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This article presents the development and application to a set of French urban agglomerations of a method for Local Climate Zones (LCZ) attribution using the open-source language R. The LCZs classify the urban fabric at high spatial scale (such as a block of houses) according to its morphological characteristicsand land use. The LCZ classification is carried out for 42 urban agglomerations and is then related to urban heat island intensity (UHII) obtained from numerical simulations at a spatial resolution of 250m. The objective is to study the adequacy of the LCZ classification to characterise the impact of urban morphology on the UHII. The variance analysis (ANOVA) carried out confirms the highly significant relationship between LCZs and the UHII for a given urban agglomeration. For all the urban agglomerations in the sample, linear regression models show a significant correlation between the percentages of surface covered by different LCZ and the mean UHII for the time periods tested (21-23 UTC), with adjusted coefficients of determination higher than 0.40.

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INFLUENCE OF THE URBAN MORPHOLOGY ON THE URBAN HEAT ISLAND INTENSITY: AN APPROACH BASED ON THE LOCAL CLIMATE ZONE CLASSIFICATION

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ABSTRACT

This article presents the development and application to a set of French urban agglomerations of a method for Local Climate Zones (LCZ) attribution using the open-source language R. The LCZs classify the urban fabric at high spatial scale (such as a block of houses) according to its morphological characteristics and land use. The LCZ classification is carried out for 42 urban agglomerations and is then related to urban heat island intensity (UHII) obtained from numerical simulations at a spatial resolution of 250m. The objective is to study the adequacy of the LCZ classification to characterise the impact of urban morphology on the UHII. The variance analysis (ANOVA) carried out confirms the highly significant relationship between LCZs and the UHII for a given urban agglomeration. For all the urban agglomerations in the sample, linear regression models show a significant correlation between the percentages of surface covered by different LCZ and the mean UHII for the time periods tested (21-23 UTC), with adjusted coefficients of determination higher than 0.40.

INTRODUCTION

At the crossroads of current issues relating to demographic pressure and urban sprawl, in a context of climate change, studying the influence of cities on the local climate remains fundamental. From a thermal point of view, this influence can be measured through the urban heat island (UHI), which is characterised by the difference in air temperature between an urban space and its surrounding countryside (Oke and Fuggle, 1972). From the beginning of UHI studies, the relationship between the size of the city and its UHI intensity was established (Oke, 1973). As reflected in Arnfield (2003), intensity and spatial variability of UHI depends of time, meteorological conditions and urban morphology. The need to have detailed databases of the urban morphology then became obvious and several urban parameters impacting energy or water budget and fluid dynamics are defined: density of built surface, vegetation surface, road surface, building height and compactness, width of the street, etc… (Ellefsen 1990-91, Cianco and Ellefsen, 1998; Burian, 2006 ; Long and Kergomard, 2005). Finally, most recently, Stewart and Oke (2012) have proposed a typology from these parameters, describing the different urban districts, , through the concept of the Local Climate Zone (LCZ). These zones are defined according to a typology applicable to a reduced area (such as

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a block of houses) and are characterised according to parameters of land use, urban morphology and human activities. Several research projects have since used LCZs in the context of studies related to climatology or urban planning. For example, Alexander et al (2015) have used them to initialise building energy simulation models on the neighbourhood scale (⩾1 sq.km). Coupled with a Geographic Information System (GIS), it is possible to use LCZs for climate-based mapping, like the work published on Hong Kong (Zheng et al., 2017) or Nagpur (India) (Kotharkar and Bagade, 2017). GIS approaches have been developed to identify LCZs of urban areas using specific databases such as satellite images, along the lines of WUDAPT (World Urban Database and Access Portal Tools) (Wang et al., 2018).

The MApUCE (Applied Modelling and Urban Planning Law: Climate and Energy) project aims to incorporate a whole host of data and indicators related to the urban climate and energy into urban planning documents. It focuses on about 80 urban agglomerations in metropolitan France.
In this framework, the objective of this study is to quantify the influence of urban agglomerations and their LCZ structure on the intensity of the UHI, across 42 urban agglomerations, representative of French urban agglomerations with more than 50,000 inhabitants and distributed according to the different climatic and geographical regions of metropolitan France. The assumption is that the different LCZs do not have the same impact on the UHI and that, depending on the type of agglomeration, this relationship will also be different. To this end, our approach was initially to adapt and automate a method developed by Hidalgo et al. (submitted) allowing the identification of LCZs and their spatialization from the database produced as part of the project (the MaPUCE database, Bocher et al., 2018). Then, statistical relationships between UHII and LCZs type and surface covered by each LCZ, have been studied by analysis of variance and linear regression models.

MATERIALS & METHODS

Land use and urban morphology data

The urban morphology and land use data are drawn from the database (DB) established as part of the MApUCE project (http://mapuce.orbisgis.org/) and concern a group of 79 urban agglomerations with over 50,000 inhabitants. Defined by the INSEE (French national statistics office), an urban agglomeration is defined as a continuous built-up and populated area (at least 2,000 inhabitants) [https://www.insee.fr/fr/metadonnees/definition/c1501]. In the MApUCE DB, each urban agglomeration is divided into reference spatial units (RSU), which correspond to building patches, delimited by a roads or water bodies (Plumejeau et al., 2015); the RSU are therefore of a size which allows the calculation of and descriptive indicators of the urban morphology. RSUs are of variable size and avoid artificial segmentations of the urban fabric, such as those generated by regular grids. Each RSU is described by 41 indicators, calculated from several databases (IGN and INSEE), characterising land use, urban morphology, demography and their belonging to an architectural typology (Bocher et al., 2018). The architectural typology distinguishes, for example, the RSU composed mainly of single family houses from those composed of apartment blocks or buildings used for activities. The variables used in this article are described in detail in Table 1.

Description of variables characterising the RSU.

Indicator	Description	Computation
pk_rsu	Primary key of the RSU	Incremental value
build_density	Building density in the RSU	Built area / Total RSU area

h_mean	Mean height of the buildings in the RSU (m)	∑ buildings area*building height / ∑ buildings area
hydro_density	Hydrographic's area density in the RSU	Water area / Total RSU area
min_m_dist	Mean of the minimum distance between buildings in the RSU (m)	∑ minimum distance between buildings / number of building in the RSU
road_density	Road area's density in the RSU	road area / Total RSU area
typo	A category describing the urban morphology of the RSU	Classification in 10 classes using a random Forest based method on urban morphological indicators

Data on urban heat island intensity

Data on UHII in 2 m above ground are taken from simulations carried out with the urban canopy parametrization TEB (Town Energy Balance) (Masson, 2000), coupled with the mesoscale atmospheric model Méso-NH (Lac et al., 2018). TEB assumes a simplified urban morphology with buildings aligned along street canyons and solves the surface energy budget of a representative roof, wall and road. Urban vegetation is taken into account with the approach of Lemonsu et al. (2012). For every agglomeration, local weather types have been determined (Hidalgo et al.,2014) and a weather type representing summer conditions favorable to the development of a pronounced UHI has been selected. For each agglomeration, a total of 6 days of the selected local weather type have been simulated to reduce uncertainty due to intra-weather type variability. In order to allow for spin-up, Méso-NH is initialized 2 days before the day with the weather type of interest. Initial and lateral boundary conditions have been taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis. Two simulations are performed to calculate the UHII: one taking account the actual urban morphology and one by replacing the urbanized area with croplands typical for its surroundings. The UHII is then defined as the difference between the urbanized and the non-urban simulation. Model output is available for the 42 agglomeration at 250 m horizontal resolution and hourly frequency. The atmospheric model takes into account various factors influencing the local climate (land use, orography, sea and water bodies), the results therefore do not only depend on urban morphology.

Methodology for calculating LCZs

The script identifying the LCZs is coded via the programming language and open-source software R, under R Studio. R was also used for the statistical processing mentioned. The display and formatting of the data was done under the QGIS open-source GIS version 2.14 LRT. The table 2 describes the different computed LCZs.

Presentation of LCZs and their definition (adapted descriptions by Stewart & Oke, 2012)

LCZ	Name	Description
1	Compact High Rise	Dense mix of tall buildings (>25m) . Few or no trees , land cover mostly paved.
2	Compact Mid Rise	Dense mix of midrise buildings (10 to 25 m). Few or no trees , land cover mostly paved.
3	Compact Low Rise	Dense mix of low-rise buildings. Few or no trees , land cover mostly paved.
4	Open High Rise	Open arrangement of tall buildings (>25m). Pervious land cover (low plants, scattered trees)
5	Open Mid Rise	Open arrangement of midrise buildings (10 to 25m). Pervious land cover (low plants, scattered trees).

6	Open Low Rise	Open arrangement of low-rise buildings. Pervious land cover (low plants, scattered trees).
7	Lightweight Low Rise	Dense mix of single-story buildings, few or no trees. Lightweight construction materials.
8	Large Low Rise	Open arrangement of large low-rise buildings. Few or no trees. Land cover mostly paved.
9	Sparsely Built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).
D	Low plants	Featureless landscape of grass or herbaceous plants/crops
E	Bare rock / Paved	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation
G	Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons

The method developed by Hidaglo & al (submitted) to attribute an LCZ class to a given RSU has been adjusted by expertise to 5 urban agglomerations of different size and morphology: Toulouse, La Rochelle, Nantes, Dijon and Besançon, then applied to all urban agglomerations. Some thresholds have been changed and some criteria added. A line was added to exclude from compact LCZs, the RSU with a build density lower than 28%. The RSU with a mean minimum distance between buildings lower than 2m are now include in compact if their building density is higher than 30%. Nature LCZs (D,E,G), are now computed with the following thresholds : Build density < 1% for Low plants, road density > 50% for bare rock/paved, hydrographic density > 50% for water.

Once an LCZ has been attributed to the RSUs of an urban unit, it becomes possible to calculate the absolute surface area of each type of LCZ and the percentage of surface area that each LCZ represents within that unit (relative surface area). This latter percentage was then compared with the simulated UHII to investigate to what extent the LCZ structure of an urban unit is related to the UHII. In order to optimise the results by simplifying the analysis, aggregated indicators grouping together certain LCZs with comparable characteristics were produced: the percentage of compact LCZs (LCZs 1, 2, 3), open LCZs (LCZs 4, 5, 6), and "nature" LCZs (D, E, G). The benefit of this aggregation also lies in avoiding possible biases related to the fact that some LCZs are not present for a certain number of urban agglomerations (Compact high-rise LCZ or Water LCZ).

To study the correlation between the percentage occupied by each LCZ of an urban unit and the UHII, the time period from 21 to 23 UTC is selected and averaged, since we expect a well-developed UHI for this time period. Mean UHII values are then spatially joined to the RSUs (via the QGIS spatial statistics tool), corresponding to the mean UHII for the RSU. This approach allows the links between LCZ and UHII to be studied on the scale of an urban agglomeration, using a one-factor ANOVA (Analysis of variance) (Miller, 1998). Our analysis then focused on links between LCZ structure of urban units and their UHII from a single table containing 42 urban agglomeration described by 18 variables: percentage of each LCZ, aggregated percentage of different types of LCZ and mean UHII. This approach requires to spatially average the UHII over the entire urban agglomeration. Multiple linear regression models are applied to investigate the correlation between aggregated indicators and UHII, and between the percentage of each LCZ and the UHII. The UHII of each urban agglomeration is compared for each LCZ category (compact, open, nature). An index summarizing these differences was calculated for each agglomeration. This is the absolute value of the UHII difference between the compact and open LCZs added to the intensity difference between the open and the nature. This index was then related to morphological and geographical variables (location, climate) to determine if these affect the observed differences between agglomerations. In order to do this, we use regional climate classification of Joly et al. (2015), who defined 8 regional climate zones in France (Table 3).

Classification of urban units by type of climate

Regional climate zone	**Concerned urban units**
Mountain climate	Belfort, Besançon, Montbéliard (3)
Semi-continental climate and climate of the mountain margins	Grenoble, Mulhouse, Nancy, Saint-Etienne, Thionville (5)
Degraded ocean climate of Centre and North	Amiens, Arras, Beauvais, Chalon-sur-Saône, Clermont-Ferrand, Compiègne, Creil, Dijon, Lille, Orléans, Reims, Tours, Valenciennes (13)
Altered ocean climate	Angers, Bordeaux, Caen, Calais, Colmar, Dunkerque, Lyon, Pau, Rouen (9)
Frankish ocean climate	Bayonne, Boulogne-sur-Mer, La Rochelle, Le Havre, Lorient, Nantes (6)
Alterd Mediterranean climate	Saint-Nazaire (1)
Southwest Basin climate	Toulouse (1)
Frankish Mediterranean climate	Avignon, Montpellier, Nice, Nîmes (4)

RESULTS

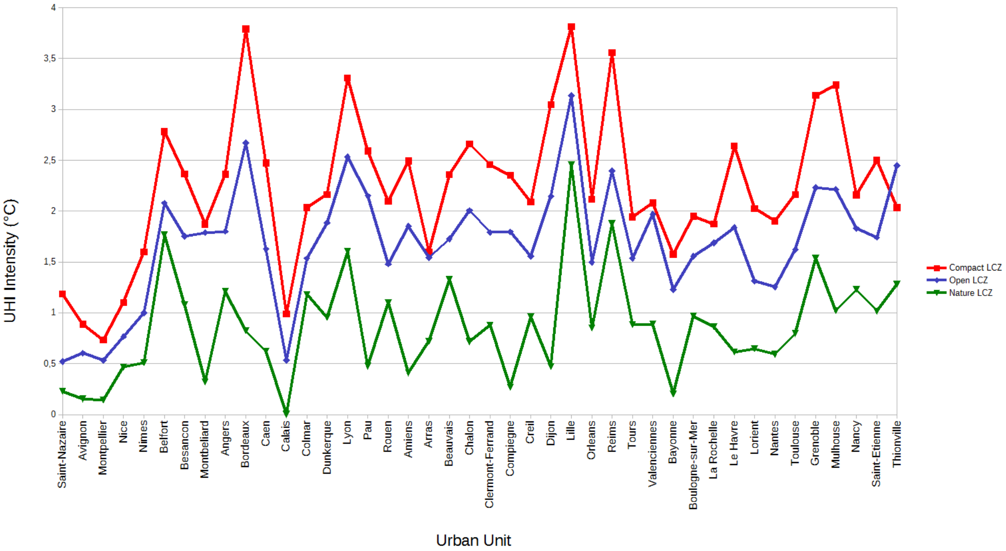
The ANOVAs performed for time period consistently show a highly significant correlation between the LCZ of an RSU and the UHII, with p-values below 10^{-5}. Multiple linear regressions performed across the entire dataset seem to confirm this trend. In the observed time period, there is a significant correlation between the LCZ structure of urban units and their simulated mean UHII. Table 4 summarises the coefficients of determination and the p-values obtained.

Statistical results of the linear regressions between the LCZ structure and the UHII.

Explanatory variables	**Adjusted R²**	**p-value**
% of each LCZ*	0.324	0.03
Aggregated indicators**	0.419	< 2.10-5

The relationship between the LCZ structure of the urban units and their mean UHII is shown in figure 1. Aggregated indicators were used for optimal readability. This type of graph makes it possible to display the types of LCZ that seem to affect the UHI intensity the most. Compact LCZs appear to particularly influence the UHII between 21 and 23 UTC.

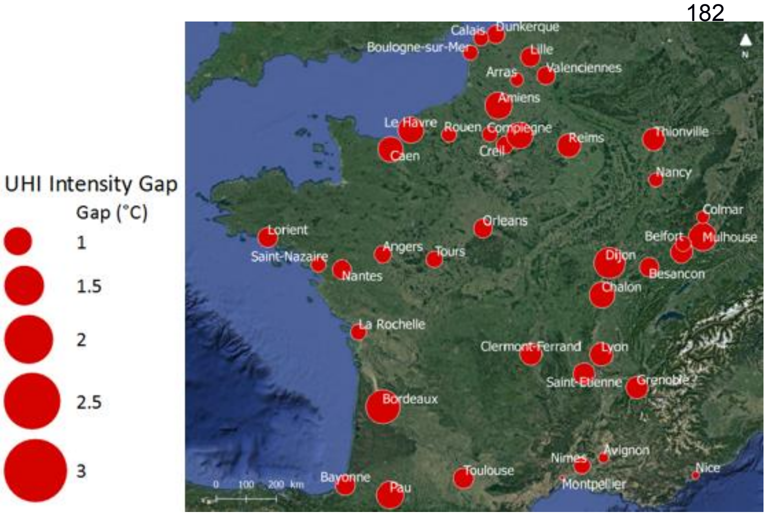
There are also significant differences between urban agglomerations. For some cases, the UHII difference between the open and compact LCZ is very marked (Dijon, Bordeaux, Pau, Reims ...), in others, much weaker (Montpellier, Nice, Avignon). The latter are located close to the Mediterranean and are affected for the selected meteorological situation by land-sea breezes (Nice and Avignon), valley breezes (Nice) and regional wind systems caused by channeling of the wind due to medium size mountain ridges (Montpellier).



Mean UHII between 21 and 23 UTC by aggregated LCZ, (summer weather type)

DISCUSSION

The results obtained (adjusted R² of the order of 0.40) show that, for all the urban agglomerations, the LCZ structure does indeed impact the UHII. However, account should be taken of the fact that the UHII is not affected solely by urban morphology but also by "external" parameters such as wind, local climate (sea and mountain breezes) and topography, which vary, in particular, according to the geographical location of the agglomeration. On the scale of an urban agglomeration, these external effects are barely visible, which may explain the high p-value obtained by ANOVAs. On all the urban agglomerations of the dataset, these effects necessarily come into play and are taken into account by the MésoNH-TEB simulation, but not by the LCZ classification. This could explain why the R² do not exceed the values quote. The fact that the importance of the differences of UHI intensity between Open and Compact LCZ varies between urban units observed on figure 2 has been summarized as an index and then mapped.



Difference of UHI intensity gap between LCZ categories for each considered urban unit
Data : MésoNH-TEB simulation, MApUCE DataBase
Background : Google Satellite (2018 TerraMetrics)

At first glance, it is difficult to identify a clear geographic trend. However, urban agglomerations located on the coast appear, on average, to have lower UHII differences between their LCZs than others located further inland. This trend was therefore studied by calculating the average gap index by climate type (Table 5).

Gap of UHI intensity between LCZ Open and Compact by climate type

Climate	Frank -med.	Weather-med.	Mountain	Frank-ocean.	SW-Basin	Deg-ocean.	Weather-ocean.	Semi-conti.
Gap 21-23h	0.762	0.957	1.283	1.345	1.367	1.527	1.537	1.562

The result seems to confirm that regional climate plays an important role in determining the gap of UHII between open and compact LCZ for a given agglomeration. Indeed, the agglomerations with a Frankish Mediterranean climate, a Weathered Mediterranean Climate and, to a lesser extent, a mountain climate, present a significantly lower gap than UUs with semi-continental climate or weathered ocean climate. This might be due to enhanced ventilation of urbanised areas in regions more close to the coast, or affected by valley breezes. However, this will have to be confirmed by a more detailed analysis.

CONCLUSIONS

It would be possible to study this hypothesis by replicating the approach on groups of cities with a local climate that is as similar as possible, provided that climate factors are clearly identified and that a sufficiently large sample is available. More time periods, both night and day, should also be explored to confirm the results reported here. The quality of LCZ identification could also be improved by correcting some limitations inherent to the database used. Vegetation variables, for example, which are currently unreliable in the administrative datasets, could better distinguish certain LCZs from one another. An update of the RSU segmentation and the addition of variables such as the Sky View Factor are currently being considered. These could enhance the proposed LCZ segmentation. In addition, the thresholds of variables used to identify the LCZs have been estimated by expertise to be usable on all the urban units concerned, in order to propose a clear and generic method. A more specific adjustment of thresholds for each urban unit could be considered, whether by expertise or from statistical analysis.

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