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Article

How to design a park and its surrounding urban morphology to optimize the spreading of cool air?

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Abstract: Green areas induce smaller increases in the air temperature than built-up areas. They can offer a solution to mitigating the Urban Heat Island impacts during heat waves since the cool air generated by a park is diffused into its immediate surroundings through forced or natural convection. The purpose of this study is to characterize the effect of several variables (park size, morphology of surrounding urban area and wind speed) on the spreading of cool air. A parametric study is performed to run computational fluid dynamic simulations. The air temperature entering the computational domain was set at 35°C, and the 2-m high surface included within the 34°C isotherm was defined as an indicator of cool air spreading. The effects of park shape and orientation are negligible in comparison with its size effects. The number of buildings is better correlated with the cooled surface area than the typical urban parameters identified in the literature (i.e. building density, aspect ratio or mean building height). Since the number of buildings is obviously related to the number of streets, this result suggests that the greater the number of streets around a park, the wider the area that cool air spreads.

Keywords: park cool island; urban cooling; urban morphology; micro-climate simulations

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) reports, heat wave intensity and frequency should increase in the coming decades [1], which may lead to situations of outdoor and indoor discomfort as well as major health impacts. During the summer of 2003, European countries recorded 70,000 excess deaths, attributing them to an unusually hot summer [2].

Urban areas are especially vulnerable when facing such problems, and this for two reasons. First, heat waves are exacerbated in cities when compared to their surroundings due to the Urban Heat Island (UHI) phenomenon [3]. Second, urban areas concentrate most of the human population (i.e. 70% in European Union countries - [4]).

In order to cool cities, several solutions are investigated: evaporative techniques (fountains, water ponds, street watering), green techniques (grass, trees, green facades or green roofs, etc.), and material techniques (reflective, water retentive, etc.). All of these techniques have shown cooling potential, but further research is still needed to improve their performance [5]. This article focuses on the use of parks as cooling solutions.

29 Several studies have shown that parks may create cool air during the day [6] but also at night
30 [7]. Moreover, this cool air may be transported to the neighborhoods surrounding parks [8,9]. The
31 ability of a park to cool the air and spread this cooler air to its vicinity depends mainly on three factors:
32 park characteristics, wind speed conditions, and urban morphology of the peripheral areas. The
33 characteristics of a park (tree species and density, presence of water ponds, soil types, etc.) are key
34 parameters in explaining its cooling potential [9]. The cool air produced within the park is transported
35 into the surrounding areas by diffusion, advection and convection. For the sake of simplification, the
36 term spreading will be used in the following sections. The spreading of cool air varies in intensity
37 depending on both wind conditions and the urban layout of the park surroundings. This article focuses
38 solely on the aspect of cool air spreading (i.e. on the effect of wind speed and urban layout on the level
39 of spreading).

40 In 1991, Jauregui [7] established that park cooling may be measured up to one park's width away
41 from its boundaries, which is consistent with several other studies [9–12]. However, the methodology
42 used to assess this distance was not clearly stated, which makes the results difficult to replicate. To
43 explain the relationship between air temperature drop and distance from the park, Shashua-Bar and
44 Hoffman [12], Doick *et al.* [13] proposed an asymptotic nonlinear model, which was then used to define
45 the Park Cool island Distance (PCD) as the 'distance [from the park] where 10% of the UHI is still
46 present' [13]. Despite its interest, this method has been applied based on air temperature observations
47 for a single park, hence the model is only valid for this specific park and cannot be used to draw general
48 conclusions. We have previously seen that the production of cool air depends on park characteristics,
49 whereas its spreading depends on both wind conditions and the layout of the urban surroundings.

50 The spreading of cool air is affected by wind speed value [14]. Under light winds, the temperature
51 difference observed between the park and the streets is responsible for the advection phenomenon
52 [15,16]. In the presence of high wind speeds, this phenomenon becomes negligible. Skoulika *et al.* [17]
53 showed that for a wind speed above 5.5 m/s, the PCD decreases linearly as wind speed value increases,
54 whereas Doick *et al.* [13], Upmanis *et al.* [15], Oke *et al.* [18] considered the PCD to be negligible
55 whenever wind speed exceeds 2.3 m/s, 5 m/s and 6 m/s, respectively. According to Doick *et al.* [13],
56 this wind speed threshold is likely a function of street geometry, but they did not study this point in
57 further detail.

58 Chandler [14] demonstrated that some urban structural parameters characterizing the
59 surroundings of a park play a key role in the spreading of cool air. Chang and Li [8] analyzed the air
60 temperature gradient around 60 parks relative to the urban canyon dimensions. Their results agreed
61 with the previous literature regarding the average cooling distance from the park, i.e. approx. one park
62 width. They were unable however to establish any relationship between cool air spreading and the
63 aspect ratio or building density. This shortcoming might be explained by the use of experimental data,
64 which make it difficult to differentiate the influence of street dimensions on both radiation trapping
65 and the reduction of cool air flow originating from the park. Moreover, the performance of the shelter
66 protecting the air temperature sensor from the sun was very sensitive to solar radiation conditions
67 [19,20]. A temperature measurement conducted with a shelter located in a street exposed to direct
68 solar radiation may be overestimated, thus complicating comparisons with a measurement performed
69 in a shaded street.

70 The objective of this article is to better understand the phenomenon of cool air drainage from
71 a park to its surroundings, particularly the effects of wind conditions and street dimensions on the
72 spreading of air. Simulation rather than observation is used in order to better control the key variables,
73 such as wind speed, urban layout, and both park and urban thermal characteristics. Simulation is also
74 appropriate to facilitate obtaining a temperature field, thus avoiding having to deploy a large number
75 of sensors, which could lead to numerous observation issues [21].

76 2. Methodology

77 2.1. Definition of urban form parameters

78 A numerical approach is used herein to establish relationships between cool air spreading and
 79 both wind speed and urban form parameters. The urban form parameters are selected from a literature
 80 review, namely: building height, building density, and aspect ratio [8,13,22]. For purposes of this
 81 analysis, a square park has been designed, and the street width (W), building footprint area (S_B) and
 82 reference area (S_{ref}) are all shown in Figure 1.

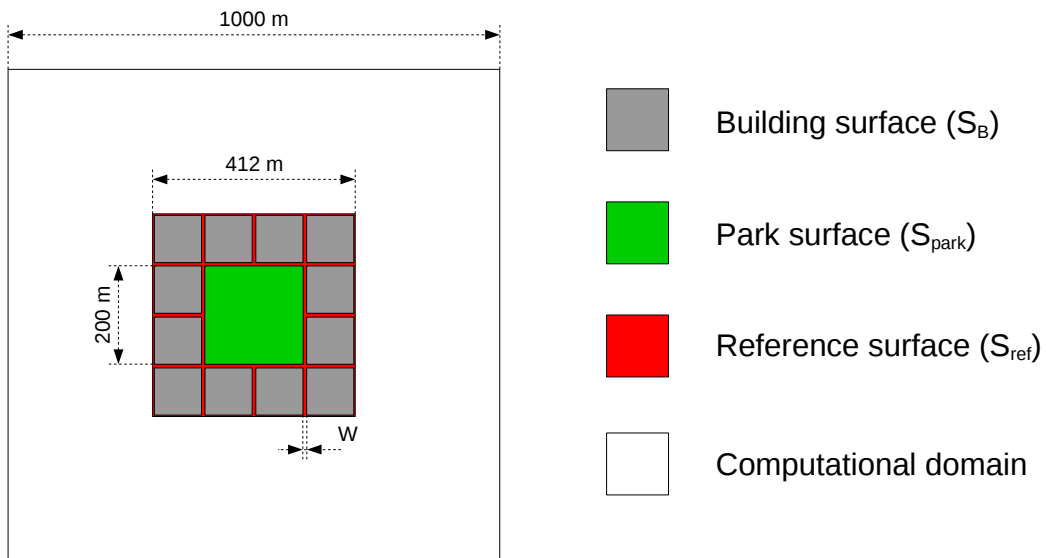


Figure 1. Study area and parameter definition - note that the reference surface consists of the entire square surface area

The aspect ratio (H/W) and building density (D_B) are calculated by means of Equations 1 and 2:

$$H/W = \frac{H}{W} \quad (1)$$

83

where H is the building height

$$D_B = \frac{S_B}{S_{ref} - S_{park}} \quad (2)$$

84

85 Since this investigation concerns the effect of the urban form on air spreading, the scenario used
 86 as a reference is represented by a park on its own (the reference area contains a park but no building
 87 and consists of the entire square surface area).

88 2.2. Model and implementation

89 The park is assumed to produce cool air that will then be spread over the urban area. Depending
 90 on the morphology of the urban area, radiation trapping may vary in intensity and thus interfere with
 91 the cool air originating from the park. To focus solely on air spreading and simplify the simulation
 92 analysis, we assume herein that the urban surfaces do not exchange any energy with the air, whereas
 93 the park surface cools the air at a constant energy rate of $300W/m^2$. This initial assumption is a major
 94 one: during a summer, Rodriguez [23] measured in Nantes (city in western France) both the latent
 95 and sensible heat fluxes according to an eddy-covariance method. At noon, they observed an average
 96 sensible heat flux value of $250W/m^2$ for a highly urban neighborhood (i.e. vegetation density less than
 97 10% in a 200-m buffer circle around the station) versus just $100W/m^2$ for a more highly vegetated area
 98 (76% vegetation). The second assumption is much closer to reality, at least for cities located in the Cfb¹
 99 or Dfb² climate zone [24]. The cooling flux of $300W/m^2$ corresponds to the maximum latent heat flux
 100 measured around noon in the urban forested park of Chicago [25] and is consistent with observations
 101 recorded in the City of Nantes in a fairly green urban neighborhood (measurement performed using
 102 the eddy-covariance method with a vegetation density in the 200-m buffer circle around the station
 103 of 76%) [23]. The results of our study may not be replicable for any park type (differences in the
 104 proportion of grass, tree, concrete, etc.) or climate zone (differences in the amount of solar radiation,
 105 air humidity, air temperature, etc.) since the cooling intensity may be affected [5]. Several other latent
 106 heat flux values (100 and $200W/m^2$) have been tested, but the natural convection effect was harder
 107 to observe. We thus decided to apply the method for the most sensible case ($300W/m^2$). The air
 108 temperature was also set very high ($35^\circ C$) to reflect the peak temperature that Europe has had to face
 109 during its most recent heat waves.

110 To assess the spreading phenomenon of the cooled air generated by a park, the Computational
 111 Fluid Dynamics (CFD) tool Code_Saturne is used in the environment of SOLENE-microclimat (Morille
 112 *et al.* [26], Musy *et al.* [27]), a numerical tool dedicated to urban climate modeling. Thanks to
 113 Code_Saturne, the airflow is computed by resolving Navier-Stokes equations (momentum, mass
 114 continuity, energy, species transport) using a $k - \epsilon$ turbulence model. The tool configuration is similar
 115 to that described in Malys [28], except that the buoyancy forces have been modeled in order to
 116 obtain realistic airflow when natural convection is predominant (i.e. under low wind speed and
 117 high temperature differences). These forces are modeled using the Boussinesq approximation, which
 118 considers air density to be a function of air temperature.

$$\rho = \rho_r \cdot (1 - \beta \cdot (T - T_r)) \quad (3)$$

119 where:

120 T_r is the reference air temperature (= 300K)

121 T the air temperature

122 ρ_r the air density at temperature T_r ($= 1.18kg \cdot m^{-3}$)

123 ρ the air density

124 β the coefficient of thermal expansion ($= \frac{1}{T_r}$)

125 The computational domain represents a 100-ha square area discretized using 270,000 tetrahedral
 126 meshes (Figure 2). The mesh size varies within the domain. The minimum size of 1.5 m for the
 127 tetrahedron side is set in the region of interest (the park and its close surroundings under 2 m high).

¹ Temperate Without dry season Warm summer

² Cold Without dry season Warm summer

128 The mesh size then increases linearly up to the limits of the domain (10 m at surface level, and 50 m at
 129 the top of the domain).

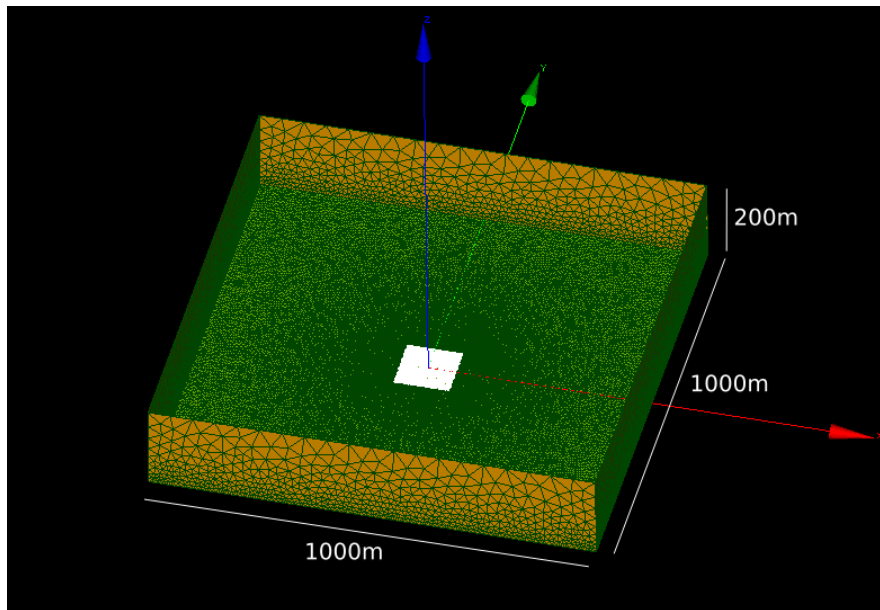


Figure 2. Meshed computational domain.

130 A sensitivity analysis has been performed in order to evaluate the effect of mesh size on air
 131 temperature and wind speed values calculated at a height of 2 m. Several meshing scenarios with
 132 different mesh sizes have been tested. For each case, air temperature and wind speed have been
 133 calculated according to the following procedure:

- 134 1. An interpolation is performed to calculate the air temperature of the vertex from the air
 135 temperature in the tetrahedron
- 136 2. A 2-m high horizontal plane on the ground is generated and intersects the tetrahedron vertex
- 137 3. The air temperature at these points is the result of a linear interpolation between the segment
 138 ends.

139 Results of this analysis revealed that between the chosen scenario (270,000 tetrahedrons) and the
 140 most accurate one (507,000 tetrahedrons), the temperature error never exceeded 0.5°C inside the park
 141 and 0.02°C outside the park.

142 For each time step, the calculation stopped under a convergence criterion that needed to be
 143 set. This threshold was chosen based on several simulations, where both park size and wind
 144 speed varied but not wind direction. For each simulation, 2,000 iterations were performed and
 145 the temperature convergence parameter always stabilized above 10^{-4} . This threshold was thus chosen
 146 as the convergence criterion.

147 2.3. Indicators of air spreading efficiency

148 To evaluate the spreading efficiency according to wind speed and urban form, performance
 149 indicators prove to be necessary. Several studies employed the concept of PCD, which is defined
 150 as the distance where the cooling induced by the park is still noticeable. In this study, the cooling
 151 effect of a park is considered to end where the 2-m high temperature drops below 1°C from the initial
 152 temperature. The PCD is then defined as the mean distance between the park boundary and the 34°C
 153 isoline at a height of 2 m above ground. The distance between each point of the isoline and the park is
 154 calculated differently depending on the specific location (Figure 3). Concerning zones 1, 2, 3 and 4, it is

155 defined as the distance between the point and the closest corner of the park. As for zones 5, 6, 7 and 8,
 156 it is defined as the minimum distance between the point and a side of the park.

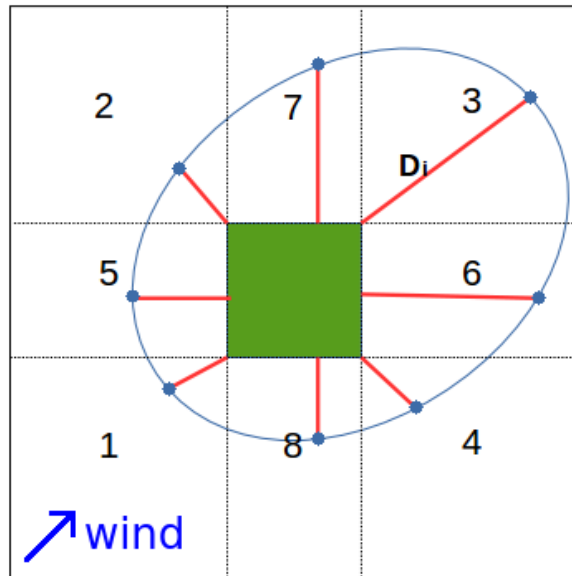


Figure 3. Zoning (dashed lines and numbers) and example of calculation (red lines) used to calculate the distance between any point on the 34°C isoline and the park boundary.

157 The PCD however is a 1-dimensional indicator: in the case of a long but narrow isotherm shape,
 158 the average distance of the 34°C isotherm can be high, whereas the surface benefiting from the cooled
 159 air may be small. The surface of the area included in the 34°C isoline is then also calculated in order
 160 to overcome the shortcomings of the PCD. Yet these results show that both indicators exhibit similar
 161 behavior for all of the following analyses. For the sake of simplification, only the results obtained with
 162 the cooled surface area will be presented and analyzed.

163 2.4. Parametric study

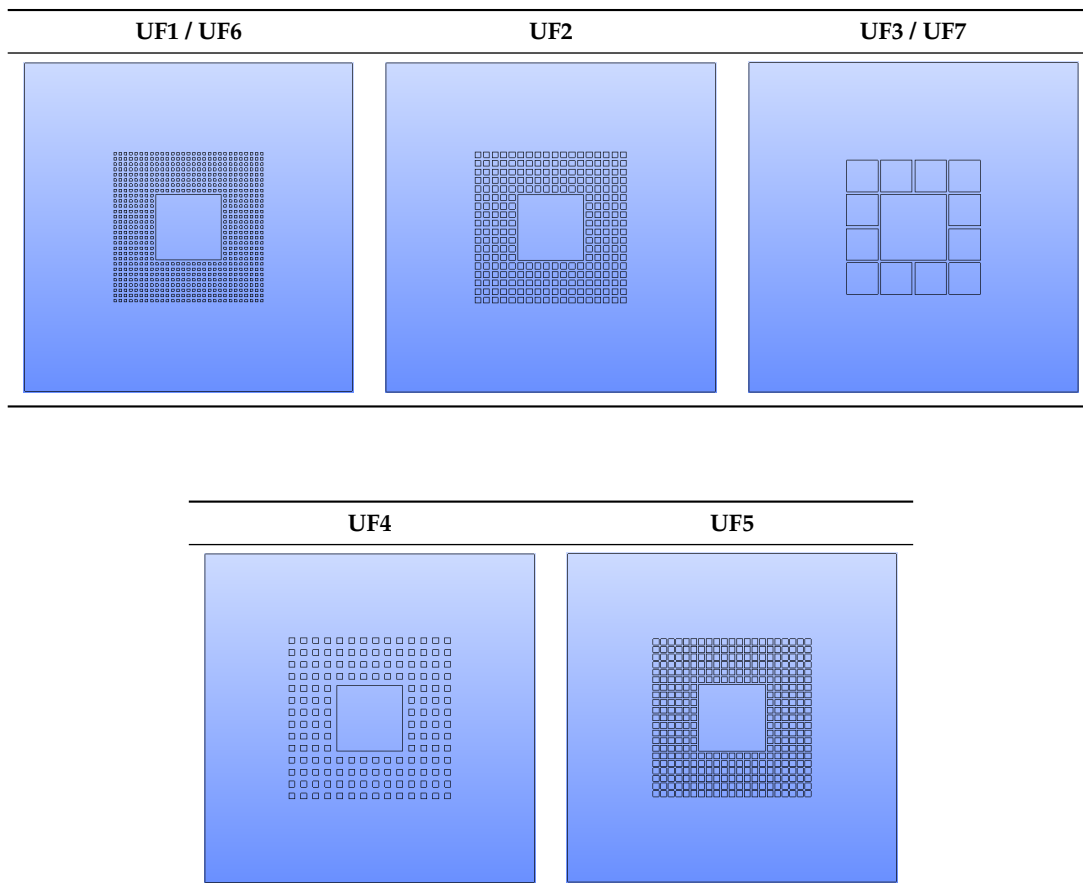
164 The cooling surface is impacted by several kinds of parameters. Three of them will be investigated
 165 herein: park size (with the shape remaining square), the urban form of its surrounding areas, and wind
 166 conditions.

167 The park width is set at 50, 100 and 200 m. One simulation is run for each park width without
 168 any adjacent buildings.

169 Several Urban Form (UF) scenarios are adopted to investigate the effect of urban parameters on
 170 the spreading of cool air. Each scenario is established to define a building height, building size and
 171 street width in order to obtain a building density and aspect ratio values (Table 1). Values are chosen
 172 so as to highlight the separate effect of H/W , D_B and H on the cool air spreading, but also to optimize
 173 the number of simulations to be carried out. Seven Urban Forms are proposed (Table 2). First, the
 174 building density influence is investigated by changing either the building size (UF 1 to 3 - method 1) or
 175 the street width (UF 2 to 4 - method 2). Three density levels are obtained and defined as low, medium
 176 and high. Next, the aspect ratio influence is investigated by adopting either a low density (UF 1 and 4)
 177 or high density (UF 3 and 5). Lastly, the height is varied while the building density remains constant
 178 at a low value (UF 1 and 6) or high value (UF 3 and 7). For each scenario, the resulting number of
 179 buildings is also given in the Table.

Table 1. Parameters set for each of the seven scenarios investigated

UF	height (m)	building width (m)	street width (m)	D_B (%)	H/W	number of buildings
1	10	8	8	25 (low)	1.25	672
2	10	18	8	48 (medium)	1.25	260
3	10	96	8	85 (high)	1.25	12
4	10	18	18	25 (low)	0.56	160
5	10	18	5	95 (high)	2.00	360
6	17	8	8	25 (low)	2.12	672
7	4	96	8	85 (high)	0.50	12

Table 2. Geometry of each urban form

180 The influence of wind speed is investigated for each of these scenarios: values are selected every
 181 0.5 m/s from 0.5 m/s to 5 m/s. The scenario combinations derived from urban form and wind speed
 182 lead to a total of 70 simulations. For all simulations, wind crosses the park along its diagonal (Figure
 183 3). The effect of wind direction and park shape have been investigated, but only the conclusions will
 184 be briefly presented in the following section.

185 3. Results

186 3.1. Influence of park size

187 For each park size (50, 125 and 200 m wide), the variation in the cooled surface area (i.e. where
 188 temperature is lower than 34°C) is evaluated for various wind speeds. It is obvious that a larger park
 189 will cool a larger area. The cooled surface is then divided by the park area in order to obtain a cooling

190 efficiency (C_e) indicator. This value may be interpreted as an equivalent surface cooled by each square
 191 meter of park.

192 The simulations show that C_e increases with park size or as wind speed decreases (Figure 4).

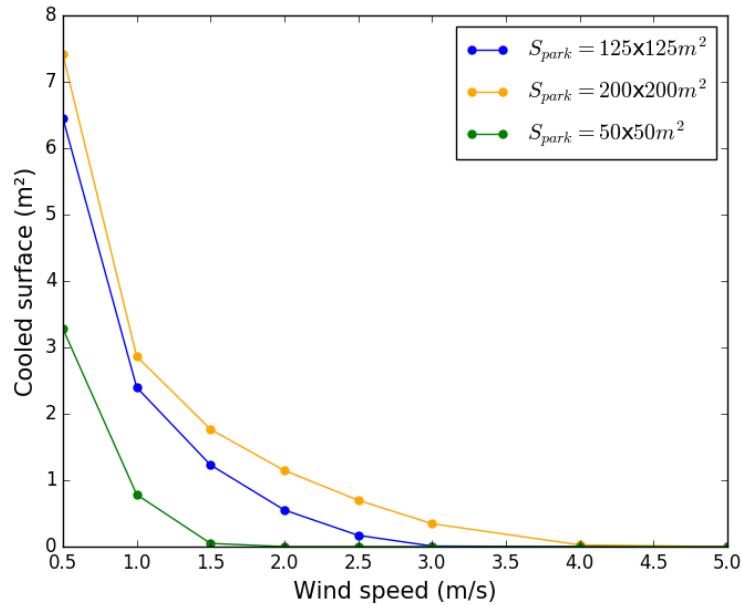


Figure 4. Cooled surface evolution with wind speed

193 The first observation implies that one square meter of a large park is more efficient than one
 194 square meter of a small park. The second observation may be attributed to the assumption made for
 195 the simulation: the cooling rate of the air located in the park is constant regardless of its air temperature
 196 or wind speed. One result of this assumption is that the longer the air stays in the park, the cooler it
 197 leaves the park. Thus, when wind speed is very low (0.5 m/s), the air temperature difference between
 198 the park and its surroundings is high (8°C). In this case, the air temperature of 34°C is easily reached
 199 and natural convection dominates: the cool air flow is emitted in all directions, including the opposite
 200 direction of the incoming wind, and the 34°C isotherm is quite large (Figure 5(a)). For higher wind
 201 speeds (2 m/s), the air temperature difference between the park and its surroundings is lower (2°C), in
 202 which case the air temperature barely reaches 34°C and spreading is mainly driven by the wind. As a
 203 result, the flow is channeled in a single direction and the 34°C isotherm is small (Figure 5(b)). Overall,
 204 upon analysis of the temperature distribution around a park, we can conclude that the lower the wind
 205 speed, the further the spreading of cooled air in the direction opposite the incoming air flow.

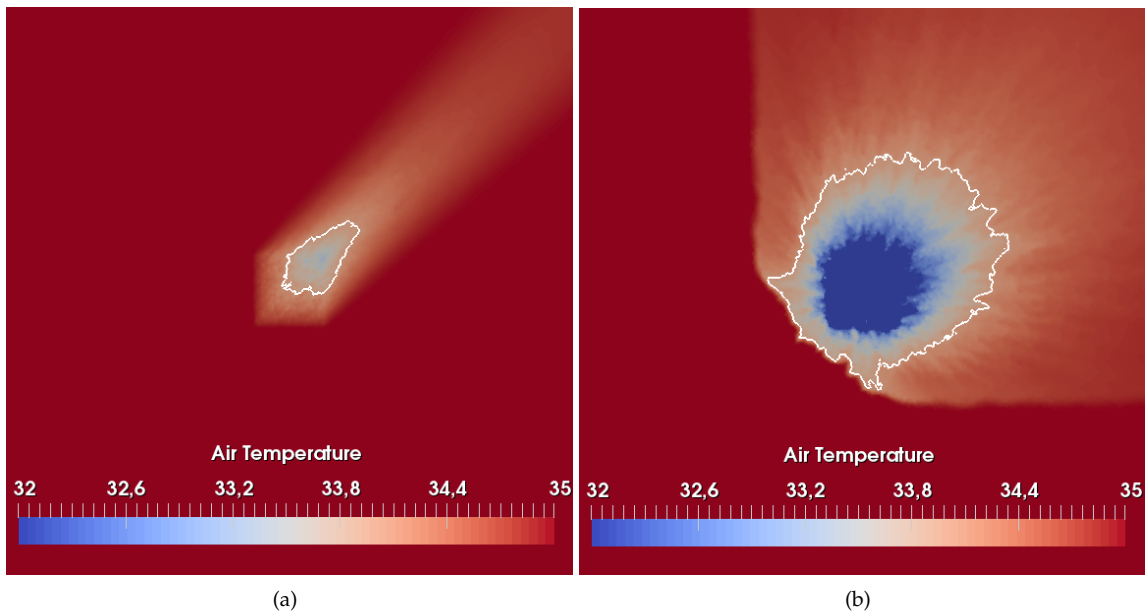


Figure 5. 2 m high air temperature distribution inside and around a park with a width of 125 m: (a) Exposed to a wind speed of 2 m/s. (b) Exposed to a wind speed of 0.5 m/s - the white line is the 34°C isoline

206 The shape and orientation of the park (with respect to wind speed) have been investigated. For a
 207 given surface area, they both exert a very limited influence compared to park size (which is why the
 208 results are not shown in this study).

209 Overall, two main observations can be drawn:

- 210 • The larger the park, the greater the cooling intensity
- 211 • The higher the wind speed, the smaller the cooled surface area.

212 In conclusion, the longer the air stays in the park, the cooler it is and the larger the size of the
 213 34° isotherm.

214 3.2. Influence of the neighboring district

215 Adding buildings around the park has a direct impact on the cooled surface shape. To investigate
 216 the influence of the neighboring district on cool air spreading, the larger park is used (200 m wide).
 217 The surface generated by the 34°C isotherm has nearly the same size for both the reference urban
 218 form (without any buildings) and the UF 1 (with buildings). However, the former is located further
 219 downstream than the latter (Figure 6). The buildings can be seen as contributing to slowing the wind
 220 speed. In agreement with the previous analysis, this finding leads to increasing the natural convection
 221 influence, diffusing the air further toward the incoming airflow direction.

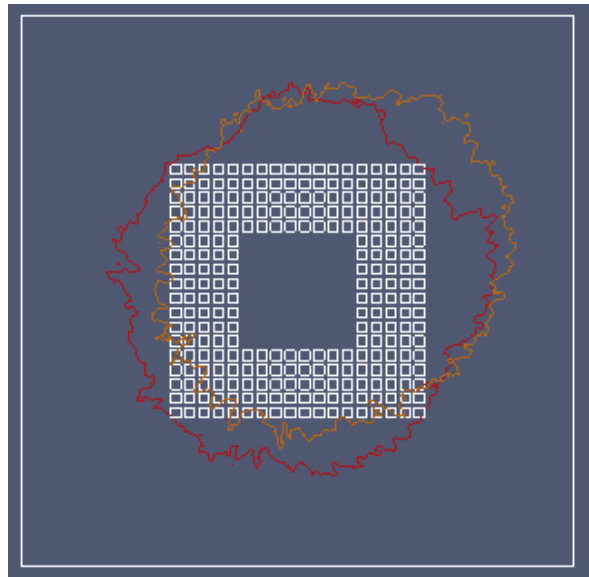


Figure 6. 34°C isotherm at a 0.5 m/s wind speed for the reference urban form (no buildings - orange line) and for the UF 1 (red line) - the small white squares represent building footprints

222 The influence of the urban form of the district surrounding the park is now investigated. Three
 223 parameters are considered: building density, aspect ratio, and building height. As described in the
 224 Methodology section, the building density is increased using two distinct methods (either the building
 225 size is modified - method 1 - or the street width is modified - method 2). These two methods are
 226 considered separately and results are shown on separate plots. As previously observed, the cooled
 227 surface decreases as wind speed increases under all scenarios (Figure 7). For a given wind speed, when
 228 building density is increased by increasing the building size, the cooled surface area decreases (Figure
 229 7(a)). In contrast, when building density is increased by increasing street width, the cooled surface
 230 area expands (Figure 7(b)).

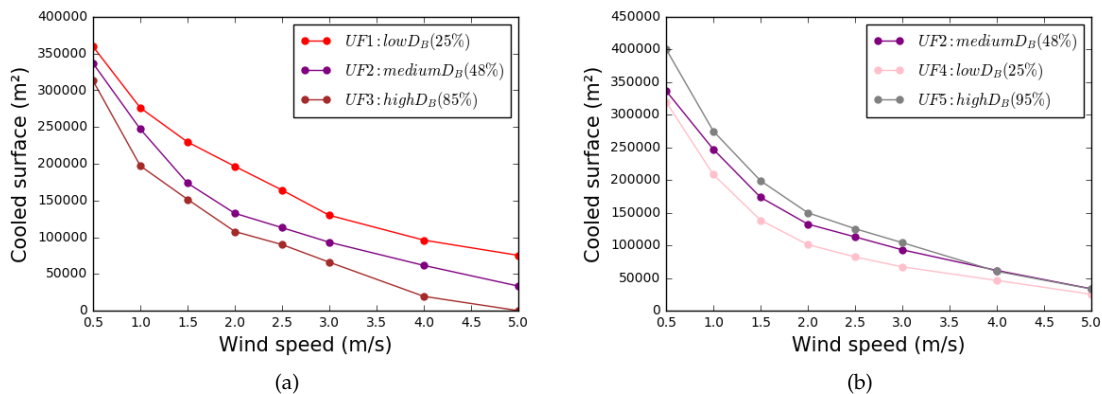


Figure 7. Influence of wind speed on the cooled surface for various building density values: (a) When building density is increased modifying the building size (b) When building density is increased modifying the street width

231 Building density cannot therefore be used as the lone parameter explaining the influence of the
 232 built environment on the cooled surface of a park.

233 The effect of the aspect ratio on the cooled surface is tested by decreasing the street width. In this
 234 manner, the aspect ratio is increased, thus keeping building density and building height constant. For

235 a given wind speed, the size of the cooled surface increases as the aspect ratio increases (as well for a
 236 given building density regardless of its value 8.

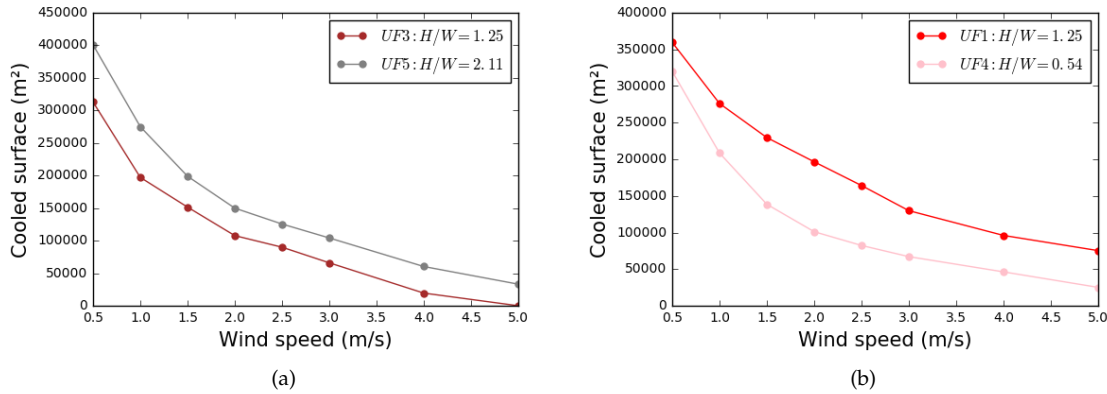


Figure 8. Influence of wind speed on the cooled surface for different aspect ratio values. (a) For high building density (b) For low building density

237 Thirdly, the building height is increased for a given building density with an increasing aspect
 238 ratio. For high building density (Figure 9(a)) and at a given wind speed, the cooled surface area is
 239 nearly similar when the building height increases from 10 m to 17 m. For the low building density case
 240 (Figure 9(b)), it increases as the building height rises from 4 m to 10 m. According to an initial analysis,
 241 we could assume that building height, like building density, is not a key parameter in explaining the
 242 cooled surface, while the aspect ratio is a key parameter. It is also possible that the effect of building
 243 height only appears at a certain threshold value. This assumption will be further analyzed in the
 244 following section.

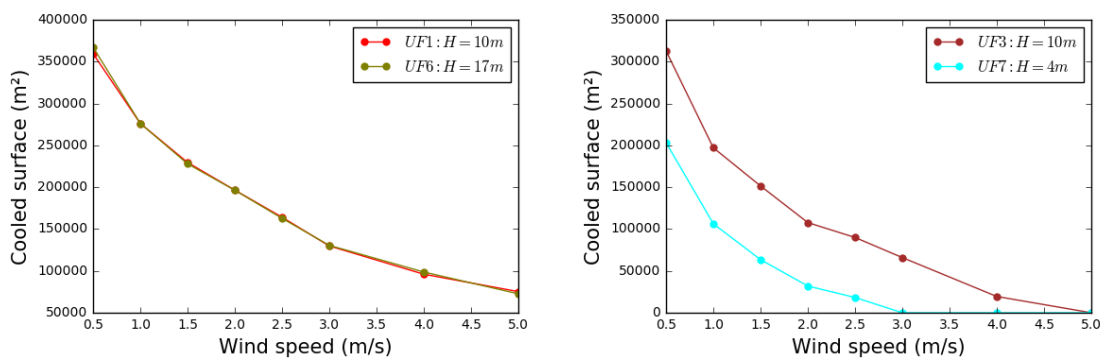


Figure 9. Influence of wind speed on the cooled surface for various building heights. (a) For a low building density district (b) For a high building density district

245 The three urban form parameters (building density, aspect ratio and height) investigated herein
 246 do not impact the air spreading pattern in a way that could have been expected:

- 247 • For a given building height and aspect ratio, the building density increase enhances or reduces
 248 the spreading of cooled air, depending on how the density is modified. Density does not seem to
 249 be a key parameter affecting air spreading.
- 250 • For a given building height and building density, the aspect ratio appears to enhance the cooling
 251 process, whereas it is not often identified in the literature as a key parameter.

- 252 • Higher buildings may increase air spreading under a certain threshold value, which has not yet
253 been identified (note that this threshold may be dependent on wind speed conditions).

254 4. Discussion

255 The results presented above lead to investigating in greater detail the simulation results and then
256 discussing them. This discussion section will focus on two points:

- 257 • An understanding of the influence of building height on air spreading based on the configuration
- 258 • The identification of other parameters that could be relevant for the air spreading characterization.

259 The air temperature field for UF 3 and UF 7 (buildings 10 m and 4 m high, respectively, in a
260 high-density district due to large buildings - few streets) is presented in Figure 10. In the low building
261 height case (UF 7), the cool air diffuses over the buildings (Figure 10(a)). In the tall building case (UF
262 3), the buildings seem to be sufficiently high to avoid air from spreading above them (Figure 10(b)). As
263 a result, the cool air is channeled into the streets, reaching a further distance from the park and thus
264 covering a wider area.

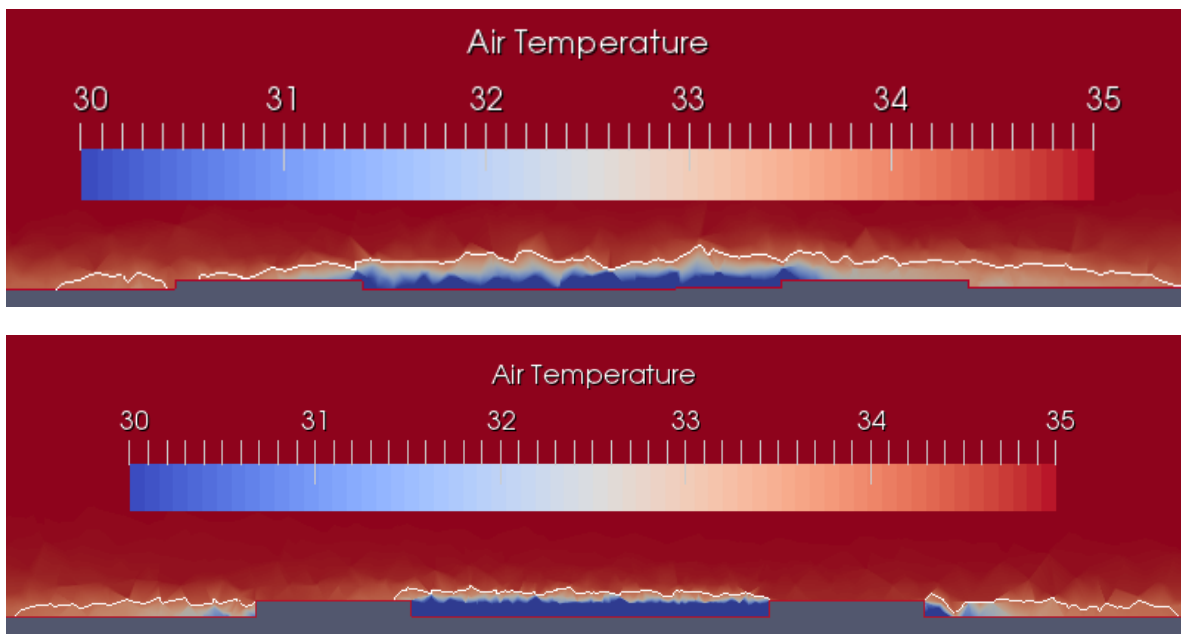


Figure 10. Vertical slice of the air temperature field for a high building density district. (a) UF 7 : buildings are 4 m high. (b) UF 3 : buildings are 10 m high - the white line is the 34°C isotherm

265 The air temperature field for the UF 1 and UF 6 (buildings 10 m and 17 m high, respectively, in
266 a low-density district - many streets) is presented Figure 11. For the UF 1, the cool air does not pass
267 over the buildings; it remains channeled in the streets. It is obvious that in this case building height
268 increases do not affect the spreading of cool air.

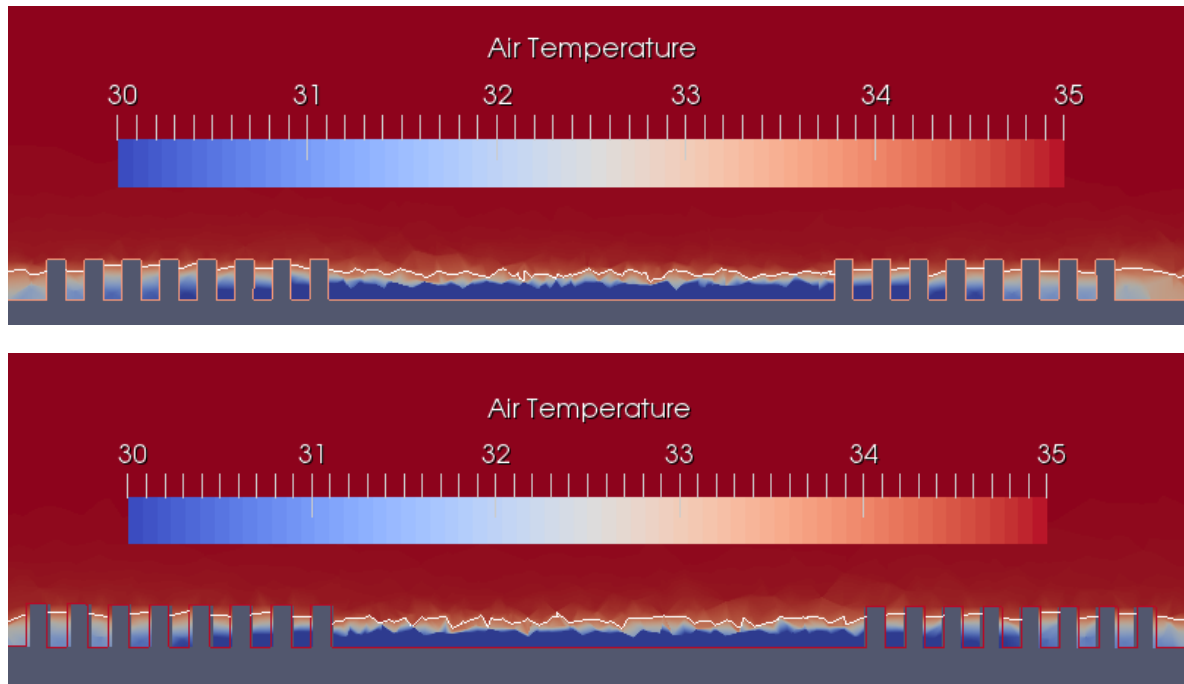


Figure 11. Vertical slice of the air temperature field for a low building density district. (a) UF 1 : buildings are 10 m high. (b) UF 6 : buildings are 17 m high) - the white line is the 34°C isotherm

269 Above a certain building height threshold, the cool air can no longer spread over the buildings.
 270 Further increasing the building height would then have no effect on the cooled surface since the air is
 271 only spreading under the urban canopy.

272 The issue of building height relevance calls into question the relevance of two other indicators,
 273 namely: urban fragmentation (e.g. number of buildings), and street width. We previously showed
 274 that the aspect ratio is positively correlated with the cooled surface area. The aspect ratio is defined as
 275 the ratio of building height to street width. Since past results have demonstrated that building height
 276 only affects the cool air spreading in very specific configurations, we might wonder whether street
 277 width is an influential parameter. Urban fragmentation was not initially identified as an important
 278 parameter as regards the cool air spreading. However, the number of buildings varies along the chosen
 279 urban form and thus its cooling potential warrants investigation. The cooled surface area is plotted
 280 versus both the number of buildings (Figure 12(a)) and the street width (Figure 12(b)). The number of
 281 buildings appears to be much more closely correlated than street width with the cooled surface area. A
 282 large variability in the cooled surface area exists for the UF with 8-m width streets, thus making this
 283 parameter insignificant (Figure 12(b)). In Figure 12(a), the cooled surface area clearly increases as the
 284 number of buildings or streets increases. Moreover, the distance to the regression line remains low
 285 (except when the number of buildings is very small).

286 Ultimately, urban fragmentation (here the number of buildings) seems to be a more relevant
 287 variable than building density, aspect ratio or building height for characterizing the cooled air spreading
 288 from a park through a district.

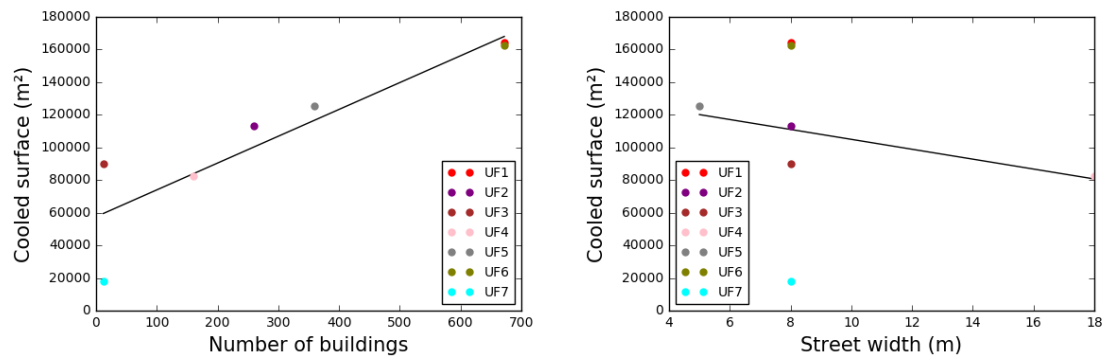


Figure 12. Cooled surface area evolution versus: (a) the number of buildings; (b) street width - wind speed set at 2.5m/s

289 5. Conclusion

290 The parameters impacting the spreading of cool air produced by a park have been investigated
 291 herein. Simulations were performed to observe the cooling distance (surface included inside the 1°C
 292 temperature decrease isoline) induced by the park and by the form of its surrounding urban district.
 293 Some of the studied parameters are intrinsic to the park (shape and size), while others describe the
 294 urban morphology of the surrounding neighborhoods (building density, building height and aspect
 295 ratio). The simulations were run for various wind speeds and under a constant cooling flux of 300
 296 W/m^2 generated by the green area.

297 The analysis of results leads to the following conclusions:

- 298 • A larger park will cool more efficiently: it will generate a greater surface area of cooled air per
 299 square meter than a smaller park.
- 300 • The building density variation can enhance or reduce the spreading of cooled air. This parameter
 301 therefore is irrelevant as regards cool air spreading.
- 302 • For a given building height and building density, the aspect ratio seems to enhance the cooling
 303 process, even though it has not often been identified in the literature as a key parameter.
- 304 • Building height does not exert any influence on air spreading above a certain threshold value.
- 305 • The number of buildings seems to be a very relevant parameter for characterizing the cooled air
 306 spreading from a park through a district. This parameter and all other fragmentation indicators
 307 (the number of buildings is an indicator of fragmentation intensity, but the direction and shape of
 308 fragmentation may also be of interest) should be further analyzed by the research community.

309 In this paper, a constant cooling flux was considered in order to focus solely on the spreading of
 310 the cool air being produced. Some bias was thus introduced when using this method for analysis (if
 311 air remains for an infinite time in the park, its temperature should be infinitely negative). In reality, the
 312 flux should have been modified by the temperature difference between the ground and the air and by
 313 the wind speed. This hypothesis could be revised in future work by employing a coupled heat transfer
 314 simulation (thermo radiative and CFD) in order to generalize the methodology proposed herein and
 315 consider a cooling flux that varies in both space and time.

316 This paper has highlighted new findings but it is based on strong hypotheses. Further
 317 investigation is thus required (empirical data should be used) to verify that these assumptions do not
 318 affect the veracity of the main findings. However, only a few studies regarding the topic of cool park air
 319 spreading have so far been performed using a numerical approach. The academic approach proposed
 320 in this paper has led to both a better understanding of the physical phenomena involved and an
 321 identification of the key parameters affecting cool air spreading. For these reasons, it is complementary
 322 to the experimental studies available in the literature.

323 **Author Contributions:** This work was been conducted within the scope of Xueyao Zhang's internship. The work
324 program was managed by Jérémy Bernard, Benjamin Morille and Auline Rodler. Xueyao Zhang studied the
325 bibliography and carried out all of the simulation runs. Jérémy Bernard, Benjamin Morille and Auline Rodler
326 wrote the paper and contributed to this effort in equal measure.

327 **Conflicts of Interest:** The authors declare no conflict of interest."

328 References

- 329 1. Revel, D.; Füßel, H.M.; Jol, A. *Climate change, impacts and vulnerability in Europe 2012*, 2012.
- 330 2. Robine, J.M.; Cheung, S.L.K.; Le Roy, S.; Van Oyen, H.; Griffiths, C.; Michel, J.P.; Herrmann, F.R. Death toll
331 exceeded 70,000 in Europe during the summer of 2003. *Comptes rendus biologies* **2008**, *331*, 171–178.
- 332 3. Oke, T.R. *Boundary layer climates*; Routledge, 2002.
- 333 4. Eurostat. *Eurostat regional yearbook 2014: Focus on european cities*, 2014.
- 334 5. Santamouris, M.; Ding, L.; Fiorito, F.; Oldfield, P.; Osmond, P.; Paolini, R.; Prasad, D.; Synnefa, A. Passive
335 and active cooling for the outdoor built environment—Analysis and assessment of the cooling potential of
336 mitigation technologies using performance data from 220 large scale projects. *Solar Energy* **2016**.
- 337 6. Barradas, V.L. Air temperature and humidity and human comfort index of some city parks of Mexico City.
338 *International Journal of Biometeorology* **1991**, *35*, 24–28.
- 339 7. Jauregui, E. Influence of a large urban park on temperature and convective precipitation in a tropical city.
340 *Energy and buildings* **1991**, *15*, 457–463.
- 341 8. Chang, C.R.; Li, M.H. Effects of urban parks on the local urban thermal environment. *Urban Forestry &*
342 *Urban Greening* **2014**, *13*, 672–681.
- 343 9. Spronken-Smith, R.; Oke, T. Scale modelling of nocturnal cooling in urban parks. *Boundary-Layer*
344 *Meteorology* **1999**, *93*, 287–312.
- 345 10. Cao, X.; Onishi, A.; Chen, J.; Imura, H. Quantifying the cool island intensity of urban parks using ASTER
346 and IKONOS data. *Landscape and urban planning* **2010**, *96*, 224–231.
- 347 11. Ca, V.T.; Asaeda, T.; Abu, E.M. Reductions in air conditioning energy caused by a nearby park. *Energy and*
348 *Buildings* **1998**, *29*, 83–92.
- 349 12. Shashua-Bar, L.; Hoffman, M.E. Vegetation as a climatic component in the design of an urban street: An
350 empirical model for predicting the cooling effect of urban green areas with trees. *Energy and Buildings* **2000**,
351 *31*, 221–235.
- 352 13. Doick, K.J.; Peace, A.; Hutchings, T.R. The role of one large greenspace in mitigating London's nocturnal
353 urban heat island. *Science of the total environment* **2014**, *493*, 662–671.
- 354 14. Chandler, T.J. *The Climates of London*; Hutchinson, 1965.
- 355 15. Upmanis, H.; Eliasson, I.; Lindqvist, S. The influence of green areas on nocturnal temperatures in a high
356 latitude city (Göteborg, Sweden). *International journal of climatology* **1998**, *18*, 681–700.
- 357 16. Jansson, C.; Jansson, P.E.; Gustafsson, D. Near surface climate in an urban vegetated park and its
358 surroundings. *Theoretical and Applied Climatology* **2007**, *89*, 185–193.
- 359 17. Skoulika, F.; Santamouris, M.; Kolokotsa, D.; Boemi, N. On the thermal characteristics and the mitigation
360 potential of a medium size urban park in Athens, Greece. *Landscape and Urban Planning* **2014**, *123*, 73–86.
- 361 18. Oke, T.R.; Crowther, J.; McNaughton, K.; Monteith, J.; Gardiner, B. The micrometeorology of the urban
362 forest [and discussion]. *Philosophical Transactions of the Royal Society B: Biological Sciences* **1989**, *324*, 335–349.
- 363 19. Lacombe, M.; Bousri, D.; Leroy, M.; Mezred, M. WMO Field Intercomparison of Thermometer
364 Screens/Shields and Humidity Measuring Instruments, Ghardaia, Algeria, November 2008–October
365 2009. Technical report, World Meteorological Organization, 2011.
- 366 20. Lacombe, M. Results of the WMO intercomparison of thermometer screens/shields and hygrometers in
367 hot desert conditions. TECO-2010–WMO Technical Conference on Meteorological and Environmental
368 Instruments and Methods of Observation, Helsinki, Finland, 30 August–1 September 2010, [http://www.wmo.int/pages/prog/www/IMOP/publications/IOM-104 TECO-2010/3 4 Lacombe France. pdf](http://www.wmo.int/pages/prog/www/IMOP/publications/IOM-104%20TECO-2010/34%20Lacombe%20France.pdf), 2010.
- 369 21. Oke, T. *Initial guidance to obtain representative meteorological observations at urban sites*; Vol. 81, World
370 Meteorological Organization Geneva, 2004.
- 371 22. Perini, K.; Magliocco, A. Effects of vegetation, urban density, building height, and atmospheric conditions
372 on local temperatures and thermal comfort. *Urban Forestry & Urban Greening* **2014**, *13*, 495–506.
- 373

- 374 23. Rodriguez, F. FluxSAP - A collaborative experimental campaign on water and energy fluxes in urban areas
375 and the relation with the vegetation : the case of a Nantes district . 9th International Conference on Urban
376 Climate (ICUC9); Météo-France, , 2015.
- 377 24. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated world map of the Köppen-Geiger climate classification.
378 *Hydrology and earth system sciences discussions* **2007**, *4*, 439–473.
- 379 25. McPherson, G.E.; Nowak, D.J.; Rowntree, R.A. Chicago's urban forest ecosystem: results of the Chicago
380 Urban Forest Climate Project **1994**.
- 381 26. Morille, B.; Lauzet, N.; Musy, M. SOLENE-microclimate: a tool to evaluate envelopes efficiency on energy
382 consumption at district scale. *Energy Procedia* **2015**, *78*, 1165–1170.
- 383 27. Musy, M.; Malys, L.; Morille, B.; Inard, C. The use of SOLENE-microclimat model to assess adaptation
384 strategies at the district scale. *Urban Climate* **2015**, *14*, 213–223.
- 385 28. Malys, L. Évaluation des impacts directs et indirects des façades et des toitures végétales sur le
386 comportement thermique des bâtiments. PhD thesis, École nationale supérieure d'architecture (Nantes),
387 2012.

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