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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 greater influence on the Urban Heat Island (UHI) phenomena than compact patterns. Three urban growth scenarios are built by 2100 following different urban patterns (edge growth, spontaneous growth and a hybrid of both). Those simulations are performed using a new spatially explicit urban growth model (SLEUTHR) which was specifically developed for that purpose. The impact of urban growth on the air temperature is estimated under the same climate conditions using the atmospheric Meso-NH model. The influence of urban form on urban microclimate is assessed by comparing the UHI map of 2006 with the UHI maps expected by 2100 with respect to the urban expansion scenarios. Simulations with Meso-NH show that, for the 2006 experience, the center of Toulouse is warmer than the surrounding rural areas by about 6.4 ℃ at both 00 LT and 06 LT. The results highlight an increase of 1 to 2 ℃ in the u rban air temperature at the beginning of the night and a lost of cool capacity in the scenarios. Furthermore, the results indicate that big differences in the scenarios are found when exploring the horizontal distribution of the UHI. The increase in the urbanized surface by 2100 leads to a general elevation of temperatures of about 1 ℃ at both 00 LT and 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 [Squires 2002]. Such irreversible transformations (low density land use, high dependence on automobiles relative to other means of transportation, fragmentation, low connectivity, loss of vegetation and evapotranspiration) influence the small scale land / atmosphere interactions [Hidalgo et al. 2008]. Indeed, they cause modifications of the surface energy balance through the urban heat island process [Hidalgo et al. 2008, Oke 1987, Houet and Pigeon 2011] which may severely impact human health [Johnson and Wilson 2009].

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]. For example, the association between the urban form and extreme heat events has been investigated by Stone et al. [2010]. The authors 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 prospect the effect of sprawl on the probability and intensity of heat waves

Forecasting future urban growth dynamics and patterns is particularly important to assess their potential impacts on urban climate. It allows to inform city managers and urban policy decision makers about sustainable urban expansion patterns.

The objective of this paper is to assess the influence of future urban growth scenarios on urban microclimate by 2100 in Toulouse metropolitan area (France). Specifically, we aim to examine the influence of different urban growth patterns on the intensity and spatial distribution of the UHI phenomenon.

2. Study Area

The urban area of Toulouse, which is located in the Western South of France (Figure 1) and dispersed within 342 communities, sums up to 4000 km^2 and is populated by 1 131 642 inhabitants in 2008. The city of Toulouse is ranked as the 4^{th} most populated town in France, after Paris, Marseille and Lyon. Each year, it hosts about 14 000 newcomers, which results in significant needs for housing, facilities and services. Consequently, the urban area of Toulouse has significantly decentralized over recent decades in an accelerated sprawling urban growth with an annual increase of +1 400 ha of urban area.

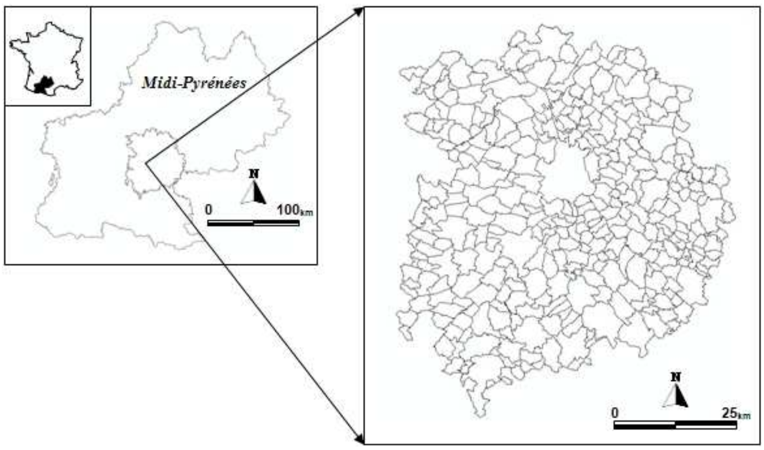


Figure 1: Urban area of Toulouse

3. Method

3.1. A scenario-based urban growth model (SLEUTHR)

The urban growth scenarios are built based on a – participatory – prospective approach [Godet 1986] regardless of the available modeling tools' capabilities. These future scenarios take into account contrasting urban planning, adaptation technologies, local trends, and major global trends assumptions. However, the majority of the existing land use and cover change models (LUCC) is not relevant enough to deal with the medium and long-term prospective scenarios particularly the exploratory and normative ones. This is why we used a scenario-based model called SLEUTHR. This new dynamic and spatially explicit model is developed through the optimization of the SLEUTH urban growth model [Clarke and Gaydos 1998]. SLEUTHR combines both economic and geographic driving forces, while allows to specify the exogenous quantity of change and the urbanization forms independently from the past LUCC trends.

3.2. Urban growth scenarios

The future urban growth by 2100 is simulated with respect to the tendency scenario which assumes the continuity of the past trends (global trends, social and economic trends at the local level). The average annual urban growth is set to 1 300 ha, while three variants of this global scenario are considered based on the urban growth form. A specific urban growth pattern is assigned to each scenario: edge growth (Scenario F1), spontaneous growth (Scenario F2) and a mix of new spreading centers, spontaneous, edge and road-influenced growth (Scenario F3).

3.3. Climate assumptions and 3D numerical simulations descriptions

A set of four numerical simulations are performed using the Meso-NH atmospheric model [Lafore et al. 1998] in order to evaluate the impact of the urban growth and form on the dynamics of the atmosphere. The meteorological context of the experiments is an idealized anticyclonic summer situation representative of the south of France. The atmosphere is characterized by an idealized vertical profile representing a sunny summer day, with a mixed layer (Brunt-Väissälä frequency N = 0 s-1) of depth (zi = 2000 m). At the top of the mixed layer, the capping temperature inversion layer was 50 m high with a strong stability (N = 0.06 s-1), allowing to be controlled for each simulation regardless of the surface heat flux imposed. At the end, the atmosphere above is represented by a stability of N = 0.01 s-1. With those initial conditions set, a run starting at 12 LT and of 36 hours of duration is performed for each of the experiments.

The integrity of the differences between the urban and rural surface turbulent sensible heat flux is set to 1350 W/m^2. The westerly zonal wind force was U = 2 m/s and the diameter of the city varies with respect to the urban growth scenarios as explained above.

The simulation is performed with a horizontal grid resolution of 250 m, which is sufficient to study the fluid motions and properties at the scale of the whole city. The horizontal domain is 50 km x 50 km. The vertical coordinate is composed of 35 levels over a vertical domain of 4 km. Vertical resolution varies from 25 m near the surface to 250 m on the top of the domain. The first atmospheric level is located in 25 m above the urban canopy. Seventeen levels are located in the first 1000 m and cyclic conditions are considered on the horizontal direction. Water vapour is considered through a vertical profile of specific humidity of 0.006 g kg^{-1} inside the boundary layer and decreasing outside until 0.0029 at 4 km of height. Figure 2 represents the diurnal cycles of urban and rural surface sensible and latent heat flux imposed on urban and rural areas. The roughness length, z0, imposed is z0R = 0.1 m for rural surfaces and z0U =1.0 m for urban surfaces. The subgrid turbulence is parameterised following the schema of Cuxart et al. [2000] and the mixing length of Bougeault and Lacarèrre [1989].

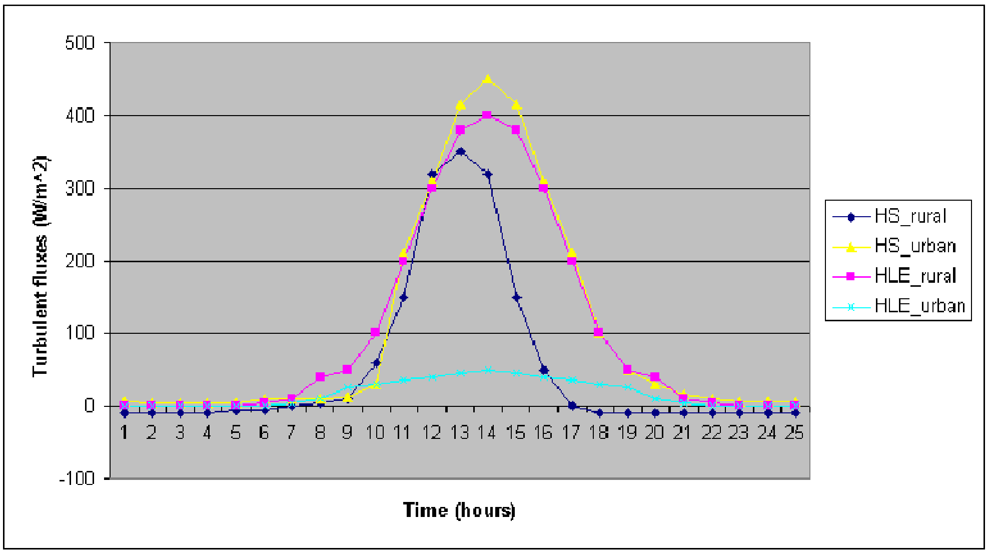
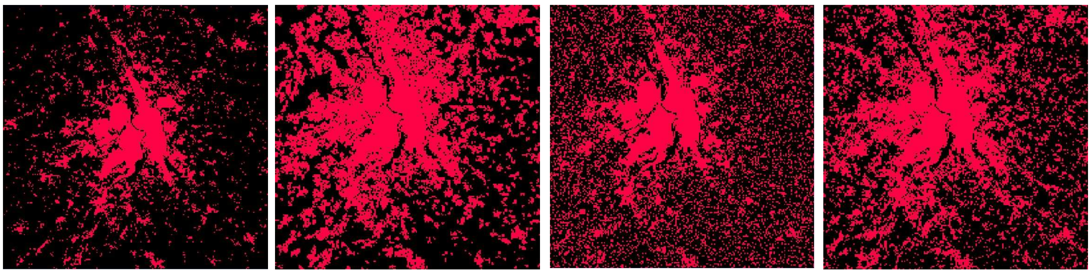


Figure 2: Diurnal cycles of rural and urban sensible heat flux (HS) and latent heat flux (HLE) imposed in the mesoscale simulations.

4. Results

4.1. 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 already implemented in the used simulation model (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. Impact of the simulated 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 boundary-layer stratified. In contrast, at the urban site, the boundary-layer is mixed due to the lower sky view factors, the thermal inertia of construction materials, and the anthropogenic sources of heat. At daytime, the solar radiation heats the rural and urban surfaces and the atmosphere is well mixed up to a high altitude [Stull 1988]. Therefore, the UHI manifests a diurnal cycle with a significant intensity during night-time, negative values during the morning and weak values during daytime.

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 06 LT (Table 1). This result agrees with the intensities observed during the summertime, which attended between 4 and 6 °C in 2004 during the CAPITOUL campaign [Hidalgo et al. 2008]. Still, the scenario F3, with less spread-out center, seems to highly favour the cool air during the night.

Table 1: Differences in temperature between the urban core and the surrounding rural areas at both 00 LT and 06 LT.

Run	00 LT			06 LT		
	Tmax	**Tmin**	**UHI**	**Tmax**	**Tmin**	**UHI**
2006 (Reference map)	24	17.6	6.4	23.6	17.2	6.4
F1 (Compact form)	25.2	19.2	8	24.5	20.5	4
F2 (Sprawling form)	25	20	5	24.5	20.5	4
F3 (Mix of different forms)	25	19.75	5.25	24.5	20.75	3.75

As showed in the Table 1, the maximum and minimum temperatures (Tmax, Tmin), expected based on the three scenarios, are globally greater than what is calculated in 2006. Indeed, the scenario F2, which corresponds to an exclusively spontaneous growth, leads an increase of the temperature of the surrounding rural areas at 00 LT. These areas are warmer at 00 LT in the scenario F2 (sprawling urban growth patterns) than the F1 (compact form) and F3 (mix of different patterns) scenarios.

Figure 4 shows the diurnal cycles of the average potential temperatures at 2 m of height. The results used in this analysis correspond to a vertical plane passing through the city center. The rural conditions are taken as the horizontal average of the mesh points contained in a line of length of 5 km at a distance of 17 km upwind of the city center. Urban conditions are taken as the horizontal average of the mesh points contained in a line of length 5 km centred at the city centre that is considered in the middle of the domain.

Furthermore, we observe an increase of 1 to 2 °C 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. The rest of the diurnal cycle is very similar between scenarios. 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.

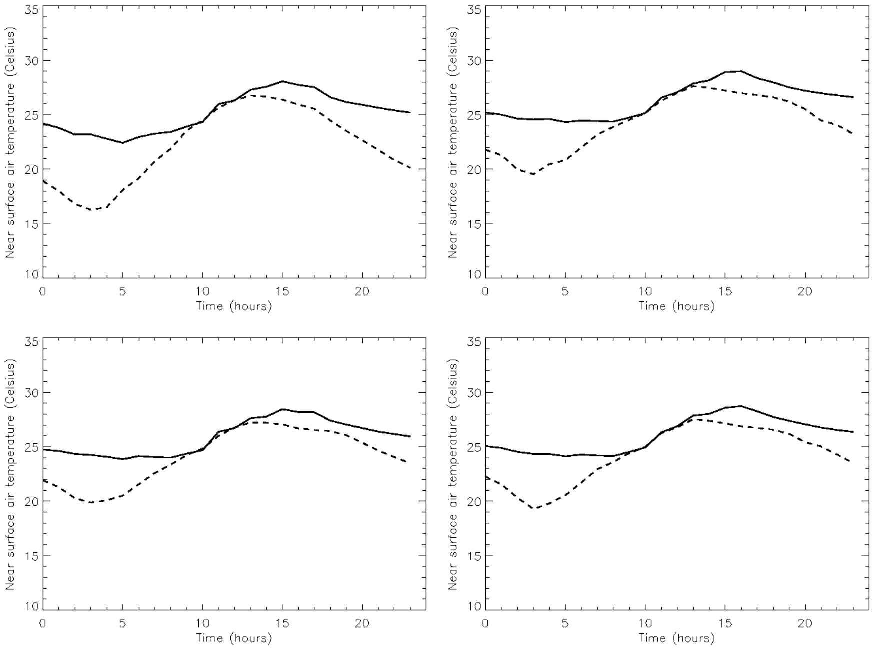


Figure 4: Diurnal cycles of average potential temperatures at 2 m of height

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 °C at both 00 LT and 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).

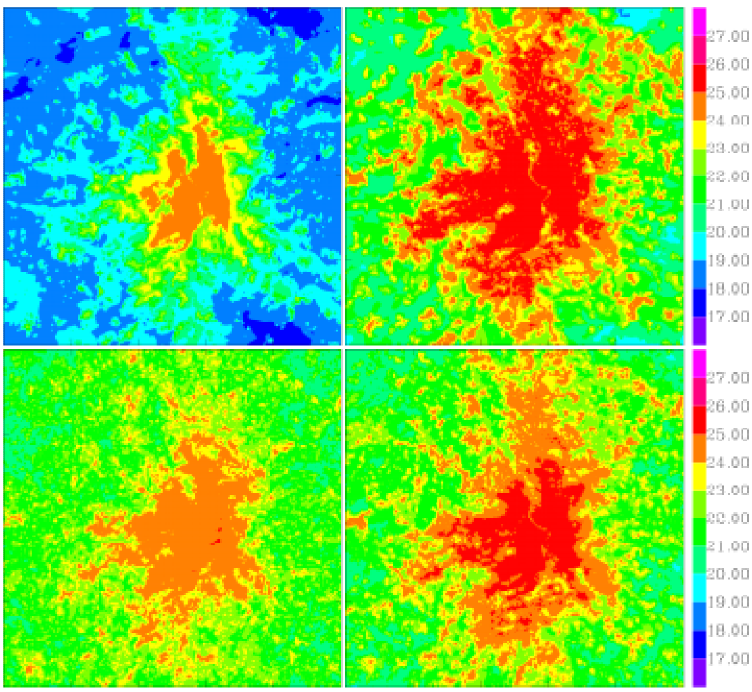


Figure 5: 2 m air temperature for 2006, F1, F2 and F3 scenarios at 00 LT

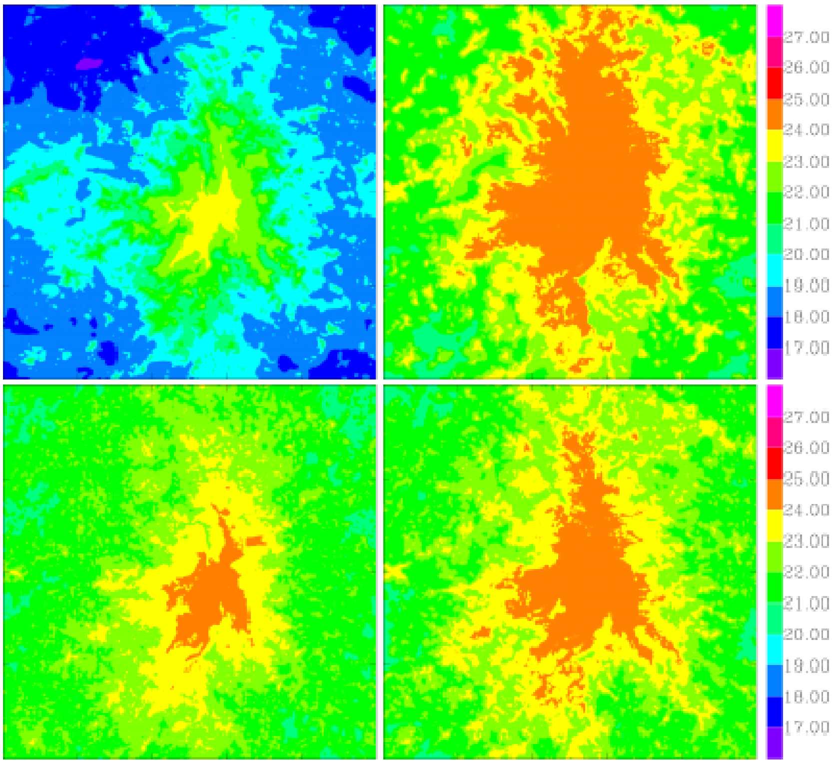


Figure 6: 2 m air temperature for 2006, F1, F2 and F3 scenarios at 06 LT

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 ℃ at 00 LT and 06 LT. This result agrees with the intensities observed in 2004 during the CAPITOUL campaign. Second, we observe an increase of 1 to 2 ℃ 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, which is high for F1, F2 and F3 scenarios, generates an UHI average lower than the 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 ℃ at 00 LT and 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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