Assessing the influence of long-term urban growth scenarios on urban climate

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Abstract: The objective of this paper is to assess the influence of future urban growth scenarios on future urban climate in Toulouse metropolitan area (France). Specifically, we aim to test the hypothesis that urban growth based on sprawling patterns has a significant influence on the Urban Heat Island (UHI) phenomena than compact patterns. Urban growth simulations, which are based on three contrasting scenarios built by 2100 with respect to different urban patterns, are made using a new spatially explicit urban growth model (SLEUTHR) which is specifically developed for that purpose. Potential UHI maps of 2006 and by 2100 are estimated under the same climate conditions using the SURFEX climate model. The influence of urban form on urban microclimate is assessed by comparing the estimated UHI map of 2006 with the potential UHI maps expected by 2100 with respect to the scenario-based urban expansion maps. Simulations with Meso-NH shows that, for the 2006 experience, the center of Toulouse is warmer than the surrounding rural areas by about 6.4°C at 00 LT and at 06 LT. The results highlight an increase of 1 to 2 degrees in the urban air temperature at the beginning of the night and a lost of cool capacity in the scenarios. Furthermore, the results show that big differences in the scenarios are found when exploring the horizontal distribution of the UHI. The increase in the urbanised surface by 2100 leads to a general elevation of temperatures of about 1°C at 00LT and at 06 LT.

Keywords: Urban growth scenarios, Urban patterns, Urban sprawl, Climate change, Urban Heat Island.

1. Introduction

Cities' growth has been primarily occurred under the urban sprawl phenomenon which is widely blamed for transforming the landscapes and causing environmental changes such as low density land use, high dependence on automobiles relative to other means of transportation (Squires 2002), fragmentation, low connectivity, loss of vegetation and evapotranspiration. Such irreversible transformations, mainly due to the urban development, influence the small scale land / atmosphere interactions and cause modifications of the surface energy balance through the urban heat island process (Hidalgo et al. 2008).

Many researchers have been interested in studying the relationship between the patterns of land use and the surface temperature in urbanized areas (Stone et al. 2010). Through the association between the urban form and extreme heat events, Stone et al. (2010) found that the rate of increase in the annual number of extreme heat events between 1956 and 2005 in sprawling U.S. cities was more than the double of the observed increase rate in compact cities. Before that, the low density and sprawling patterns of the urban development have also been associated with enhanced surface temperatures in cities (Stone and Norman 2006) in order to
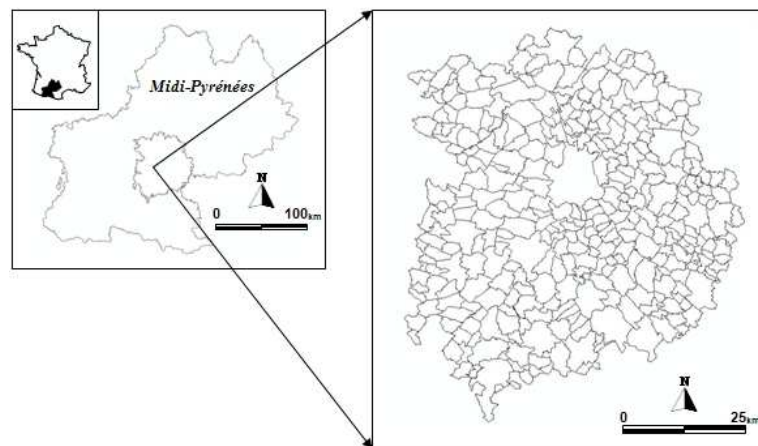
59 prospect the effect of sprawl on the probability and intensity of heat waves. Indeed,
60 urban forms strongly influence urban climate events such as the urban heat island
61 phenomenon (Oke 1987, Houet and Pigeon 2011) which may severely impact
62 human health (Johnson and Wilson 2009).
63
64 Forecasting future urban growth dynamics and patterns is particularly important to
65 assess the possible impacts of future climate changes on the urban areas. Giving
66 multiple long-term visions of future urban patterns, based on urban expansion
67 simulation, is essential to inform city managers and urban policy decision makers
68 about sustainable patterns of future urban development.
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70 The aim of this paper is to assess the influence of the patterns of future urban
71 growth scenarios on urban microclimate. Specifically, we aim to examine the
72 influence of the urban form on the intensity and spatial distribution of the UHI
73 phenomenon by 2100.
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76 **2.   Study Area**
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78 The urban area of Toulouse, which is located in the Western South of France
79 (Figure 1) and dispersed within 342 communities, sums up to 4000 km^2 and is
80 populated by 1,131,642 inhabitants in 2008. The city of Toulouse is ranked as the
81 4th most populated town in France, after Paris, Marseille and Lyon. Each year, it
82 hosts about 14,000 newcomers, which results in significant needs for housing,
83 facilities and services. Consequently, the urban area of Toulouse has significantly
84 decentralized over recent decades in an accelerated sprawling urban growth
85 representing annually approximately +1,400 ha of urban area.
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100 **Figure 1:** Urban area of Toulouse
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103 **3.   Method**
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105   **3.1. A scenario-based urban growth model (SLEUTHR)**
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107 The urban growth scenarios are built based on a – participatory – prospective
108 approach (Godet 1986) using contrasting urban planning, adaptation technologies,
109 local trends, and major global trends assumptions regardless of capabilities of
110 available modeling tools. However, no one of those models is relevant enough to
111 deal with medium and long-term prospective scenarios particularly exploratory and
112 normative ones. This is why we developed a new tool, which is a based-scenarios
113 model, through the optimization of the SLEUTH urban growth model (Clarke and
114 Gaydos 1998). Our new spatially explicit model deals with limitations of the majority
115 of existing LUCC models. This new dynamic model, which combines both

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116 economic and geographic driving forces, allows the user to specify the expected
117 amount of change and urbanization forms that are appropriate to each scenario.
118 Furthermore, the exogenous quantity and urban forms mean that the model's user
119 can specify the amount of expected built-up areas and patterns in the prediction
120 map independently from past LULC trends.
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123 ### 3.2. Urban growth scenarios
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125 The future urban growth by 2100 is simulated with respect to the tendency
126 scenario which assumes the continuity of the actual tendency in the metropolitan
127 area (global trends, social and economic trends at the local level). Besides, the
128 annual rate of the urban growth at the urban area of Toulouse is set to 1300 ha.
129 In order to assess the impact of the sprawling patterns of the urban development
130 on the urban heat island, three variants of this global scenario are considered
131 based on the urban form: scenario F1, F2 and F3. A specific urban growth pattern
132 is assigned to each scenario: edge growth (scenario F1), spontaneous growth
133 (scenario F2) and a mix of new spreading centers, spontaneous, edge and road-
134 Influenced growth (scenario F3). These scenarios provide three potential urban
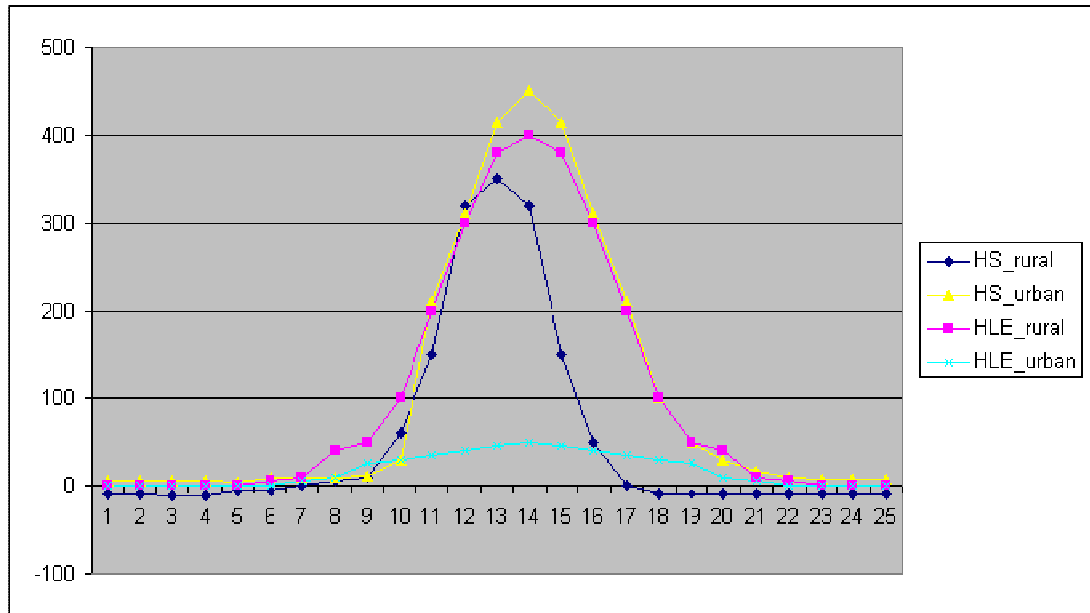135 forms, serving as basis for a comparative analysis.
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138 ### 3.3. Climate assumptions and 3D numerical simulations descriptions
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140 A set of five numerical simulations are performed using the Meso-NH atmospheric
141 model in order to evaluate the impact of the urban growth and form on the
142 dynamics of the atmosphere. The meteorological context of the experiments is an
143 idealised anticyclonic summer situation representative of the south of France. The
144 atmosphere is characterised by an idealised vertical profile representing a sunny
145 summer day, with a mixed layer (Brunt-Väissälä frequency $N = 0$ s-1) of depth ($z_i =$
146 2000 m). At the top of the mixed layer, the capping temperature inversion layer
147 was 50 m high with a strong stability ($N = 0.06$ s-1), allowing to be controlled for
148 each simulation regardless of the surface heat flux imposed. At the end, the
149 atmosphere above is represented by a stability of $N = 0.01$ s-1. With those initial
150 conditions set, a run starting at 12LT and of 36 hours of duration is performed for
151 each of the experiments.
152
153 The integrity of the differences between the urban and rural surface turbulent
154 sensible heat flux is set to 1350 W/m2. The westerly zonal wind force was $U = 2$
155 m/s and the diameter of the city varies with respect to the urban growth scenarios
156 as explained above.
157
158 The simulation is performed with a horizontal grid resolution of 250 m, which is
159 sufficient to study the fluid motions and properties at the scale of the whole city. The
160 horizontal domain is 50 km x 50 km. The vertical coordinate is composed of 35
161 levels over a vertical domain of 4 km. Vertical resolution varies from 25 m near the
162 surface to 250 m on the top of the domain. The first atmospheric level is located in
163 25 m above the urban canopy. Seventeen levels are located in the first 1000 m and
164 cyclic conditions are considered on the horizontal direction. Water vapour is
165 considered through a vertical profile of specific humidity of 0.006 g kg^{-1} inside the
166 boundary layer and decreasing outside until 0.0029 at 4 km of height. Figure 2
167 represents the diurnal cycles of urban and rural surface sensible and latent heat
168 flux imposed on urban and rural areas. The roughness length, z0, imposed is z0R =
169 0.1 m for rural surfaces and z0U =1.0 m for urban surfaces. The subgrid turbulence
170 is parameterised following the schema of Cuxart et al. (2000) and the mixing length
171 of Bougeault and Lacarèrre (1989).
172
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Figure 2: Diurnal cycles of rural and urban sensible heat flux (HS) and latent heat flux (HLE) imposed in the mesoscale simulations.

4. Results

4.1. The simulation of urban growth scenarios

As illustrated in figure 3, three urban expansion simulations are carried out by 2100 based on the actual urban map of 2006 and with respect to the fourth urban forms implemented in the basic SLEUTH version (spontaneous growth, new spreading centers, edge growth and road-Influenced growth). In the first two maps, built-up areas are respectively and exclusively simulated through edge growth and diffusion forms, while the last one combines the fourth forms (**10%** spontaneous growth, **10%** new spreading centers, **75%** edge growth, **5%** road-Influenced growth).

Built-up areas in 2006   Compact patterns (F1)   Sprawling patterns (F2)   Mix of patterns (F3)
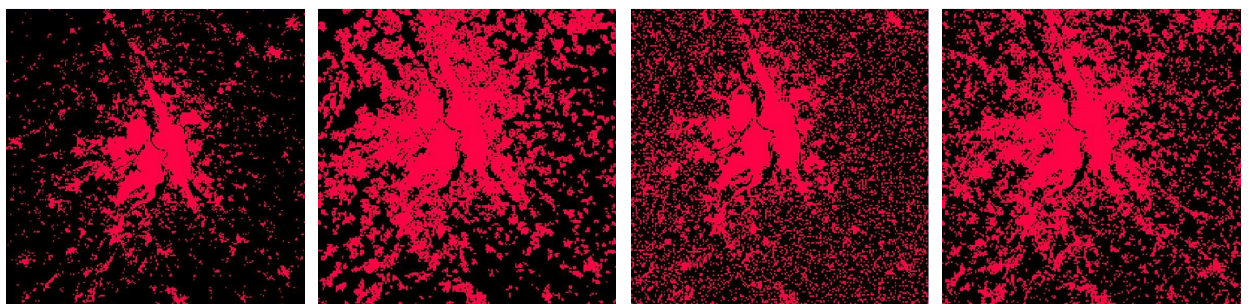
Figure 3: Built-up areas in 2006 and urban growth simulations by 2100 based on compact, sprawling and combined patterns.

4.2. The impact of the urban development on near surface air temperature

In mid-latitudes, during the night, the long-wave radiation exchange between the rural surface and the sky keeps the surface colder than the air above it, and the

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214 boundary-layer stratified. In contrast, at the urban site, the boundary-layer is mixed
215 due to the lower sky view factors, the thermal inertia of construction materials, and
216 the anthropogenic sources of heat. At daytime, the solar radiation heats the rural
217 and urban surfaces and the atmosphere is well mixed up to a high altitude (Stull
218 1988). Therefore, the UHI manifests a diurnal cycle with a significant intensity
219 during night-time, negative values during the morning and weak values during
220 daytime.
221
222 Simulations with Meso-NH shows that, for the 2006 experience, the center of
223 Toulouse is warmer than the surrounding rural areas by about 6.4 degrees Celsius
224 at 00 LT and at 06 LT (Table 1). This result agrees with the intensities observed
225 during the summertime, which attended between 4 and 6 C in 2004 during the
226 CAPITOUL campaign (Hidalgo et al. 2008). Still, the scenario F3, with less spread-
227 out center, seems to highly favour the cool air during the night.
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229 **Table 1:** Differences in temperature between the urban core and the surrounding
230 rural areas at both 00 LT and 06 LT.

Run	00 LT			06 LT		
	Tmax	Tmin	UHI	Tmax	Tmin	UHI
2006	24	17,6	6,4	23,6	17,2	6,4
F1	25,2	19,2	6	24,5	20,5	4
F2	25	20	5	24,5	20,5	4
F3	25	19,75	5,25	24,5	20,75	3,75

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232
233 As showed in the table 1, the maximum and minimum temperatures (Tmax, Tmin),
234 expected based on the three scenarios, are globally greater than what is calculated
235 in 2006. Indeed, the scenario F2, which corresponds to an exclusively spontaneous
236 growth, leads an increase of the temperature of the surrounding rural areas at 00
237 LT. These areas are warmer at 00 LT in the scenario F2 (sprawling urban growth
238 patterns) than the F1 (compact form) and F3 (mix of different patterns) scenarios.
239
240 Figure 4 shows the diurnal cycles of the average potential temperatures at 2 m of
241 height. The results used in this analysis correspond to a vertical plane passing
242 through the city center. The rural conditions are taken as the horizontal average of
243 the mesh points contained in a line of length of 5 km at a distance of 17 km upwind
244 of the city center. Urban conditions are taken as the horizontal average of the mesh
245 points contained in a line of length 5 km centred at the city centre that is considered
246 in the middle of the domain.
247
248 Furthermore, we observe an increase of 1 to 2 degrees in the urban air
249 temperature at the beginning of the night and a lost of cool capacity in the scenarios
250 with an air temperature quasi constant over the city center. The rest of the diurnal
251 cycle is very similar between scenarios. The rural temperature is higher for F1, F2
252 and F3 scenarios creating a relative UHI mean lower than that of 2006 situation. In
253 fact, the UHI intensity is not a good indicator to study the impact of the scenarios on
254 microclimate; still, it must be combined with the absolute temperature at the city
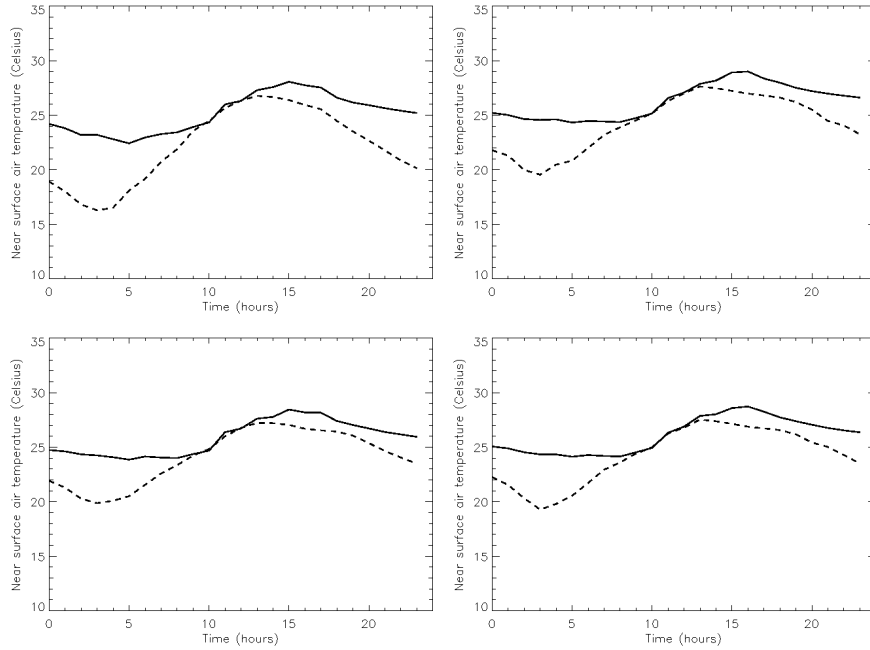255 center.
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Figure 4: Diurnal cycles of average potential temperatures at 2 m of height

Big differences in the scenarios are found when exploring the horizontal distribution of the UHI. Figure 5 shows the 2 m air potential temperature at 00 LT for 2006 and F1, F2, and F3 scenarios respectively. The increase in urbanised surface leads to a general elevation of temperatures of about 1 degree Celsius at 00LT and at 06 LT (Figures 5 and 6). Moreover, the fraction of city center affected by this elevation varies in function of the scenarios. In particular at 06 LT, the scenario F2 decreases the area of impact more than three times compared with the scenario F3 and between five to six times compared with the scenario F1 (Figure 6).
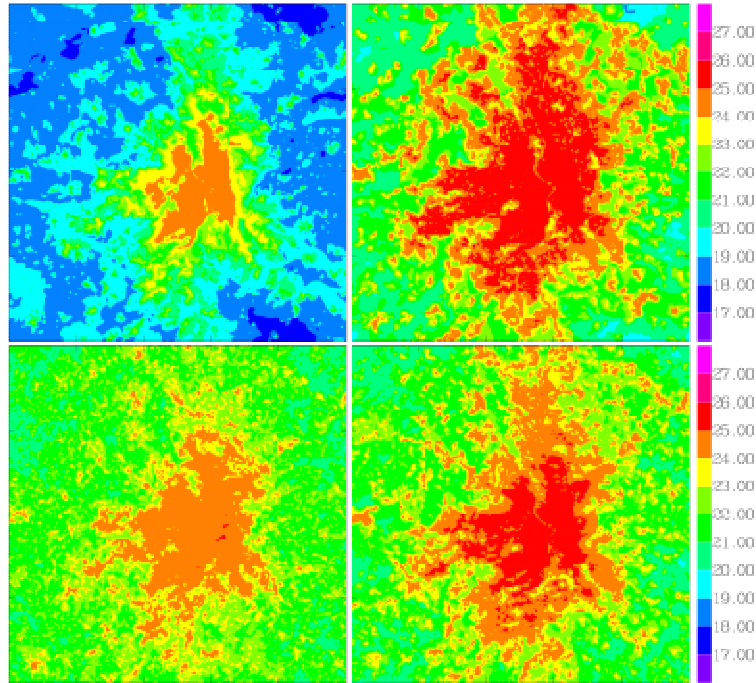

Figure 5: 2 m air temperature for 2006, F1, F2 and F3 scenarios at 00LT
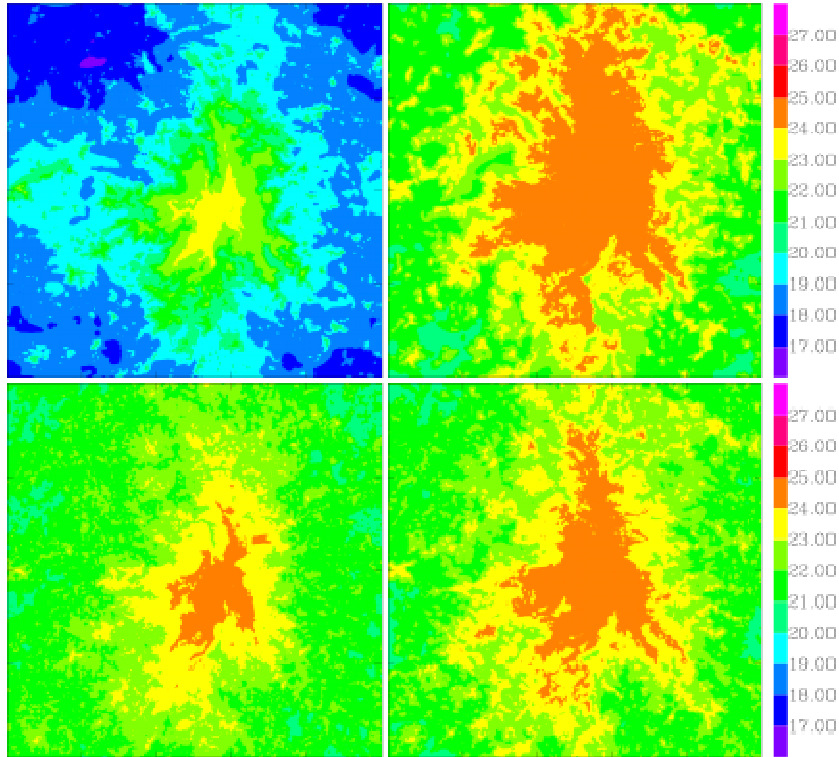
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Figure 6: 2 m air temperature for 2006, F1, F2 and F3 scenarios at 06LT

5.   Conclusions and Recommendations

This research yields four principal findings. First, simulations with Meso-NH shows that, for the 2006 experience, the center of Toulouse is warmer than the surrounding rural areas by about 6.4°C at 00 LT and at 06 LT. This result agrees with the intensities observed in 2004 during the CAPITOUL campaign. Second, we observe an increase of 1 to 2 degrees in the urban air temperature at the beginning of the night and a lost of cool capacity in the scenarios with an air temperature quasi constant over the city center. Third, the rural temperature is higher for F1, F2 and F3 scenarios creating a relative UHI mean lower than that of 2006 situation. In fact, the UHI intensity is not a good indicator to study the impact of the scenarios on microclimate; still, it must be combined with the absolute temperature at the city center. Finally, the results show that big differences in the scenarios are found when exploring the horizontal distribution of the UHI. In fact, the increase in the urbanised surface by 2100 leads to a general elevation of temperatures of about 1°C at 00LT and at 06 LT. Indeed, the area of impact affected by this elevation increases as the city spreads horizontally based on an edge growth form. However, in compact cities, the buildings are strongly expected to be high in the city center inducing a decrease in the temperature due to the shadow.

To better understand the relationship between the urban growth patterns and the urban climate, future researches should be conducted. The effect of climate change scenarios must be evaluated by comparing, for a given scenario-based urban map by 2100, the urban heat island maps with respect to various climate change conditions. Furthermore, the green space and water surfaces should be considered in the urban growth simulation for their role in the evapotransipration process.

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