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# Evaluation of Urban Weather Generator for air temperature and urban heat islands simulation over Toulouse (France)

Hiba Hamdi   
Kermap  
CNRS, UMR 6545 LETG  
Cesson-Sévigné and Rennes, France

Laure Roupioz   
Onera, DOTA  
Université de Toulouse  
Toulouse, France

Thomas Corpetti   
CNRS, UMR 6545 LETG  
Rennes, France

Xavier Briottet   
Onera, DOTA  
Université de Toulouse  
Toulouse, France

Antoine Lefebvre   
Kermap  
Cesson-Sévigné, France

**Abstract**—In recent years, the significant increase both in terms of frequency and intensity of heat waves has dramatic consequences in urban areas. The amplification of the urban heat island (that can exceed  $10^{\circ}\text{C}$ ) has indeed hazardous impacts on health or biodiversity and it becomes urgent to set up early warning systems. Understanding and simulating the Urban Heat Island (UHI) is therefore of prime importance to help city planners in the conception of more resilient cities. In practice, because of the complexity of this phenomenon, no trivial model exists and number of contributions have been proposed (mostly based on physics or statistics), all of them requiring a variety of input parameters related to urban morphology, land use, material properties or meteorological conditions. In this paper, we analyze the performances of the open source Urban Weather Generator (UWG) model in the context of Toulouse, one of the biggest French cities. Morphological and land cover parameters are derived from remote sensing and performances of UWG are analyzed on various Local Climate Zones (LCZs). Simulated air temperatures showed good consistency on different LCZs with a mean bias error (MBE) ranging between  $-0.51^{\circ}\text{C}$  to  $0.37^{\circ}\text{C}$  and a root mean square error (RMSE) between  $1.73^{\circ}\text{C}$  to  $2.35^{\circ}\text{C}$ . We also show that best performances are achieved on dense urbanized areas.

**Index Terms**—Urban Heat Island, Local Climate Zones, Remote Sensing, Urban Weather Generator Model, Air temperature

## I. INTRODUCTION

Since two decades, the urban heat island (UHI) gathers many actors (researchers, city planners, etc.) as this phenomenon has become drastically sound with negative impacts mostly in terms of health, biodiversity or global warming. It is now well understood that UHI is due to artificialisation, which has replaced natural surfaces with heat-retaining materials (buildings, pavements, ...). In a context of dense urbanization (it is expected that 70% of the world population will live in cities by 2050) and global warming, helping city planners in modifying/constructing new areas able to limit UHI is of prime importance.

Because of the complexity of UHI phenomenon, the definition of physical models is still an open issue for which several techniques have been proposed [1], each of them having their pros and cons. Complementary, some statistical models have also been defined to link land surface to air temperatures measured from meteorological networks or even crowd sourcing [2], [3]. In a prospective context, the use of consistent simulation tools to generate air temperatures on the basis of urban morphology and land cover is crucial to evaluate the impact of an urban development plan or to help decisions regarding city management.

Among existing models, Urban Weather Generator [4] is appealing since it is open source, easy to operate and applicable at city scale. Therefore this paper presents an evaluation of its performances to simulate urban air temperatures and to derive UHI over Toulouse. To this end we use remote sensing data to extract the required surface parameters used in UWG. The analysis is performed on various LCZs in the city of Toulouse, France, for which a large meteorological network is available to evaluate UWG simulations.

## II. MATERIALS AND METHODS

### A. Study Area

Toulouse is the fourth largest city of France with almost 500.000 inhabitants. Located in the southwest of France, its climate is generally characterized by warm and clear summers and cold and partly cloudy winters. In the past years, longer periods with extreme temperatures, above  $35^{\circ}\text{C}$  during daytime and  $25^{\circ}\text{C}$  during nighttime, were observed leading to urban heat island effects. A large network of meteorological stations monitoring mainly air temperature and humidity was set through the city and its surroundings, providing a unique dataset to investigate their variability at city scale.

Toulouse meteorological network is composed of 76 weather stations representing a range of LCZs [5]. All the stations are showed in Fig. 1. However, all of them were not simultaneously active and some had to be removed for

consistency reasons (see [6] for more information). The stations used in this study were chosen along a North/South transect, yielding different LCZs ranging from heavily wooded landscape (urban park) to area with tightly packed buildings of 3 to 9 stories tall and little or no green space.

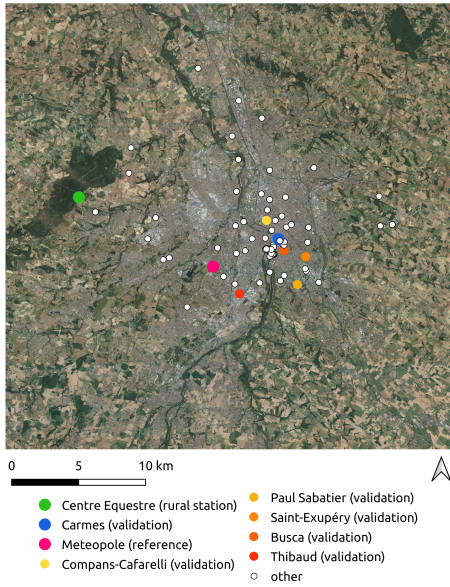


Fig. 1. Toulouse **weather stations** map. [6], [7]

### B. Urban Weather Generator

Urban Weather Generator (UWG) is a computationally efficient tool simulating hourly canopy level air temperature from meteorological information acquired at a rural reference weather station located close to the city [4]. Based on the Town Energy Balance (TEB) scheme, UWG offers an easy to use alternative to computationally expensive physical models. Along with the meteorological data provided by the rural reference station, it requires a parametric description of the urban surface to characterise the studied area. The fact that the source code is open<sup>1</sup> is also a major asset for an easy use of the model as well as for future improvements.

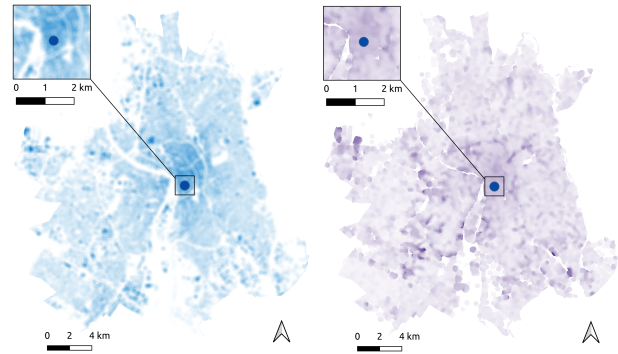
### C. Remote sensing for urban surface parametric description

UWG simulates the canyon air temperature for a single location corresponding to a specific urban configuration described by several parameters such as building density and height or land cover distribution. These parameters are provided for a given spatial resolution, being usually a few hundred meters in coherence with the physical concepts of the modeling approach. When working at city scale, it is of interest to derive the surface parameters from remote sensing data to properly apprehend the urban spatial variability.

In this study, the surface parameters are first generated at the native spatial resolution of the initial dataset and then aggregated at 200m (using a convolution kernel). Two main

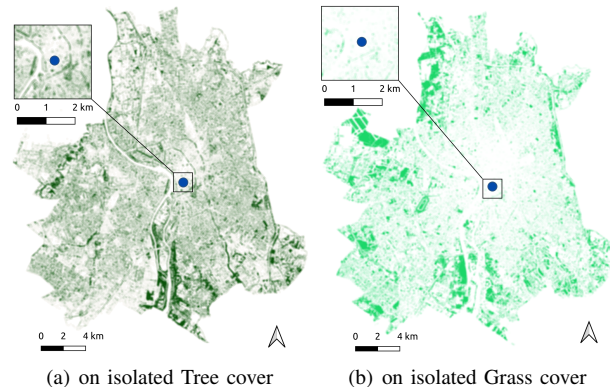
families of parameters are computed from remote sensing sources:

- **Topological parameters.** In practice we rely on the BD TOPO 2021, from the french National Institute of Geographic and Forest Information (IGN) [8]. It represents Digital Surface Models (DSM) at 1m spatial resolution, computed in practice from ortho-images [7]. From DSM, we derive 3 main geomorphological indicators: build density, build height and vertical to horizontal height ratio. An illustration of the two first indicators is visible in Fig. 2;
- **Vegetation parameters.** From the same ortho-images, we derive the grass and tree cover information at 50cm resolution using specific vegetation classification criteria mixed with deep neural networks [9]–[11]. Results have been refined by Computer-Assisted Photo Interpretation (CAPI). From such data we compute grass and tree cover percentage, as illustrated in Fig. 3.



(a) Build Density : issued from a (b) Build Height : issued from the mask of DSM (1 = if built, 0 = building height attribute of DSM otherwise)

Fig. 2. **UWG inputs related to built area** issued from DSM and filtered at the scale of 200m: building density (a) and building height (b).



(a) on isolated Tree cover (b) on isolated Grass cover

Fig. 3. **UWG inputs related to vegetation** issued from ortho-images at the scale of 200m: tree cover (a) and grass cover (b).

### D. Validation approach

The validation is performed on specific days in 2020 year favorable for UHI: no clouds, low wind, high air

<sup>1</sup>see: <https://github.com/ladybug-tools/uwg>

temperatures, atmospheric pressure and humidity. The 5, 6, 19 and 20 of August 2020 are selected based on these criteria.

As for the Rural Reference station, we rely on *Centre équestre* (in green in Fig. (1)) as it meets the constraints set in the bibliography: it is neither close to urban land use, nor mountains or large water bodies [12]. The *Carmes* station (in blue in Fig. (1)) is selected as urban reference for the first validation of the estimated air temperature as it is located in one of the most urbanized areas and is usually the one recording the highest air temperature values. Then, the validation was extended to five other stations from different LCZs (visible in the Tab. I) in order to compare the performance of UWG for difference spatial context. Finally, the urban heat island was estimated for every station.

### III. RESULTS

In this section, we first analyze the performances of UWG for the 6 chosen LCZs and in section III-B we carry out UHI simulations for 3 different LCZs.

#### A. Validation of UWG simulated air temperature

The air temperature simulations for the *Carmes* station are visible on the Fig. 4.

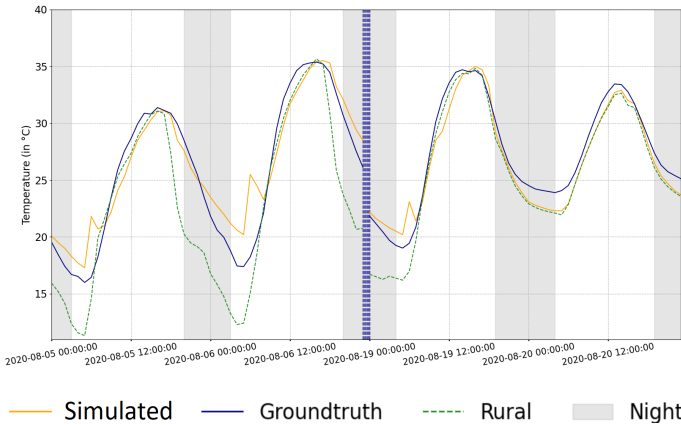


Fig. 4. Comparison of **hourly** (at Universal Time Coordinated (UTC)) **air temperature** measured at the rural reference station, the *Carmes* station (Groundtruth) and simulated by UWG for selected UHI favorable days.

As shown in this figure, there is an overall good agreement between the simulated air temperature and the values measured at *Carmes* station, with a MBE of  $0.02^{\circ}\text{C}$  and a RMSE of  $1.73^{\circ}\text{C}$ . Some differences are observed on the 5<sup>th</sup>, 6<sup>th</sup> and 19<sup>th</sup> of August with an overestimation of the air temperature starting in the middle of the night until early morning followed by a slight underestimation until sunset. At the beginning of night, the simulation sticks well to the measured values. The day of the 20<sup>th</sup> has a different behaviour, with very low differences between rural, urban station and simulated values. Except on the last day, anomaly peaks occur at around 4 am, which corresponds to the sunrise UTC hour and this regardless the station used for validation. The absence of anomaly on the 20<sup>th</sup> of August may be due to the fact that the night before

was the hottest of the studied period (minimum  $22^{\circ}\text{C}$ ) and, as mentioned previously, that there is low difference between the rural and in city air temperature values that day. This point would require further investigations. In the meantime, it appears relevant to automatically detect this anomaly at 4am, to filter it out and to linearly interpolate it. This process is applied for all validation stations.

A comparative table of UWG performances on the different LCZs (before and after removing the 4am outlier) is presented in Tab. I, as well as MBE and RMSE for each station. On this table, one can observe a global consistency of UWG simulations, both in terms on RMSE and bias. It is also interesting to outline that best estimations are obtained for the *Carmes* station, i.e. the most urbanized one, and that the performance slightly decreases when the urbanisation decreases.

TABLE I  
PERFORMANCE INDICATORS OF THE 6 CHOSEN STATIONS BETWEEN SIMULATED AIR TEMPERATURES AND GROUND TRUTH (VALUES BEFORE REMOVING ANOMALIES ARE IN BRACKETS)

Station	RMSE ( $^{\circ}\text{C}$ )	MBE ( $^{\circ}\text{C}$ )	LCZ [13]
C-Cafarelli	<b>2.01</b> (2.35)	<b>-0.37</b> (-0.51)	11-Dense trees
P. Sabatier	<b>1.98</b> (2.2)	<b>-0.26</b> (-0.39)	5-Open mid-rise
St-Exupery	<b>1.94</b> (2.2)	<b>0.02</b> (0.11)	6-Open low-rise
Busca	<b>1.77</b> (2.1)	<b>0.5</b> (0.37)	3-Compact low-rise
Thibaud	<b>1.77</b> (2.06)	<b>-0.03</b> (-0.16)	8-Large low-rise
Carmes	<b>1.41</b> (1.73)	<b>0.14</b> (0.02)	2-Compact mid-rise

#### B. Computation of UHI from UWG simulations

The hourly UHI simulated by UWG for the *Carmes* station is presented in Fig. 5. The other stations showed similar patterns with, as expected from the previous results, an overestimation of UHI during the day, slight underestimation at night and the best results obtained over the most urbanized LCZs. As for the air temperature, the UHI pattern is different for the 20<sup>th</sup> of August. The values of humidity, wind speed, atmospheric pressure, downward short-wave and long-wave radiations were checked over the simulation period. They are all stable over the entire period except the downward long-wave radiation that shows higher values during the night between the 19<sup>th</sup> and the 20<sup>th</sup> of August. This could explain the different behaviour observed that day, with rural air temperature close to the city centre ones, as compared to the three other days. Even though UHI simulations from UWG are globally coherent with ground truth, the absence of spatial gradient between the air temperature values simulated for the different LCZs tend to homogenize the UHI effect over the city and to mask the differences between the various urban configurations. The root mean pairwise square differences of simulated temperatures (or UHI) is about  $0.14^{\circ}\text{C}$  (the root median pairwise square differences is about  $0.1^{\circ}\text{C}$ ). Thus, in this context, UWG appears to be limited to generate UHI maps and to detect the spatial variability over Toulouse.

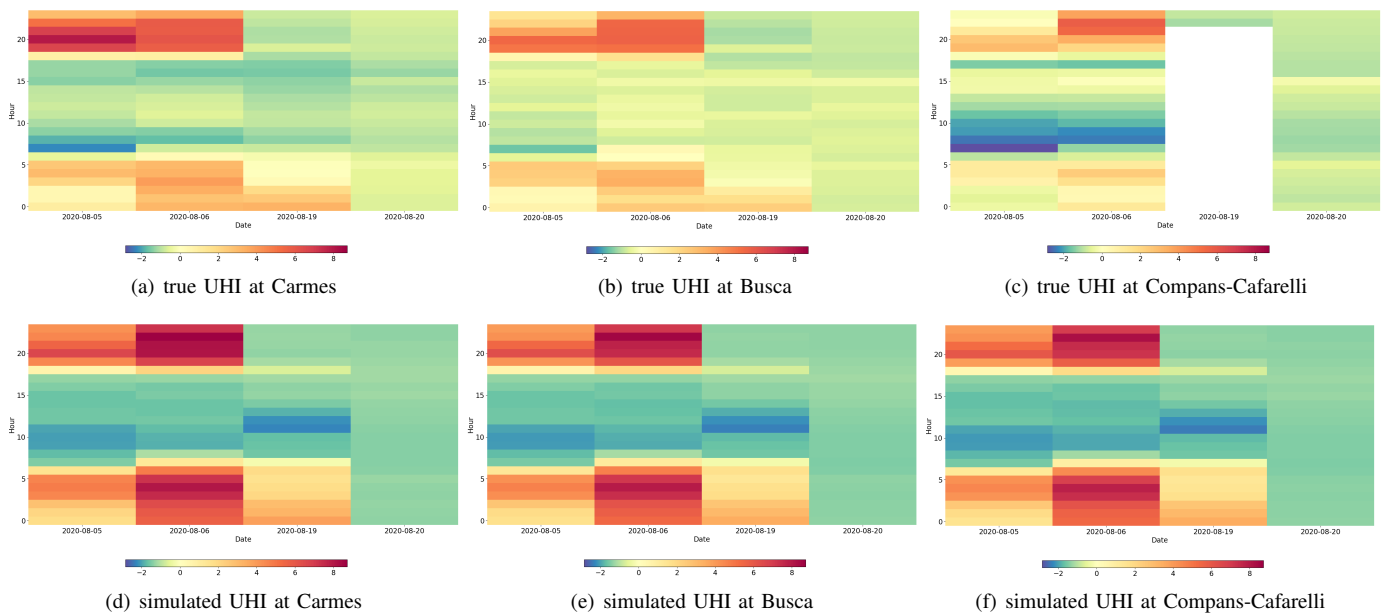


Fig. 5. Comparison of **hourly UHI** (in °C) : true (top) vs simulated (bottom) at different stations in Toulouse on sunny and hot days in August 2020

#### IV. CONCLUSION

In this paper, Urban Weather Generator, an accessible and computationally efficient tool, has been evaluated for the simulation of air temperatures on different LCZs over the city of Toulouse. The simulated air temperature values are then used to derive UHI. While it provides reliable results over densely urbanised areas, the performances decrease when the rate of urbanization decreases and the model does not appear to be so sensitive to variations in the urban surface such as different building density or the presence of vegetation. Consequently, better results were also obtained for UHI derived for the most urbanized areas. In the context of this study on the city of Toulouse, the lack of spatial variability in the values simulated by UWG did not allow to investigate the patterns of the UHI phenomenon over the different LCZs, despite very efficient results and consistent UHI patterns in dense areas. Future works should concern the adaptation of UWG on various spatial contexts.

#### ACKNOWLEDGMENT

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