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International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

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℃ 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℃ 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 prospect the effect of sprawl on the probability and intensity of heat waves. Indeed, urban forms strongly influence urban climate events such as the urban heat island phenomenon (Oke 1987, Houet and Pigeon 2011) which may severely impact human health (Johnson and Wilson 2009).

Forecasting future urban growth dynamics and patterns is particularly important to assess the possible impacts of future climate changes on the urban areas. Giving multiple long-term visions of future urban patterns, based on urban expansion simulation, is essential to inform city managers and urban policy decision makers about sustainable patterns of future urban development.

The aim of this paper is to assess the influence of the patterns of future urban growth scenarios on urban microclimate. Specifically, we aim to examine the influence of the urban form on the intensity and spatial distribution of the UHI phenomenon by 2100.

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 4th 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 representing annually approximately +1,400 ha of urban area.

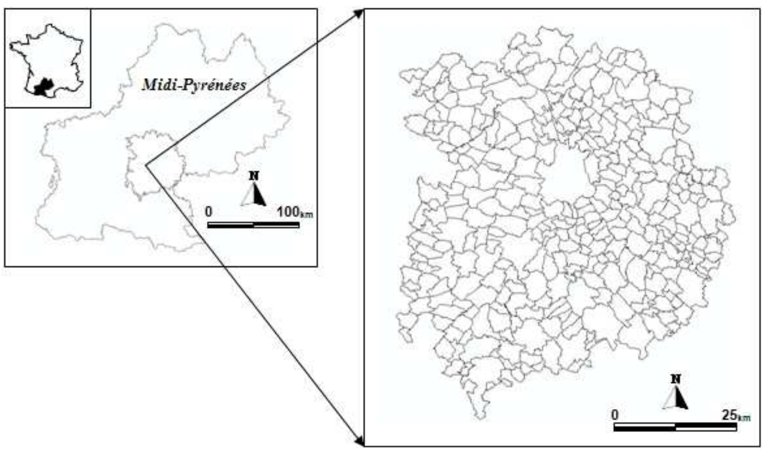


Figure 1: Urban area of Toulouse

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) using contrasting urban planning, adaptation technologies, local trends, and major global trends assumptions regardless of capabilities of available modeling tools. However, no one of those models is relevant enough to deal with medium and long-term prospective scenarios particularly exploratory and normative ones. This is why we developed a new tool, which is a based-scenarios model, through the optimization of the SLEUTH urban growth model (Clarke and Gaydos 1998). Our new spatially explicit model deals with limitations of the majority of existing LUCC models. This new dynamic model, which combines both economic and geographic driving forces, allows the user to specify the expected amount of change and urbanization forms that are appropriate to each scenario. Furthermore, the exogenous quantity and urban forms mean that the model's user can specify the amount of expected built-up areas and patterns in the prediction map independently from past LULC 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 actual tendency in the metropolitan area (global trends, social and economic trends at the local level). Besides, the annual rate of the urban growth at the urban area of Toulouse is set to 1300 ha. In order to assess the impact of the sprawling patterns of the urban development on the urban heat island, three variants of this global scenario are considered based on the urban form: scenario F1, F2 and F3. 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). These scenarios provide three potential urban forms, serving as basis for a comparative analysis.

3.3. Climate assumptions and 3D numerical simulations descriptions

A set of five numerical simulations are performed using the Meso-NH atmospheric model 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 idealised anticyclonic summer situation representative of the south of France. The atmosphere is characterised by an idealised 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 12LT 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/m2. 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).

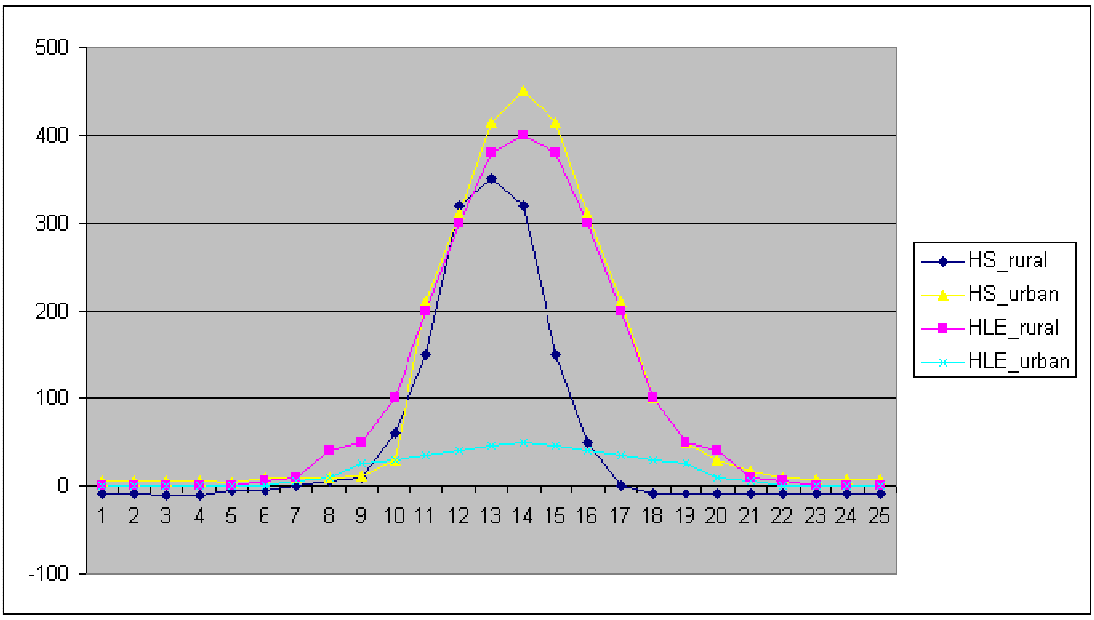
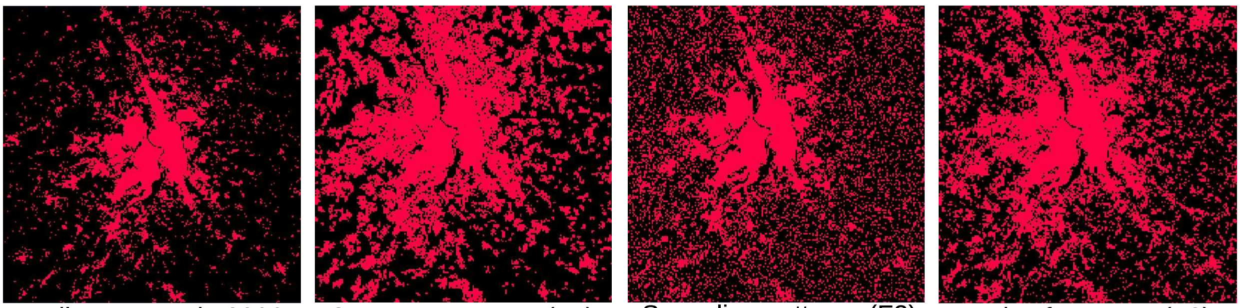


Figure 2: Diurnal cycles of rural and urban sensible heat flux (HS) and latent heat flux (HLE) imposed in the mesoscale simulations.

4. Results

4.1. 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 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 degrees Celsius at 00 LT and at 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.

	00 LT			06 LT		
Run	**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

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 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. 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.

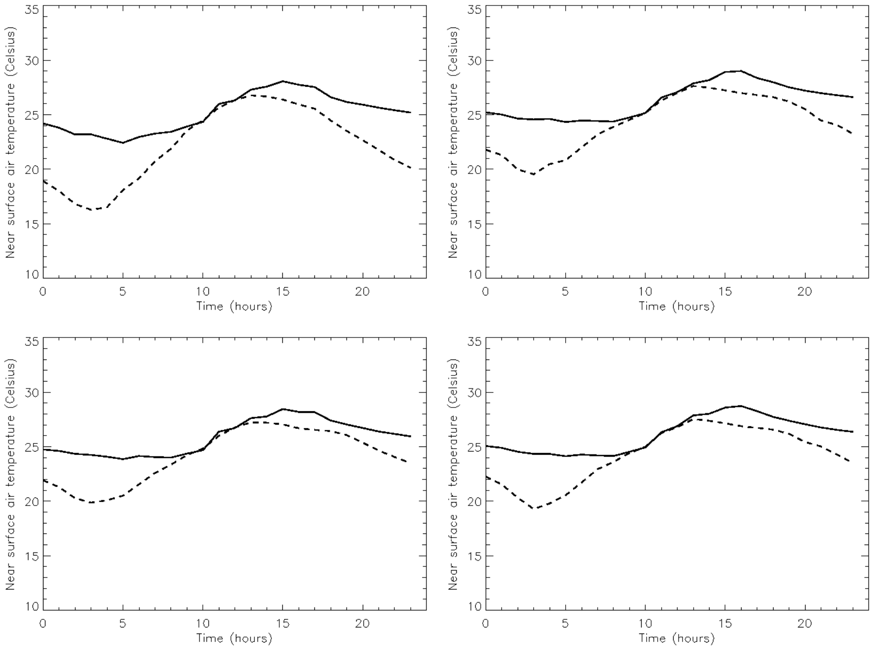


Figure 4: Diurnal cycles of average potential temperatures at 2 m of height

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 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).

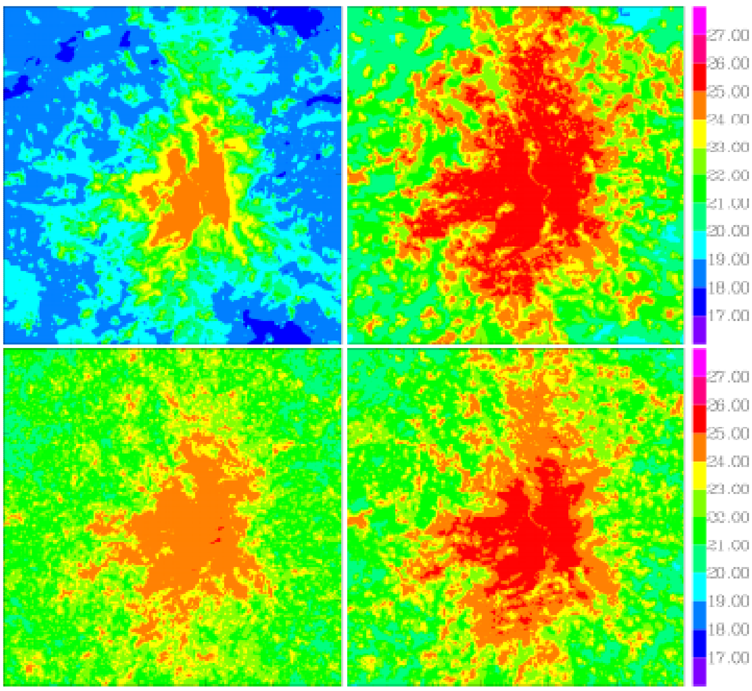


Figure 5: 2 m air temperature for 2006, F1, F2 and F3 scenarios at 00LT

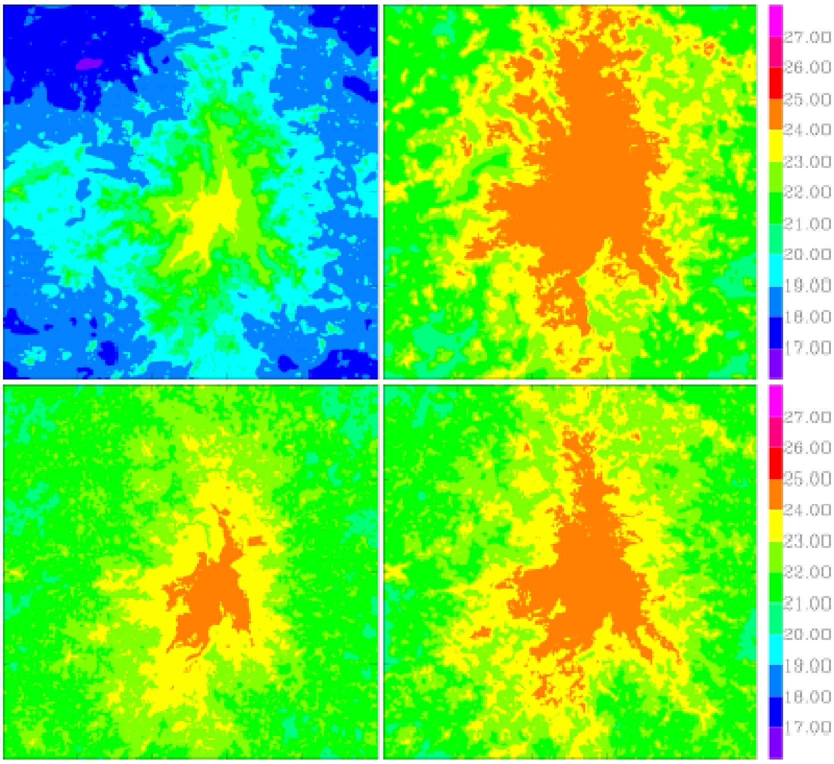


Figure 6: 2 m air temperature for 2006, F1, F2 and F3 scenarios at 06LT

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℃ 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℃ 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.

ACKNEWLEDGEMENTS

This work is performed in the ACCLIMAT project which is supported by the RTRA-STAE foundation. The authors would like to thank the anonymous reviewers for their relevant and constructive comments and suggestions.

REFERENCES

Bougeault, P., Lacarrère, P., (1989): Parameterization of orography-induced turbulence in a meso-beta scale model. Mon. Wea. Rev.,117: 1870-1888.

Clarke, K.C., Gaydos, L., (1998): Long term urban growth prediction using a cellular automaton model and GIS: Applications in San Francisco and Washington/Baltimore. International Journal of Geographical Information Science.

Cuxart, J., Bougeault, P., Redelsperger, J.-L., (2000): A Turbulence Scheme Allowing for Mesoscale and Large-Eddy Simulations. Quart. J. Roy. Meteorol. Soc. 126, 1–30.

Doukari, O., Aguejdad, R., Houet, T., (2012): A scenario-based spatially explicit urban model for forecasting long term urban growth. iEMSs Conference 2012, session F1 (submitted).

Godet, M., (1986): Introduction to la prospective: seven key ideas and one scenario method. Futures 18:134–157.

Hidalgo, J., Masson, V., Baklanov A., Pigeon, G., Gimeno, L., (2008): Advances in Urban Climate Modeling. Trends and Directions in Climate Research: Ann. N.Y. Acad. Sci. 1146: 354–374.

Houet T. and Pigeon G. (2011), Mapping urban climate zones and quantifying climate behaviors - an application on Toulouse urban area (France), Environmental Pollution, Vol 159, Iss 8-9, 2180-2192

Johnson, D.P., Wilson, J.S., (2009): The socio-spatial dynamics of extreme urban heat events: the case of heat-related deaths in Philadelphia. Applied Geography 29:419–434.

Martin, E., Le Moigne, P., Masson, V., and coauthors, (2007): Le code de surface externalisé SURFEX de MétéoFrance. Atelier de Modélisation de l'Atmosphère <http://www.cnrm.meteo.fr/ama2007/>, Toulouse, 16-18, January.

Oke, T.R., 1987. Boundary Layer Climates. Methuen, London and New York.

Squires, G.D., (2002): Urban sprawl and the uneven development of metropolitan America. In: Urban Sprawl: Causes, Consequences, and Policy Responses (Squires GD, ed). Washington, DC: Urban Institute Press, 1–22.

Stone, B., Hess, J.J., Frumkin, H., (2010): Urban Form and Extreme Heat Events: Are Sprawling Cities More Vulnerable to Climate Change Than Compact Cities? Environmental Health Perspectives, volume 118 (10): 1425-1428.

Stone, B.Jr., Norman, J., (2006): Land use planning and surface heat island formation: a parcel-based radiation flux approach. Atmos Environ 40(2006): 3561–3573.

Stull, R.B., (1988): An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Dordrecht, 666 pp.