea breeze and the greater distance from the  
373 coast compared to the urban location.

### 374 3.2 Urban heat island and overheating intensity

375 In this section, we analyze the experimental and numerical results using the previously  
376 defined indicators.

377 First, for the UHI intensity (see 2.4.1), the hourly rural temperature variation and the  
378 temperature difference  $\Delta T = T_{\text{urb}} - T_{\text{rur}}$ , estimated with the UWG model, are represented in  
379 Figure 8 for the summer (from June 1<sup>st</sup> to September 1<sup>st</sup>, 2019). Figure 8-a represents the rural  
380 temperature, Figure 8-b represents the daily maximum and minimum temperature differences,  
381 and Figure 8-c represents the hourly temperature difference distribution. The previously  
382 studied heatwave period is highlighted in black in Figure 8-c.

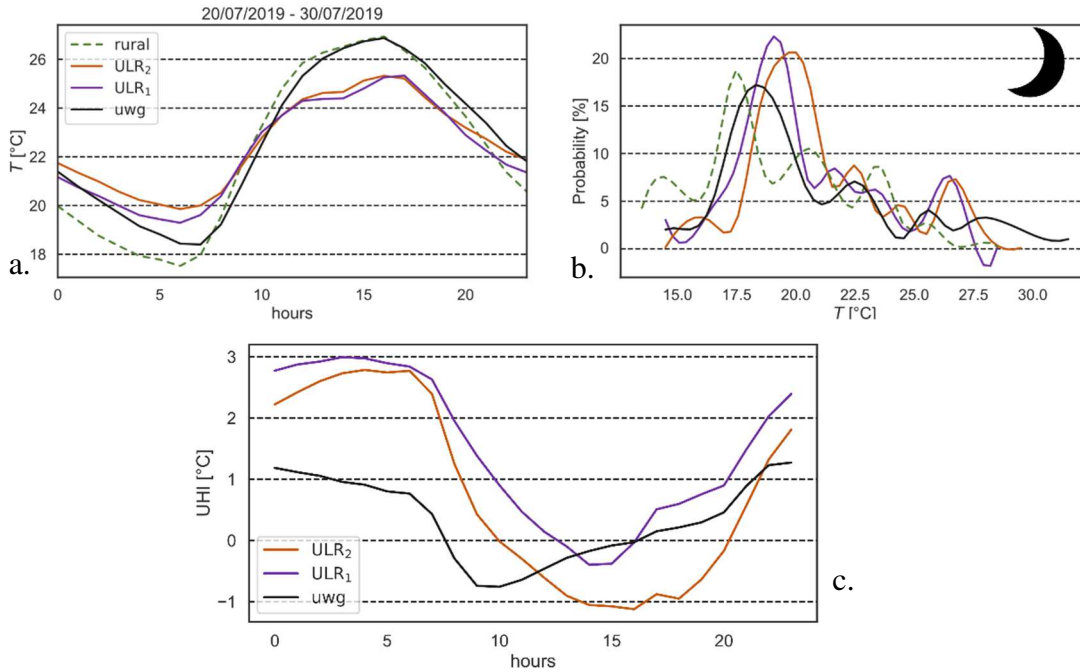


384

385 Figure 8: Daily rural temperature (a), daily maximum/minimum UHI temperature difference (b), and hourly UHI  
 386 temperature difference (c) for the La Rochelle University location, obtained with the UWG model, from June 01  
 387 to September 01.

388 In Figure 8-c, the cool island effects ( $\Delta T < 0$ ) were observed between 7 AM and 6 PM (blue  
 389 color, these values were excluded from the  $UHI_{exp}$  calculation). The urban local microclimate  
 390 is often cooler than the rural area during daytime, which is due to the thermal mass of the  
 391 buildings and the shadow effects in the urban context that are taken into account by the UWG  
 392 model. However, the daytime hourly cooling effect from the UWG model was underestimated  
 393 compared to the measurements, as UWG does not account for the presence of the sea. The  
 394 UHI (red-colored hours) mainly occurred at night. In comparison with the measurements, for  
 395 both urban locations ( $ULR_1$  and  $ULR_2$ ), UHI exposure ( $UHI_{exp}$ ) during the heatwave (July  
 396 20<sup>th</sup> to 30<sup>th</sup>, 2019) was around seven times higher during nighttime than daytime. During this  
 397 period, the modelled values (Figure 8-c) of the nighttime  $UHI_{exp}$  (128 °C.h) were slightly  
 398 underestimated compared to the experimental  $UHI_{exp}$  values, 153 °C.h and 213 °C.h for  $ULR_1$   
 399 and  $ULR_2$ , respectively.

400 For the same period, Figure 9a presents the average daily temperature profile obtained from  
 401 ULR<sub>1</sub>, ULR<sub>2</sub>, and the rural weather stations, and the modelled urban area with UWG. Figure  
 402 9b presents the temperature distribution during the same heatwave for the UHI at night.

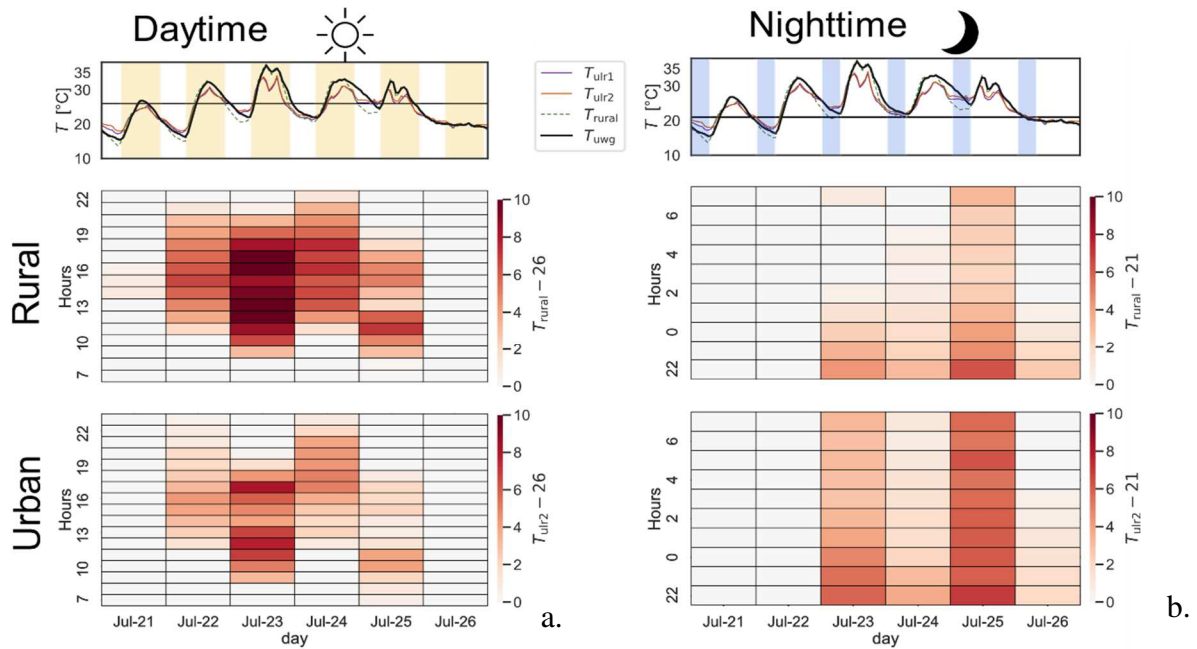


403  
 404 Figure 9: (a) Daily temperature profile for ULR<sub>1</sub>, ULR<sub>2</sub>, the rural weather station and UWG (from July 20 to 30,  
 405 2019), (b) The probability distribution for nighttime temperature and (c) The UHI distribution for ULR<sub>1</sub>, ULR<sub>2</sub>  
 406 and UWG

407 At night, the UHI effect observed by the model was close to the measurements, and the  
 408 temperature in urban areas was 1.5 °C higher than in rural areas. (Figure 9a). The variation in  
 409 UWG temperature was consistent with the measurement from 10 PM to 4 AM. However, as  
 410 previously observed (Figure 6), the early morning temperatures were underestimated by the  
 411 model, while the calculated temperatures did not represent correctly the observed daytime  
 412 temperature decrease in an urban context, which was due to the coastal effects.

413 In terms of outdoor overheating (defined in 2.4.1), and focusing on the hottest days (from July  
 414 21<sup>st</sup> to July 26<sup>th</sup>, 2019), Figure 10 shows the hourly variation of the  $OH_{exp}$  for both the rural  
 415 and urban weather station ULR<sub>2</sub>. The figure shows the temporal series of ULR<sub>1</sub>, ULR<sub>2</sub>, the  
 416 rural stations and UWG. In addition, we chose to present heatmaps of the indicators,

417 comparing the rural and the ULR<sub>2</sub> weather stations; ULR<sub>2</sub> was selected because it is in a more  
 418 urbanized location than URL<sub>1</sub> and has a higher risk of overheating.



419  
 420 Figure 10: Hourly temperature variation (top), and hourly overheating variation for rural and urban (bottom) -  
 421 during daytime (a) and nighttime (b) - from July 21<sup>st</sup> to July 26<sup>th</sup>

422 The hourly temperature variation is presented at the top of Figure 10. The periods are  
 423 highlighted in yellow for daytime (7 AM to 10 PM, Figure 10a) and in blue for nighttime  
 424 (10 PM to 6 AM, Figure 10b). During daytime (Figure 10a), the rural area was more  
 425 vulnerable to the heatwave than the urban area (ULR<sub>2</sub>). On July 23<sup>rd</sup> (daytime), the maximum  
 426 overheating intensity reached +10 °C at the rural station, while that of urban stations close to  
 427 the coast and cooler than the rural stations was only + 7 ° C. In contrast, nighttime  
 428 overheating was higher in the urban area, where it increased up to +6.3 °C, compared to +4  
 429 °C at the rural station. This maximum nighttime overheating (Figure 10b) was observed two  
 430 days later (July 25<sup>th</sup>). For the hottest day (July 23<sup>rd</sup>), urban nighttime overheating remained  
 431 much lower than rural overheating. Over the period, urban (ULR<sub>2</sub>) daytime overheating  
 432 (OH<sub>exp</sub> = 140 °Ch) was 45 % lower than that in the rural area (OH<sub>exp</sub> = 249 °Ch). Nighttime



433 overheating for the urban area was well quantified by the same  $OH_{exp}$  indicator, which was  
 434 95 % higher than the rural indicator, 126 °Ch and 64 °Ch, respectively.

435 Table 2 summarizes the  $UHI_{exp}$  and  $OH_{exp}$  indicators for daytime and nighttime as well as for  
 436 different urban/rural areas and the UWG model.

437 Table 2:  $UHI_{exp}$  and  $OH_{exp}$  indicators for daytime and nighttime, obtained from the urban weather stations  
 438 ( $ULR_1$  and  $ULR_2$ ) and the model (UWG), for the heatwave period (July 20<sup>th</sup> to 30<sup>th</sup>, 2019)

		<b>ULR<sub>1</sub></b>	<b>ULR<sub>2</sub></b>	<b>UWG</b>	<b>rural</b>
$UHI_{exp}$ [°C.h]	Day	20	25	29	-
	Night	153	213	128	-
$OH_{exp}$ [°C.h]	Day	133	140	248	249
	Night	107	126	134	64

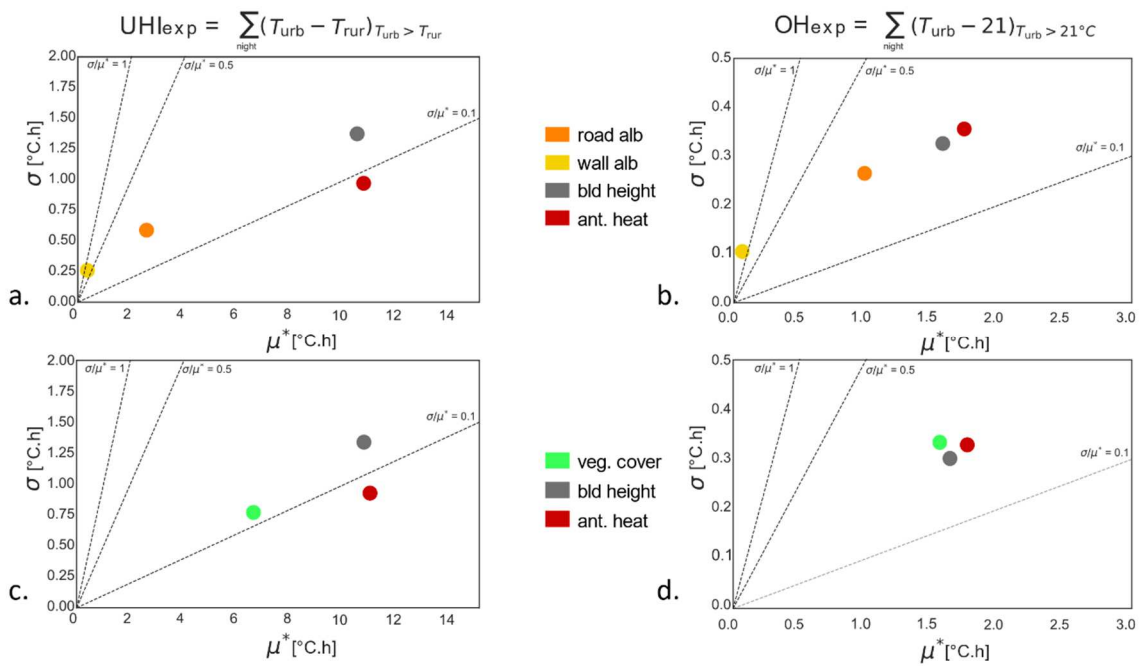
439  
 440 Within the same LCZ 5 neighborhood ( $ULR_1$  and  $ULR_2$  weather stations), the  $UHI_{exp}$  was  
 441 amplified from day to night by a factor of about seven. However, significant  $UHI_{exp}$   
 442 differences were observed between  $ULR_1$  and  $ULR_2$ , with 25 % for daytime and 39 % for  
 443 nighttime, respectively (Table 2). This can be explained by the vegetated area surrounding the  
 444  $ULR_1$  weather station, which was also more exposed to winds, while the  $ULR_2$  weather  
 445 station was located within a courtyard surrounded by buildings. While the simplified UWG  
 446 model was not consistent with daily urban temperature variations (grayed in Table 2), this  
 447 approach gave a good representation of the nighttime variations.

448 Overheating exposure was much more homogeneous within the neighborhood under study, as  
 449 observed for  $ULR_1$  and  $ULR_2$ , with a 5 %  $OH_{exp}$  difference for daytime, and a 18 %  $OH_{exp}$   
 450 difference for nighttime (Table 2). As expected, the simplified modelling approach (UWG)  
 451 significantly overestimated daytime overheating. However, this model (UWG) gave a good  
 452 assessment of nighttime overheating compared to the urbanized area, represented by the  $ULR_2$   
 453 station, where the overestimation of the nighttime  $OH_{exp}$  was only about 6%.

454 Therefore, the modelling approach and the proposed indicators were further analyzed during  
 455 nighttime for the UHI intensity and overheating effects.

456 3.3 Neighborhood design parameters

457 The key urban parameters for this case study, for both the intensity of outdoor overheating  
 458 and UHI ( $OH_{exp}$  and  $UHI_{exp}$ ), were identified using the sensitivity analysis (SA) results  
 459 (Figure 11). The SA objective functions ( $OH_{exp}$  and  $UHI_{exp}$ ) were numerically determined  
 460 with the UWG model, over the nighttime summer period from June 1<sup>st</sup> to September 1<sup>st</sup>.  
 461 Indeed, we excluded the daytime periods as they include sea breeze events not taken into  
 462 account by the model. This was observed in the experimental comparison of  $OH_{exp}$  and  
 463  $UHI_{exp}$  (Table 2). The SA model inputs are the urban design parameters, and its output  
 464 objective function is either the indicator  $UHI_{exp}$ , or  $OH_{exp}$ . The UWG model was run several  
 465 times through the Morris design matrix to identify the most influential parameters. The SA  
 466 results provided the average variation  $\mu^*$  [ $^{\circ}Ch$ ] (x-axis) and the standard deviation  $\sigma$  [ $^{\circ}Ch$ ] (y-  
 467 axis) of the elementary effects for each parameter. A parameter effect is considered as almost  
 468 linear if  $\sigma / \mu^* < 0.1$ , quasi-monotonic if  $0.5 < \sigma / \mu^* < 1$ , and non-monotonic (i.e., interactions  
 469 with other parameters) if  $\sigma / \mu^* > 1$ . If  $\sigma / \mu^* < 0.5$ , the parameter can be considered as  
 470 independent from the other parameters.



471

472 Figure 11: sensitivity analysis for UHI intensity (left) and overheating (right) - for albedo strategies (top) and  
473 vegetation (bottom) - from July 20<sup>th</sup> to 30<sup>th</sup>, 2019.

474 The results for UHI exposure for the nighttime summer period (Figure 11a,c) for variations in  
475 both albedo and vegetation cover, suggest that the parameters are independent, with an almost  
476 linear effect. The height of the buildings, anthropogenic heat and vegetation cover were the  
477 parameters that had the most impact, regarding the absolute values  $\mu^*$ . This means that, of the  
478 parameters studied, these have the highest potential to mitigate urban heat stress. The road  
479 and wall albedo had a smaller effect, which could be due to the lower impacts of daily solar  
480 heat gain over the nighttime period for this case study. For the overheating exposure  $OH_{exp}$   
481 during the nighttime summer period (Figure 11b,d), the key parameter sensitivities were  
482 similarly classified, except road albedo (orange point, Figure 11) and vegetation cover (green  
483 point, Figure 11), which had a relative increased sensitivity. While the impacts of vegetation  
484 on the urban microclimate are well documented, this approach highlights possible differences  
485 depending on the indicator of interest. The importance of urban morphology parameters was  
486 also emphasized by Salvati *et al.*[20] using the UWG model. While the use of the Morris  
487 method requires a certain expertise, the results can easily be used by city stakeholders to rank  
488 the impact of the parameters on urban overheating. These help to identify the main strategies  
489 that should be implemented to mitigate the hot spots of a city previously identified during the  
490 mapping of the urban zones (Figure 2). Therefore, this method helps establish priorities in the  
491 plans of action.

## 492 **4 Discussion**

493 For this coastal city case study, the measurements revealed a cooling sea breeze effect during  
494 the daytime. Although both ULR<sub>1</sub> and ULR<sub>2</sub> weather stations were close to each other and  
495 had similar variations in temperature, significant differences were obtained for both UHI and  
496 overheating exposure. These results highlight the impact of the thermal heterogeneity of the  
497 urban environment. Moreover, beyond the usual characterization of a LCZ, the indicators

498 obtained show that the evaluation of the risk of overheating in inhabited places may require  
499 multiplying the measurement points within this LCZ.

500 Similarly to our case study, the littoral urban microclimate was characterized in Sydney by  
501 Khan *et al.* [76] during a heatwave in 2017. A significant difference of 10 °C was measured  
502 between urban and rural areas. Wind intensity and direction were identified as key parameters  
503 for the advective heat fluxes. It was observed that the humidity difference between the urban  
504 zone and the rural surroundings was also an important factor affecting the urban  
505 microclimate. Unlike our case study, Khan *et al.* observed a higher UHI intensity during  
506 daytime, which they explained by the surrounding desert of Sydney. Yet, the same cooling-  
507 down effect was observed at the end of the night at the coastal stations. Founda and  
508 Santamouris [8] observed sea breeze effects on the urban air temperature and humidity for the  
509 Mediterranean city of Athens, Greece. They underlined the fact that the water heat capacity  
510 dampens the daily temperature variations and the daytime UHI, as in Figure 9a. This  
511 phenomenon was also noted by Long *et al.* [7] during the ESCOMPTE project for the  
512 Mediterranean city of Marseille, France. While our measurements confirm the tendencies  
513 found in other studies, the main findings of this case study concern the variations in exposure  
514 (Table 2), especially between day and night. The comparison of this evaluation process for  
515 other locations and cities will give a better understanding of the variation in amplitude of  
516 these exposure indicators.

517 From a modelling point of view, UWG is a practical tool for comparing urban design options,  
518 based on a reduced number of inputs. However, as a counterpart to the simplicity of this one-  
519 node model at the neighborhood scale, it cannot englobe the spatial heterogeneity for a deeper  
520 analysis within the zone, nor account for the regional surroundings, such as large bodies of  
521 water. Indeed, a comparison of the two urban stations revealed episodic differences. More  
522 complex models could be used [77], with a refined spatial resolution to access urban fabric

523 temperature distribution, more realistic shadow effects, and wind patterns. Yet, such a  
524 detailed analysis is not suitable for decision support for stakeholders in the initial steps of the  
525 design stage. So, determining the tendencies of the impacts of these simple design parameters,  
526 such as vegetation cover, will then guide urban planners for much more detailed plans, given  
527 the complex urban constraints that cannot be taken into account in the extensive sensitivity  
528 analysis. In a further step, new or innovative greening techniques could, for example, be used  
529 to maximize the vegetation effects identified here.

530 The adaptation strategies suggested by the SA results are highly dependent on the period of  
531 investigation, the indicators, and the range of variation of the input parameters. The proposed  
532 SA was restricted to the nighttime periods, which was relevant for this case-study as the UHI  
533 intensity was higher at night. The results showed that vegetation cover, the height of the  
534 buildings, and anthropogenic heat had the most impact on the variations in  $UHI_{exp}$  and  $OH_{exp}$ .  
535 The results may differ for other cities with higher daytime UHI effects or other indicators,  
536 such as the surface UHI effect.

## 537 **5 Conclusions**

538 We propose a methodology that meets the need to characterize the UHI effect at the  
539 neighborhood scale. This methodology was used in a coastal case-study of the university  
540 neighborhood in La Rochelle, close to the city center. An extended study including additional  
541 weather stations within the city is ongoing. While the coastal effect demonstrated a mitigation  
542 effect during the daytime, the UHI was more pronounced during nighttime, which is expected  
543 in French cities. The measurements revealed a nocturnal UHI effect, with an average  
544 temperature increase of +2 °C, which reached +8 °C on the warmest days. This high increase  
545 during a heatwave stresses the importance of this work, which is designed to provide key  
546 indicators and general guidelines for stakeholders to reduce urban heat stress during future  
547 heatwaves. Both UHI and overheating intensities were studied and quantified through  $UHI_{exp}$

548 and  $OH_{exp}$  indicators, which we defined to assist the analysis of the results. The UHI intensity  
549 increased by seven from day to night for both urban locations. The urban outdoor overheating  
550 exposure, quantified by the sum of urban hourly air temperatures above specific daytime and  
551 nighttime thresholds, was higher during daytime. The experimental part of this research work  
552 highlighted the pitfalls to avoid in order to improve measurement reliability. The  
553 methodology could be enriched with a more detailed urban microclimate model.

554 The analysis highlighted non-negligible differences in these indicators between the two urban  
555 weather stations, located within the same LCZ. These results are limited to a single case  
556 study, yet they are consistent with more extensive studies on temperature variation within  
557 LCZs [45]. While the LCZ scale is a useful initial approach to roughly classify a city into  
558 zones with UHI or overheating risks, as proposed in our methodology (see Figure 2), and to  
559 analyze the various neighborhood scale strategies (see section 3.3), urban planners need to  
560 assess more precisely the risk of overheating at the building or inhabitant scale. The  
561 experiments confirmed the ability of both aggregated and simple indicators to capture local  
562 variations. They have the potential to be a convenient tool for the evaluation of urban  
563 strategies. Furthermore, this emphasizes the need to be cautious when using LCZ-scale results  
564 in implementing urban cooling strategies.

565 The consistency of the UWG model in representing nighttime UHI and overheating  
566 intensities, in comparison with the measurements made it possible to study the sensitivity of  
567 several urban design parameters during the extended summer period. The results showed that  
568 anthropogenic heat release, vegetation cover and the height of buildings were key design  
569 parameters that need to be taken into account in order to mitigate the local microclimate air  
570 temperature in a given neighborhood. The adaptation strategies we identified could help to  
571 define strategies to mitigate the expected increase of UHI and outdoor overheating, while the

572 precise detection of hot spots will provide insights into where it is most efficient to implement  
573 these strategies.

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## 580 **7 References**

- 581 [1] K.C. Seto, M. Fragkias, B. Güneralp, M.K. Reilly, A Meta-Analysis of Global Urban Land  
582 Expansion, PLOS ONE. 6 (2011) e23777. <https://doi.org/10.1371/journal.pone.0023777>.
- 583 [2] M. Santamouris, Energy and Climate in the Urban Built Environment, Routledge, 2013.
- 584 [3] H.H. KIM, Urban heat island, International Journal of Remote Sensing. 13 (1992) 2319–  
585 2336. <https://doi.org/10.1080/01431169208904271>.
- 586 [4] C. Heaviside, S. Vardoulakis, X.-M. Cai, Attribution of mortality to the urban heat island  
587 during heatwaves in the West Midlands, UK, Environmental Health. 15 (2016) S27.  
588 <https://doi.org/10.1186/s12940-016-0100-9>.
- 589 [5] J. Paravantis, M. Santamouris, C. Cartalis, C. Efthymiou, N. Kontoulis, Mortality Associated  
590 with High Ambient Temperatures, Heatwaves, and the Urban Heat Island in Athens,  
591 Greece, Sustainability. 9 (2017) 606. <https://doi.org/10.3390/su9040606>.
- 592 [6] X.-M. Hu, M. Xue, Influence of Synoptic Sea-Breeze Fronts on the Urban Heat Island  
593 Intensity in Dallas–Fort Worth, Texas, Mon. Wea. Rev. 144 (2015) 1487–1507.  
594 <https://doi.org/10.1175/MWR-D-15-0201.1>.
- 595 [7] N. Long, G. Pigeon, P.G. MESTAYER, P. Durand, C. Kergomard, Correlation between  
596 temperature and classification of urban fabric on Marseille during ESCOMPTE, in: 5th  
597 International Conference on Urban Climate, Lodz, Poland, 2003. [https://hal.archives-  
598 ouvertes.fr/hal-01155989](https://hal.archives-ouvertes.fr/hal-01155989) (accessed May 15, 2020).
- 599 [8] D. Founda, M. Santamouris, Synergies between Urban Heat Island and Heat Waves in  
600 Athens (Greece), during an extremely hot summer (2012), Scientific Reports. 7 (2017)  
601 10973. <https://doi.org/10.1038/s41598-017-11407-6>.
- 602 [9] G. Ulpiani, On the linkage between urban heat island and urban pollution island: Three-  
603 decade literature review towards a conceptual framework, Science of The Total  
604 Environment. 751 (2021) 141727. <https://doi.org/10.1016/j.scitotenv.2020.141727>.
- 605 [10] B.-J. He, J. Wang, H. Liu, G. Ulpiani, Localized synergies between heat waves and urban  
606 heat islands: Implications on human thermal comfort and urban heat management,  
607 Environmental Research. 193 (2021). <https://doi.org/10.1016/j.envres.2020.110584>.
- 608 [11] P. Kristensen, European Environment Agency, Climate change, impacts and vulnerability  
609 in Europe 2012: an indicator-based report, Publications Office, Luxembourg, 2012.

- 610 [12] S. Kovats, T. Wolf, B. Menne, Heatwave of August 2003 in Europe: provisional estimates  
611 of the impact on mortality, *Weekly Releases (1997–2007)*. 8 (2004) 2409.  
612 <https://doi.org/10.2807/esw.08.11.02409-en>.
- 613 [13] J.-M. Robine, S.L.K. Cheung, S. Le Roy, H. Van Oyen, C. Griffiths, J.-P. Michel, F.R.  
614 Herrmann, Death toll exceeded 70,000 in Europe during the summer of 2003, *C. R. Biol.*  
615 331 (2008) 171–178. <https://doi.org/10.1016/j.crv.2007.12.001>.
- 616 [14] K. Laaidi, A. Zeghnoun, B. Dousset, P. Bretin, S. Vandentorren, E. Giraudet, P. Beaudeau,  
617 The Impact of Heat Islands on Mortality in Paris during the August 2003 Heat Wave,  
618 *Environ Health Perspect.* 120 (2012) 254–259. <https://doi.org/10/dpkxqr>.
- 619 [15] The SW Ecodistrict, *A Vision Plan for a More Sustainable Future*, (n.d.) 122.
- 620 [16] EcoDistricts | AustinTexas.gov, (n.d.).  
621 <https://www.austintexas.gov/departments/ecodistricts-0> (accessed September 13, 2021).
- 622 [17] A. Machard, S. Martinez, E. Bozonnet, E. Lacedra, C. Inard, How to assess ecodistrict  
623 resilience to urban heat stress under future heatwaves? A case study for the city of  
624 Paris., 1st International Conference on Climate Resilient Built Environment-ICRBE, 21-23  
625 September 2020, Bali, Indonesia. 1st International Conference on Climate Resilient Built  
626 Environment-ICRBE, 21-23 September 2020, Bali, Indonesia (2020).
- 627 [18] I.D. Stewart, T.R. Oke, Local Climate Zones for Urban Temperature Studies, *Bulletin of*  
628 *the American Meteorological Society.* 93 (2012) 1879–1900.  
629 <https://doi.org/10.1175/BAMS-D-11-00019.1>.
- 630 [19] A. Nakano, B. Bueno, L. Norford, C.F. Reinhart, Urban Weather Generator - a Novel  
631 Workflow for Integrating Urban Heat Island Effect within Urban Design Process, MIT  
632 Web Domain. (2015). <https://dspace.mit.edu/handle/1721.1/108779> (accessed July 29,  
633 2020).
- 634 [20] A. Salvati, M. Palme, G. Chiesa, M. Kolokotroni, Built form, urban climate and building  
635 energy modelling: case-studies in Rome and Antofagasta, *Journal of Building*  
636 *Performance Simulation.* 13 (2020) 209–225.  
637 <https://doi.org/10.1080/19401493.2019.1707876>.
- 638 [21] M. Palme, L. Inostroza, G. Villacreses, A. Lobato-Cordero, C. Carrasco, From urban  
639 climate to energy consumption. Enhancing building performance simulation by  
640 including the urban heat island effect, *Energy and Buildings.* 145 (2017) 107–120.  
641 <https://doi.org/10.1016/j.enbuild.2017.03.069>.
- 642 [22] J. Parker, The Leeds urban heat island and its implications for energy use and thermal  
643 comfort, *Energy and Buildings.* 235 (2021) 110636.  
644 <https://doi.org/10.1016/j.enbuild.2020.110636>.
- 645 [23] A. Boccalatte, M. Fossa, L. Gaillard, C. Menezo, Microclimate and urban morphology  
646 effects on building energy demand in different European cities, *Energy and Buildings.*  
647 224 (2020) 110129. <https://doi.org/10.1016/j.enbuild.2020.110129>.
- 648 [24] S. Tsoka, K. Tolika, T. Theodosiou, K. Tsikaloudaki, D. Bikas, A method to account for the  
649 urban microclimate on the creation of ‘typical weather year’ datasets for building energy  
650 simulation, using stochastically generated data, *Energy and Buildings.* 165 (2018) 270–  
651 283. <https://doi.org/10.1016/j.enbuild.2018.01.016>.
- 652 [25] L.G.R. Santos, A. Afshari, L.K. Norford, J. Mao, Evaluating approaches for district-wide  
653 energy model calibration considering the Urban Heat Island effect, *Applied Energy.* 215  
654 (2018) 31–40. <https://doi.org/10.1016/j.apenergy.2018.01.089>.



- 655 [26] L.G.R. Santos, I. Nevat, G. Pignatta, L.K. Norford, Climate-informed decision-making for  
656 urban design: Assessing the impact of urban morphology on urban heat island, *Urban*  
657 *Climate*. 36 (2021) 100776. <https://doi.org/10.1016/j.uclim.2021.100776>.
- 658 [27] A. Salvati, M. Palme, G. Chiesa, M. Kolokotroni, Built form, urban climate and building  
659 energy modelling: case-studies in Rome and Antofagasta, *Journal of Building*  
660 *Performance Simulation*. 13 (2020) 209–225.  
661 <https://doi.org/10.1080/19401493.2019.1707876>.
- 662 [28] L. Chapman, J.A. Azevedo, T. Prieto-Lopez, Urban heat & critical infrastructure networks:  
663 A viewpoint, *Urban Climate*. 3 (2013) 7–12. <https://doi.org/10.1016/j.uclim.2013.04.001>.
- 664 [29] T.R. Oke, City size and the urban heat island, *Atmospheric Environment* (1967). 7 (1973)  
665 769–779. [https://doi.org/10.1016/0004-6981\(73\)90140-6](https://doi.org/10.1016/0004-6981(73)90140-6).
- 666 [30] M. Santamouris, Recent progress on urban overheating and heat island research.  
667 Integrated assessment of the energy, environmental, vulnerability and health impact.  
668 Synergies with the global climate change, *Energy and Buildings*. 207 (2020) 109482.  
669 <https://doi.org/10.1016/j.enbuild.2019.109482>.
- 670 [31] M. Santamouris, C. Cartalis, A. Synnefa, D. Kolokotsa, On the impact of urban heat island  
671 and global warming on the power demand and electricity consumption of buildings—A  
672 review, *Energy and Buildings*. 98 (2015) 119–124.  
673 <https://doi.org/10.1016/j.enbuild.2014.09.052>.
- 674 [32] T. Susca, S.R. Gaffin, G.R. Dell’Osso, Positive effects of vegetation: Urban heat island and  
675 green roofs, *Environmental Pollution*. 159 (2011) 2119–2126.  
676 <https://doi.org/10.1016/j.envpol.2011.03.007>.
- 677 [33] S. Bonafoni, G. Baldinelli, P. Verducci, Sustainable strategies for smart cities: Analysis of  
678 the town development effect on surface urban heat island through remote sensing  
679 methodologies, *Sustainable Cities and Society*. 29 (2017) 211–218.  
680 <https://doi.org/10.1016/j.scs.2016.11.005>.
- 681 [34] H. Taha, H. Akbari, A. Rosenfeld, J. Huang, Residential cooling loads and the urban heat  
682 island—the effects of albedo, *Building and Environment*. 23 (1988) 271–283.  
683 [https://doi.org/10.1016/0360-1323\(88\)90033-9](https://doi.org/10.1016/0360-1323(88)90033-9).
- 684 [35] A.G. Touchaei, M. Hosseini, H. Akbari, Energy savings potentials of commercial buildings  
685 by urban heat island reduction strategies in Montreal (Canada), *Energy and Buildings*.  
686 110 (2016) 41–48. <https://doi.org/10.1016/j.enbuild.2015.10.018>.
- 687 [36] E.J. Gago, J. Roldan, R. Pacheco-Torres, J. Ordóñez, The city and urban heat islands: A  
688 review of strategies to mitigate adverse effects, *Renewable and Sustainable Energy*  
689 *Reviews*. 25 (2013) 749–758. <https://doi.org/10.1016/j.rser.2013.05.057>.
- 690 [37] M. Santamouris, Using cool pavements as a mitigation strategy to fight urban heat  
691 island—A review of the actual developments, *Renewable and Sustainable Energy*  
692 *Reviews*. 26 (2013) 224–240. <https://doi.org/10.1016/j.rser.2013.05.047>.
- 693 [38] W.P. Lowry, Empirical Estimation of Urban Effects on Climate: A Problem Analysis,  
694 *Journal of Applied Meteorology and Climatology*. 16 (1977) 129–135.  
695 [https://doi.org/10.1175/1520-0450\(1977\)016<0129:EEOUEO>2.0.CO;2](https://doi.org/10.1175/1520-0450(1977)016<0129:EEOUEO>2.0.CO;2).
- 696 [39] I.D. Stewart, A systematic review and scientific critique of methodology in modern urban  
697 heat island literature, *Int. J. Climatol*. 31 (2011) 200–217.  
698 <https://doi.org/10.1002/joc.2141>.
- 699 [40] G. Pigeon, A. Lemonsu, N. Long, J. Barrié, V. Masson, P. Durand, Urban Thermodynamic  
700 Island in a Coastal City Analysed from an Optimized Surface Network, *Boundary-Layer*  
701 *Meteorol*. 120 (2006) 315–351. <https://doi.org/10.1007/s10546-006-9050-z>.

- 702 [41] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World Map of the Köppen-Geiger  
703 climate classification updated, *Meteorologische Zeitschrift*. (2006) 259–263.  
704 <https://doi.org/10.1127/0941-2948/2006/0130>.
- 705 [42] N.G.R. Perera, R. Emmanuel, A “Local Climate Zone” based approach to urban planning  
706 in Colombo, Sri Lanka, *Urban Climate*. 23 (2018) 188–203.  
707 <https://doi.org/10.1016/j.uclim.2016.11.006>.
- 708 [43] B. Bechtel, P.J. Alexander, J. Böhner, J. Ching, O. Conrad, J. Feddema, G. Mills, L. See, I.  
709 Stewart, Mapping Local Climate Zones for a Worldwide Database of the Form and  
710 Function of Cities, *ISPRS International Journal of Geo-Information*. 4 (2015) 199–219.  
711 <https://doi.org/10.3390/ijgi4010199>.
- 712 [44] T. Gardes, R. Schoetter, J. Hidalgo, N. Long, E. Marquès, V. Masson, Statistical prediction  
713 of the nocturnal urban heat island intensity based on urban morphology and  
714 geographical factors - An investigation based on numerical model results for a large  
715 ensemble of French cities, *Science of The Total Environment*. 737 (2020) 139253.  
716 <https://doi.org/10.1016/j.scitotenv.2020.139253>.
- 717 [45] N. Long, T. Gardes, J. Hidalgo, V. Masson, R. Schoetter, Influence of the urban  
718 morphology on the urban heat island intensity: an approach based on the Local Climate  
719 Zone classification, *PeerJ Inc.*, 2018. <https://doi.org/10.7287/peerj.preprints.27208v1>.
- 720 [46] Y. Richard, J. Emery, J. Dudek, J. Pergaud, C. Chateau-Smith, S. Zito, M. Rega, T. Vairet, T.  
721 Castel, T. Thévenin, B. Pohl, How relevant are local climate zones and urban climate  
722 zones for urban climate research? Dijon (France) as a case study, *Urban Climate*. 26  
723 (2018) 258–274. <https://doi.org/10.1016/j.uclim.2018.10.002>.
- 724 [47] T. Houet, G. Pigeon, Mapping urban climate zones and quantifying climate behaviors -  
725 An application on Toulouse urban area (France), *Environmental Pollution*. 159 (2011)  
726 2180–2192. <https://doi.org/10.1016/j.envpol.2010.12.027>.
- 727 [48] T.R. Oke, INSTRUMENTS AND OBSERVING METHODS REPORT No. 8, (n.d.) 51.
- 728 [49] OpenStreetMap, OpenStreetMap. (n.d.). <https://www.openstreetmap.org/copyright>  
729 (accessed June 8, 2021).
- 730 [50] N. Haala, C. Brenner, Extraction of buildings and trees in urban environments, *ISPRS*  
731 *Journal of Photogrammetry and Remote Sensing*. 54 (1999) 130–137.  
732 [https://doi.org/10.1016/S0924-2716\(99\)00010-6](https://doi.org/10.1016/S0924-2716(99)00010-6).
- 733 [51] G. Pigeon, D. Legain, P. Durand, V. Masson, Anthropogenic heat release in an old  
734 European agglomeration (Toulouse, France), *International Journal of Climatology*. 27  
735 (2007) 1969–1981. <https://doi.org/10.1002/joc.1530>.
- 736 [52] D.J. Sailor, A review of methods for estimating anthropogenic heat and moisture  
737 emissions in the urban environment, *International Journal of Climatology*. 31 (2011)  
738 189–199. <https://doi.org/10.1002/joc.2106>.
- 739 [53] I.D. Stewart, T.R. Oke, Local Climate Zones for Urban Temperature Studies, *Bull. Amer.*  
740 *Meteor. Soc.* 93 (2012) 1879–1900. <https://doi.org/10.1175/BAMS-D-11-00019.1>.
- 741 [54] F. Leconte, J. Bouyer, R. Claverie, M. Pétrissans, Using Local Climate Zone scheme for UHI  
742 assessment: Evaluation of the method using mobile measurements, *Building and*  
743 *Environment*. 83 (2015) 39–49. <https://doi.org/10.1016/j.buildenv.2014.05.005>.
- 744 [55] W.F. Holmgren, C.W. Hansen, M.A. Mikofski, pvlib python: a python package for  
745 modeling solar energy systems, *Journal of Open Source Software*. 3 (2018) 884.  
746 <https://doi.org/10.21105/joss.00884>.

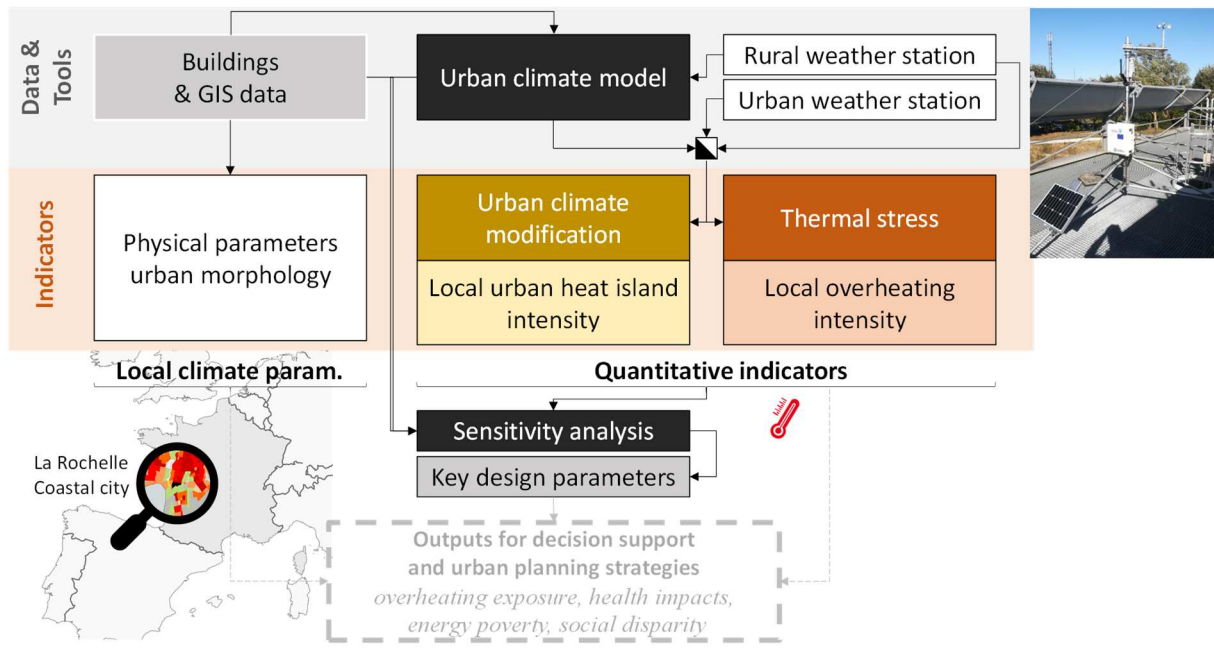
- 747 [56] E.L. Maxwell, A quasi-physical model for converting hourly global horizontal to direct  
748 normal insolation, Solar Energy Research Inst., Golden, CO (USA), 1987.  
749 <https://www.osti.gov/biblio/5987868> (accessed March 3, 2020).
- 750 [57] B.C. Rhodes, PyEphem: Astronomical Ephemeris for Python, Astrophysics Source Code  
751 Library, Record Ascl:1112.014. (2011) ascl:1112.014.
- 752 [58] B. Bueno, A. Nakano, L. Norford, Urban weather generator: a method to predict  
753 neighborhood-specific urban temperatures for use in building energy simulations, (n.d.)  
754 6.
- 755 [59] O. US EPA, Measuring Heat Islands, US EPA. (2014).  
756 <https://www.epa.gov/heatislands/measuring-heat-islands> (accessed July 12, 2021).
- 757 [60] ADEME, Urban overheating diagnostic - Diagnostic de la surchauffe urbaine, ADEME,  
758 2017. [https://www.adaptation-changement-climatique.fr/centre-ressources/diagnostic-](https://www.adaptation-changement-climatique.fr/centre-ressources/diagnostic-la-surchauffe-urbaine)  
759 [la-surchauffe-urbaine](https://www.adaptation-changement-climatique.fr/centre-ressources/diagnostic-la-surchauffe-urbaine).
- 760 [61] A. Martilli, E.S. Krayenhoff, N. Nazarian, Is the Urban Heat Island intensity relevant for  
761 heat mitigation studies?, Urban Climate. 31 (2020) 100541.  
762 <https://doi.org/10.1016/j.uclim.2019.100541>.
- 763 [62] N. Schwarz, S. Lautenbach, R. Seppelt, Exploring indicators for quantifying surface urban  
764 heat islands of European cities with MODIS land surface temperatures, Remote Sensing  
765 of Environment. 115 (2011) 3175–3186. <https://doi.org/10.1016/j.rse.2011.07.003>.
- 766 [63] N. Magee, G. Wendler, J. Curtis, The Urban Heat Island Effect at Fairbanks, Alaska,  
767 Theoretical and Applied Climatology. 64 (1999) 39–47.  
768 <https://doi.org/10.1007/s007040050109>.
- 769 [64] R.A. Memon, D.Y.C. Leung, C.-H. Liu, An investigation of urban heat island intensity  
770 (UHII) as an indicator of urban heating, Atmospheric Research. 94 (2009) 491–500.  
771 <https://doi.org/10.1016/j.atmosres.2009.07.006>.
- 772 [65] J. Martin-Vide, P. Sarricolea, M.C. Moreno-García, On the definition of urban heat island  
773 intensity: the “rural” reference, Front. Earth Sci. 3 (2015).  
774 <https://doi.org/10.3389/feart.2015.00024>.
- 775 [66] T.W. Hawkins, A.J. Brazel, W.L. Stefanov, W. Bigler, E.M. Saffell, The Role of Rural  
776 Variability in Urban Heat Island Determination for Phoenix, Arizona, Journal of Applied  
777 Meteorology and Climatology. 43 (2004) 476–486. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0450(2004)043<0476:TRORVI>2.0.CO;2)  
778 [0450\(2004\)043<0476:TRORVI>2.0.CO;2](https://doi.org/10.1175/1520-0450(2004)043<0476:TRORVI>2.0.CO;2).
- 779 [67] J. Vogel, A. Afshari, Comparison of urban heat island intensity estimation methods using  
780 urbanized WRF in Berlin, Germany, (2020) 25.
- 781 [68] M. Kolokotroni, Y. Zhang, R. Giridharan, Heating and cooling degree day prediction  
782 within the London urban heat island area, Building Services Engineering Research and  
783 Technology. 30 (2009) 183–202. <https://doi.org/10.1177/0143624409104733>.
- 784 [69] B. à É.P. et R. Carbone, Projet de documents méthode pour la Réglementation  
785 environnementale 2020 (RE2020), (2020). [http://www-maj.batiment-](http://www-maj.batiment-energiecarbone.e2.rie.gouv.fr/projet-de-documents-methode-pour-la-reglementation-a126.html)  
786 [energiecarbone.e2.rie.gouv.fr/projet-de-documents-methode-pour-la-reglementation-](http://www-maj.batiment-energiecarbone.e2.rie.gouv.fr/projet-de-documents-methode-pour-la-reglementation-a126.html)  
787 [a126.html](http://www-maj.batiment-energiecarbone.e2.rie.gouv.fr/projet-de-documents-methode-pour-la-reglementation-a126.html) (accessed June 8, 2021).
- 788 [70] M.D. Morris, Factorial Sampling Plans for Preliminary Computational Experiments,  
789 Technometrics. 33 (1991) 161–174. <https://doi.org/10.1080/00401706.1991.10484804>.
- 790 [71] A.-T. Nguyen, S. Reiter, A performance comparison of sensitivity analysis methods for  
791 building energy models, Build. Simul. 8 (2015) 651–664. [https://doi.org/10.1007/s12273-](https://doi.org/10.1007/s12273-015-0245-4)  
792 [015-0245-4](https://doi.org/10.1007/s12273-015-0245-4).

- 793 [72] W. Tian, A review of sensitivity analysis methods in building energy analysis, *Renewable*  
794 *and Sustainable Energy Reviews*. 20 (2013) 411–419.  
795 <https://doi.org/10.1016/j.rser.2012.12.014>.
- 796 [73] V. Corrado, H.E. Mechri, Uncertainty and Sensitivity Analysis for Building Energy Rating,  
797 *Journal of Building Physics*. 33 (2009) 125–156.  
798 <https://doi.org/10.1177/1744259109104884>.
- 799 [74] L. Bande, A. Afshari, D. Al Masri, M. Jha, L. Norford, A. Tsoupos, P. Marpu, Y. Pasha, P.  
800 Armstrong, Validation of UWG and ENVI-Met Models in an Abu Dhabi District, Based on  
801 Site Measurements, *Sustainability*. 11 (2019) 4378. <https://doi.org/10.3390/su11164378>.
- 802 [75] M. Moradi, B. Dyer, A. Nazem, M.K. Nambiar, M.R. Nahian, B. Bueno, C. Mackey, S.  
803 Vasanthakumar, N. Nazarian, E.S. Krayenhoff, L.K. Norford, A.A. Aliabadi, The Vertical City  
804 Weather Generator (VCWG v1.3.2), *Geoscientific Model Development*. 14 (2021) 961–  
805 984. <https://doi.org/10.5194/gmd-14-961-2021>.
- 806 [76] H.S. Khan, R. Paolini, M. Santamouris, P. Caccetta, Exploring the Synergies between  
807 Urban Overheating and Heatwaves (HWs) in Western Sydney, *Energies*. 13 (2020) 470.  
808 <https://doi.org/10.3390/en13020470>.
- 809 [77] T. Hong, Y. Chen, X. Luo, N. Luo, S.H. Lee, Ten questions on urban building energy  
810 modeling, *Building and Environment*. 168 (2020) 106508.  
811 <https://doi.org/10.1016/j.buildenv.2019.106508>.

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# 1 Graphical abstract



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