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1. Introduction

1 Not only has urban growth changed natural landscape into artificial constructions but it has also produced numerous sources of anthropogenic heat and pollutants, which have gradually modified the local meteorology and climate (Grimmond et al. 2010). Under the conditions of climate change and rapid urbanization, urban climate information needs to be considered and incorporated into the processes of urban

planning to achieve sustainable development and healthy living goals. However, there are several constraints in urban climate application which have led to limited actual implementations in planning, including: 1) different languages and knowledge between urban climate research and urban planning application; 2) urban morphological data availability; 3) limited urban climatic application tools to translate climatic knowledge into actions (Hidalgo et al. 2019, Ng and Ren 2015, Eliasson 2000). This article intends to contribute to this last point.

2 Currently, there are two popular conceptual frameworks for urban climatic evaluation and application: the climatopes of the Urban Climatic Map (UCMap) system (Ren, Ng and Katzschner 2011) and local climate zones (LCZs) (Stewart and Oke 2009, Stewart and Oke 2012).

3 As a layered approach, the concept of UCMap is featured as a cartographic representation of climatic information and translating climatic evaluation results into planning language. After a first proposition in Germany in the late 1970s, the Association of German Engineers (in German: Verein Deutscher Ingenieure, VDI) published a national standard in 1990s, i.e., VDI 3787-Part 1 (2015), for guiding the application of UCMap in local practices. Basing on this guideline, over 15 countries around the world have developed their own UCMaps (Ren et al. 2011). The UCMap system normally consists of two components, namely Urban Climatic Analysis Map (UC-AnMap) and an Urban Climatic Planning Recommendation Map (UC-ReMap) (Figure 1). The UC-AnMap visualizes various climatic information and assessment by ‘climatopes’. The UC-ReMap contains planning instructions from the urban climatic point of view. The ‘climatopes’ stand for the ‘climates of special places’ and demonstrate homogeneous microclimatic conditions across local areas via integration of various factors, including land use, density of development, sealing level, surface structure, roughness, relief, vegetation type and location in the urban area. According to VDI 3787-Part 1, 9 climatopes are classified and listed in Table 1, including four natural climatopes (from Water Body to Urban Green Space) and five built-up climatopes (from Garden City to Commercial/Industry). The typical spatial scale of climatopes are normally at district level according to the land use information offered by local administration.

Figure 1. A partial plan of the UC-AnMap for Stuttgart urban areas (source from VDI 3787-Part 1)

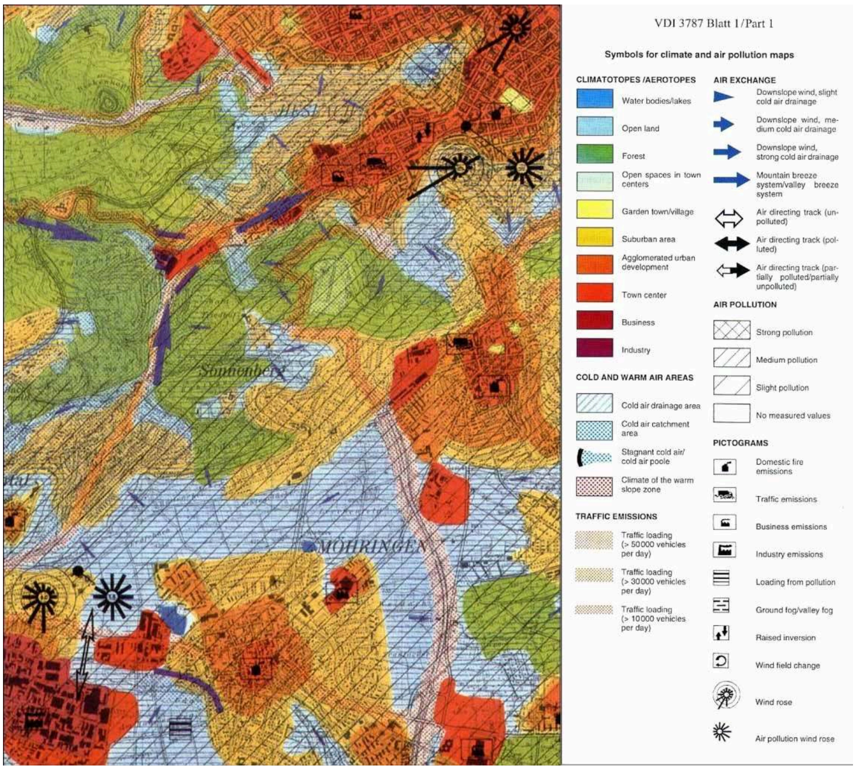


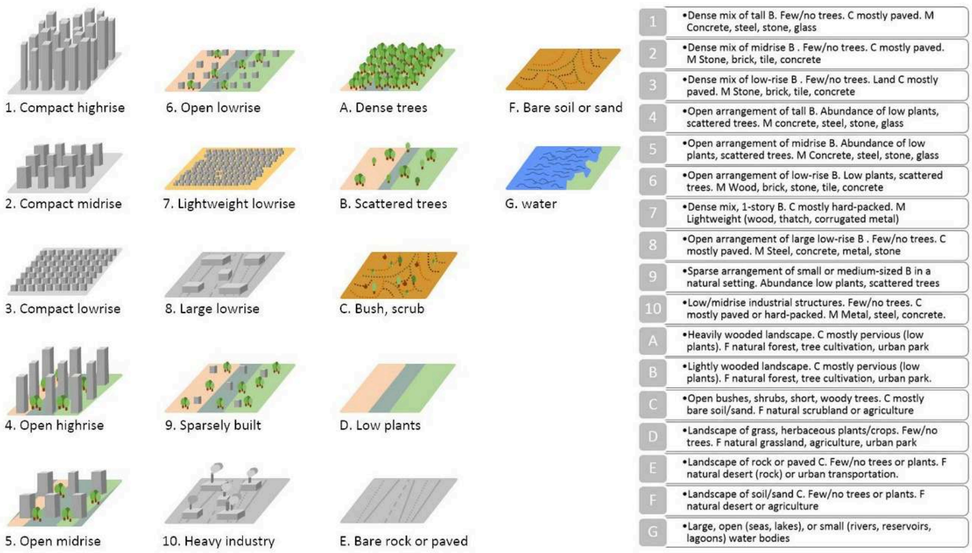
Table 1. Nine climatopes and two specific climate conditions with their corresponding land use types according to VDI 3787-Part 1 (2015)

Climatope	**Land Use Type**
Water Body	Water bodies
Open Land	Mineral extraction and dump sites; Construction sites; Land without current use; Arable land (annual crops); Permanent crops (vineyards, fruit trees, and olive groves); Pasture land
Forest	Forests
Urban Green Space	Isolated structures; Green urban areas; Sports and leisure facilities
Garden City	Discontinuous low-density urban fabric (sealing level: <30%)
Suburban	Discontinuous medium density urban fabric (sealing level: 30–50%)
City	Discontinuous dense urban fabric (sealing level: 50–80%)
Inner City	Continuous urban fabric (sealing level: >80%)
Commercial/ Industry	Industrial, commercial, public, military, and private units

Specific Climate Conditions	**Land Use Type**
Traffic	Railway lines; Fast transit and other roads
Airport	Airports

4 In 2012, LCZs were proposed by Stewart and Oke (2012) as a relatively new conceptual framework for urban climatology and succeeded in presenting both characteristics of urban climate and urban morphology at the city level world widely. Based on generalized knowledge of building forms and land cover, the LCZ system contains 17 classes, with the thermal climate of each class determined by its unique surface characteristics, including thermal, radiative, geometric, metabolic, and surface cover properties. Specifically, LCZs 1–10 describe “built-up” types representing urban landscapes, building density, and open space, while LCZs A–G describe “natural” types representing permeable land cover, water bodies, and greenery (Figure 2). Benefiting from the standardization of the LCZ definitions and classifications, different UHI studies within and between cities can easily be cross compared (Stewart and Oke 2015).

Figure 2. The urban (1–10) and natural (A–G) LCZ types and their characteristics (adapted from Table 2 in Stewart and Oke (2012), text shortened, icons reworked. The acronyms mean as follow. B: Buildings; C: cover; M: materials; F: function; Tall: >10 stories, Mid-rise: 3–9 stories, Low: 1–3 stories). Source from Verdonck et al. (2019).



1.1 Comparing UCMap with LCZ

5 Even though the frameworks of UCMap and LCZ appear very similar, both the initial motives for their development and the applications of these tools are fundamentally different, especially on the aspects of data sources, classification standards, and application hierarchy. Here is a discussion point by point:

6 First, the data applied for developing UCMap and LCZ are compared in Table 2. The climatic, geographic terrain, greenery and planning information were widely used in

developing UCMap, while the data for LCZ map mainly consist of geometric and surface cover. UCMap system is highly reliant on data availability, especially spatial digital data, including the land use, elevation, and wind environment. These required data are primarily derived from administrative datasets, which may not be open for public use. Though many morphological data are required in developing LCZ, the "World Urban Database and Access Portal Tools " project proposes an open-source-based method to generate LCZ maps using freely available Landsat data (Bechtel et al. 2015). More accurate LCZ classification results can be achieved by processing detailed urban morphological data to extract objective parameters (Wang et al. 2018, Zheng et al. 2018, Hidalgo et al. 2019, Unger, Lelovics and Gál 2014).

Table 2. The comparison on data applied for developing UCMap and LCZ. The data for UCMap were reviewed by Ren et al. (2011). The data for LCZ are summarized from Unger et al. (2014), Zheng et al. (2018), Hidalgo et al. (2019).

<table>
<tr><th colspan="2">UCMap</th><th colspan="2">LCZ</th></tr>
<tr><td>Climatic elements</td><td>Air temperature,
Atomospheric humidity,
Wind velocity & direction
Precipitation
Fog/ mist
Air pollution</td><td rowspan="3">Geometric & surface cover</td><td rowspan="3">Building typology,
Building height,
Aspect ratio,
Sky view factor,
Building surface fraction,
Pervious surface fraction,
Impervious surface fraction,
surface albedo,
Land use information</td></tr>
<tr><td>Geographic Terrain Information</td><td>Topographic Map
Slop/ Valley Map
Soil Type Map</td></tr>
<tr><td>Greenery Information & Planning Parameters</td><td>Land use map
Landscape map
Building info map</td></tr>
</table>

7 Second, differing from a standardized classification in LCZ scheme, the classification of climatopes in UCMap system varies from case to case. For example, 11 climatopes were identified in Stuttgart (Klimaatlas 1992), while many more were documented in Basel (Scherer et al. 1999). Though the VDI 3787-Part 1 proposes a detailed guideline for defining climatopes into 9 classes, the method might not be suited for worldwide cities since it is mainly developed based on the morphological characters in German or European cities for representing the thermal load and dynamic potential comprehensively. Conversely, the classification of the LCZ scheme is fundamentally derived from a generalized knowledge of how urban morphology influences surface thermal climatic conditions and is standardized into 17 classes. However, the information about the land use and topography are less considered in the original LCZ system. Both the anthropogenic heat emission from buildings and background relief are assumed relatively simple or uniform across all LCZ classes. The LCZ might not achieve the climatic mapping in a case with heterogeneous building occupancies and

significant local terrain changes unless additional data including local relief, airflow, humidity, and so on is brought with (Stewart and Oke 2015).

8 Third, though the spatial resolution in these two systems is usually similar, the application hierarchies of UCMap and LCZ system are initially different. The UCMap system aims to provide climate information at the regional or urban scale for planners and policymakers by grouping similar climatopes into zones. The recommendations for planning and actions to ameliorate thermal load and reduce pollution are proposed from a macroscopic view in corresponding zones or specific climatope. Conversely, the LCZ system is designed to demonstrate the heterogeneous thermal environment within an urban area at neighborhood scale via the classification of the surface cover, structure, and material of the urban morphology into uniform spatial units (Stewart and Oke 2012). Meanwhile, no further planning recommendations are proposed for improving built environment in the original LCZ scheme.

1.2 Potential mutual benefits

9 Given the above differences, the potential mutual benefits of the two methods to advance scientific and climatological knowledge in climate-adaptive urban planning should also be noted. As firstly mentioned in Stewart and Oke (2015), the data extracted from LCZ specification sheets are valuable for UCMap system, since new layers can be generated from LCZ and further integrated with existing UCMap according to the specific needs of planners and climatologists. For instance, Wicki and Parlow (2017) added the LCZ as an attribution to the land use/land cover data for describing the morphological characters in the historical city centers in Basel and promoting the accuracy of LCZ classification. Additionally, as a holistic classification scheme, the UCMap system considers multiple information about climatic conditions, building occupancy, surface relief, etc., which can be the additional data for LCZ scheme to achieve climatic study. For example, a pilot evidence-based study in Taipei combined air temperature data from UCMap with LCZs and verified the benefit of assessing the relationship between the thermal condition and the urban morphology (Chen et al. 2019). So far, the synthetization of VDI-based climatopes and LCZs in UCMaps has not yet been investigated.

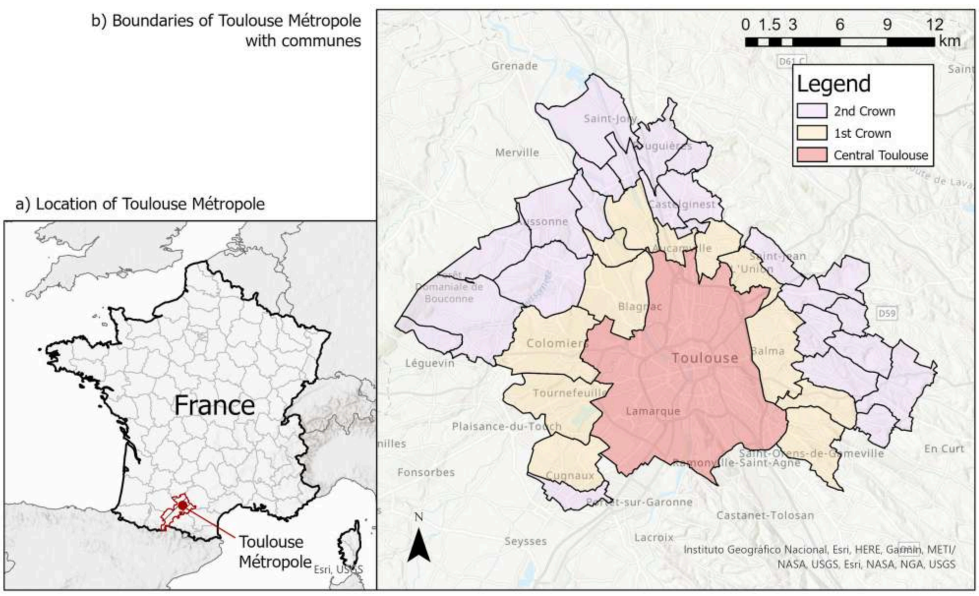
1.3 Research objective

10 The Toulouse Metropole (centred at 43.60° N, 1.44° E), the sixth largest urban agglomeration in France, is selected for this case study. Three targets are investigated as following: (1) correlating the spatial distribution between VDI-based climatopes and LCZs, (2) introducing wind and thermal information to help analyze the meteorological characteristics in different climatopes coupled with the LCZ classes, and (3) proposing urban climatic planning recommendations for LCZs based on the relevant environmental performance and climate mitigation guidelines from VDI 3787-Part 1 (2015).

1.4 Study area

11 Toulouse Metropole is located in the southwestern Occitanie region with over 0.7 million inhabitants in an area of approximately 460 km^2. In total 37 communes belong to this region and are grouped into Central Toulouse, first Crown (communes in the immediate periphery of Central Toulouse), and second Crown (the remaining communes) to facilitate further investigation on the climatic characters and planning recommendations. Having a degraded oceanic climate, the daily temperature in Toulouse exhibits large fluctuations varying from 15°C to 30°C during the daytime in the summer season, with frequent extreme heatwave periods with temperatures as high as 40°C (Martins et al. 2016). The surface relief of Toulouse is relatively flat, ranging from 102 m to 273 m, and is primarily influenced by the Garonne affluent valleys. Because of its extensive distance from the ocean and its flat terrain, cooling benefits from sea and valley breezes are very limited. Therefore, influences from topography on the urban climate are minor, making comparisons between the UCMap and LCZ systems more consistent in its built-up environments. In addition, the process of urbanization in this region has not stopped yet and a strong urban sprawl is observed. Therefore, a comprehensive understanding of the climate and environmental conditions in Toulouse and pertinent planning recommendations are very important.

Figure 3. Location and boundaries of the Toulouse Metropole, including 37 communes, which are split into Central Toulouse, 1st Crown (communes in the immediate periphery of Central Toulouse), and 2nd Crown (the remaining communes).



12 Given the opportunities brought about by methodological improvements, as well as the challenges of sustainable development and climate-adaptive urban planning, the Applied Modeling and Urban Planning Laws: Urban Climate and Energy (MApUCE) project was launched in France to define a methodological guideline for how to generate a cartographic representation of the climatic situation and to become part of the French urban planning and legal framework. The project provides high-quality climate data from various numerical simulations. One of the MApUCE pilot cities, Toulouse, is currently working on its new land use plan (Plan Local d'Urbanisme Intercommunal, de Toulouse Metropole) (Toulouse 2018), and urban climatic

evaluation and application tools are important to improve the scientific understanding of local climate and urban comfort in the planning process.

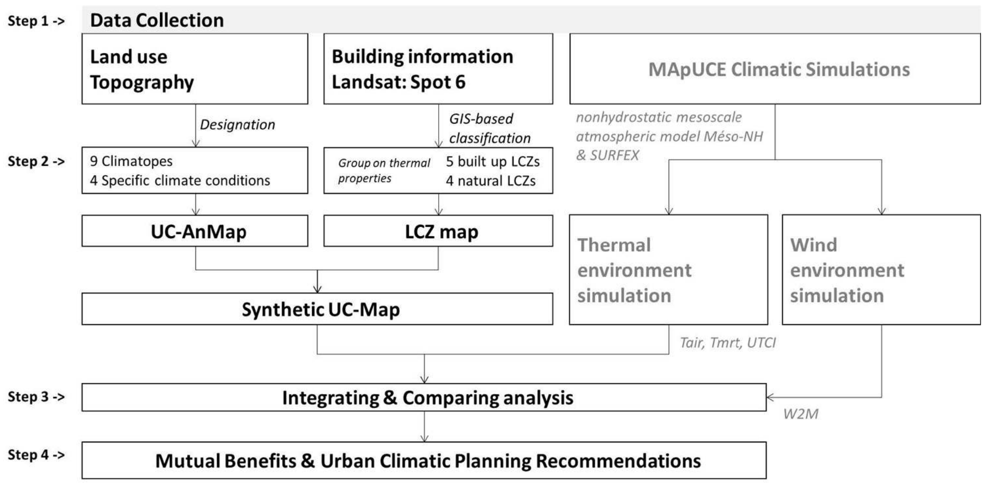
2. Methodology

13 As shown in Figure 5, this study is divided into the following steps and more detailed information is listed in the Annex section:

1. collecting data, including land use, and topographical data from 2012 Urban Atlas (European Environment 2012), vegetation information from SPOT 6 satellite images (Crombette, Le Corre and Tinel 2014), building morphological data from the MApUCE morphological database (Bocher et al. 2018) and meteorological data from MApUCE model simulation Kwok et al. (2019);
2. classifying the climatopes, following the VDI 3787-Part 1 for an initial UC-AnMap, deriving LCZ classification data constructed under a vector-based GIS framework, from Hidalgo et al. (2019), then, integrating the two results into a hybrid Climatope-LCZ map based on their spatial locations;
3. analyzing the spatial and environmental characteristics of the hybrid Climatope-LCZ map. Identifying the dominant building morphology and land cover types in each climatope, or simultaneously, the predominant land uses and human activities in each LCZ. Comparing the wind speed (*ff*), air temperature (T_{air}), mean radiant temperature (T_{mrt}), and Universal Thermal Climate Index (UTCI) at 2m in each hybrid area under summertime weather types in Toulouse(Hidalgo and Jougla 2018) during three time periods, i.e., early afternoon (1–4 p.m. local time), late afternoon (5–8 p.m. local time), and night (3–6 a.m. local time).
4. detecting the hot spots with heat risk in hybrid Climatope-LCZ map, discussing mutual benefits and finally proposing urban climatic planning recommendations for the LCZs in Toulouse.

14 To contribute the open science movement, all shapefiles of the cartographic figures, including UC-AnMap, LCZ map, hybrid Climatope-LCZ map and maps of hot spots in three time periods, are open for download as part of this paper's materials.

Figure 4. Research steps taken in this study.

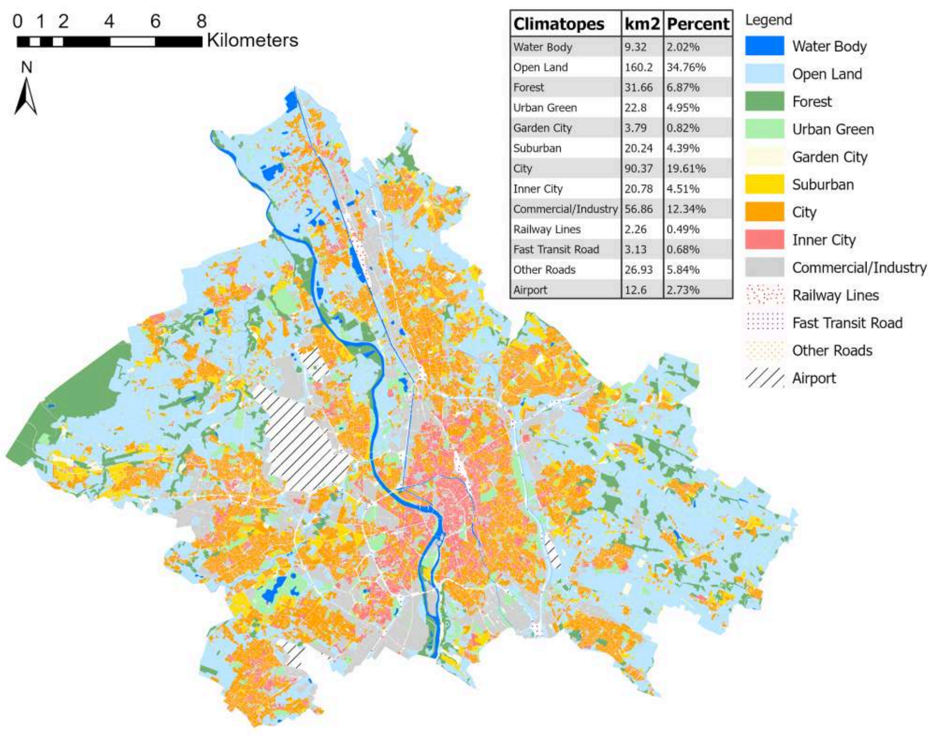


3. Results

3.1 Initial UC-AnMap

15 The climatope area percentages for the entire Toulouse Metropole region can be found in Figure 7. The dominant climatope in Toulouse is Open Land, which covers 34% of the Toulouse Metropole and is primarily distributed in the outskirt areas of the second ring of suburbs of the metropole, i.e., the 2nd Crown (Figure 1). The majority of land uses in the Open Land climatope are agriculture and pasture land. The City climatope is the second largest class, consisting of a discontinuous dense urban fabric (most are residential developments) with an impervious level between 50% and 80%. The Inner City climatope has a continuous urban fabric with a sealing level of over 80%. Except for a large area with forests in the western corner of the region, the other climatopes consist of scattered patches.

Figure 5. The initial UC-AnMap based on VDI 3787 showing the corresponding areas and area percentages of each climatope.

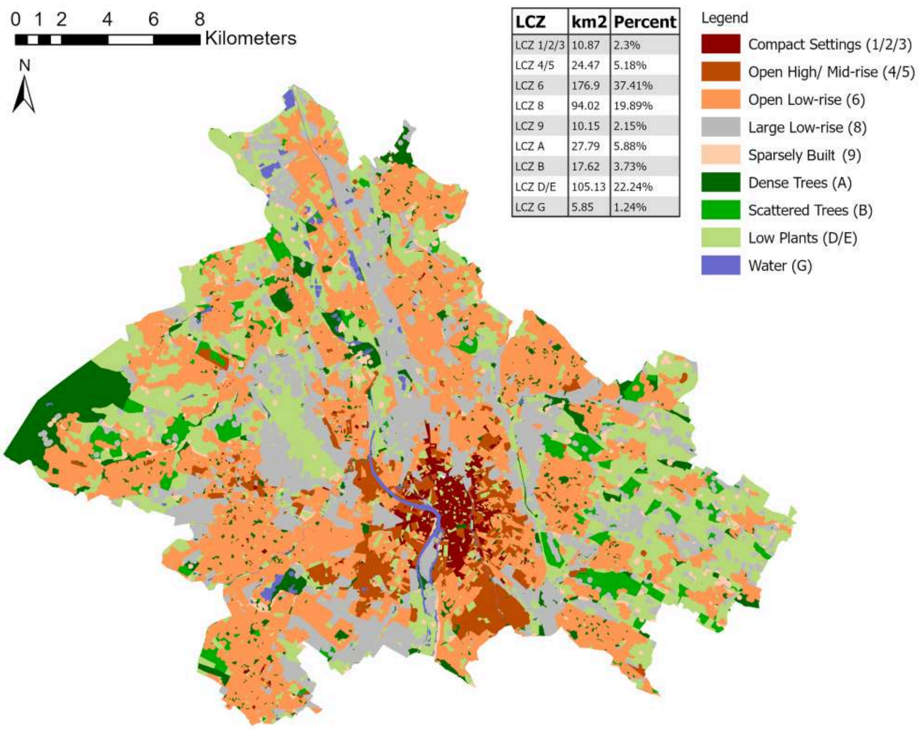


3.2 LCZ map

16 As shown in Figure 8, the LCZ classification result indicates that Open Low-rise (LCZ 6), Low Plants (LCZ D/E), and Large Low-rise (LCZ 8) are three significantly dominant LCZs in Toulouse. Dense Trees (LCZ A) primarily consists of forested areas in the western corner of the region, while Scattered Trees (LCZ B) appears in patches throughout the Toulouse Metropole. The built-up LCZs, i.e., Compact Settings (LCZ 1/2/3) and Open High/Mid-rises (LCZ 4/5), are clustered in the core of Central Toulouse. Therefore, even though the Toulouse Metropole is an agglomeration area with low density, the urban

sprawl trend arising from the growth of individual housing land and expansion of commercial and industrial areas is substantial.

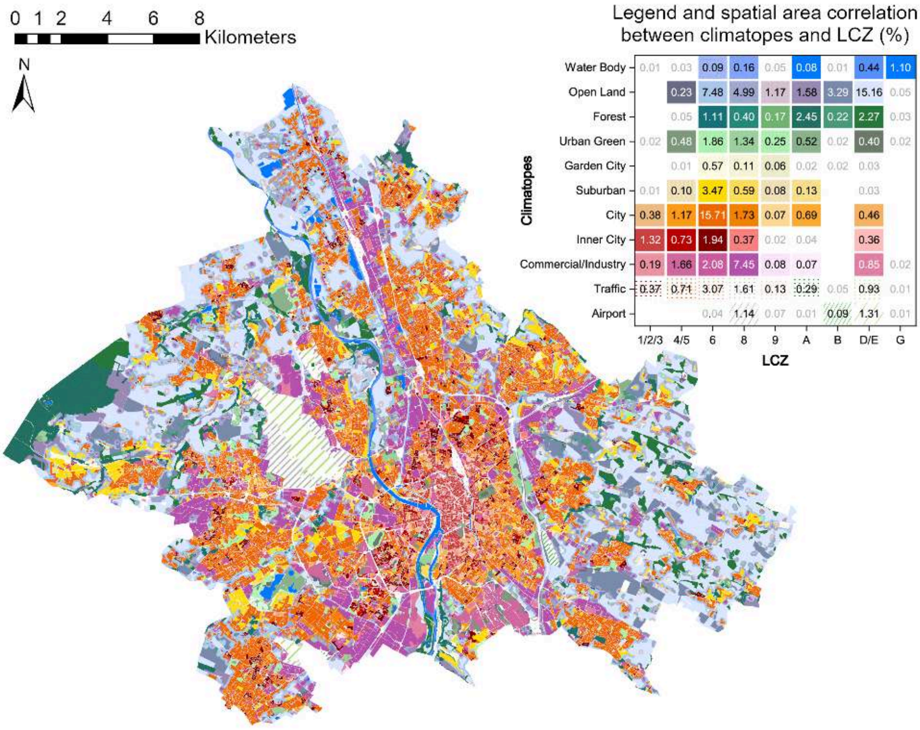
Figure 6. Grouped local climate zone (LCZ) map of the Toulouse Metropole and corresponding areas and the area percentages for each LCZ group.



3.3 Hybrid Climatope-LCZ map

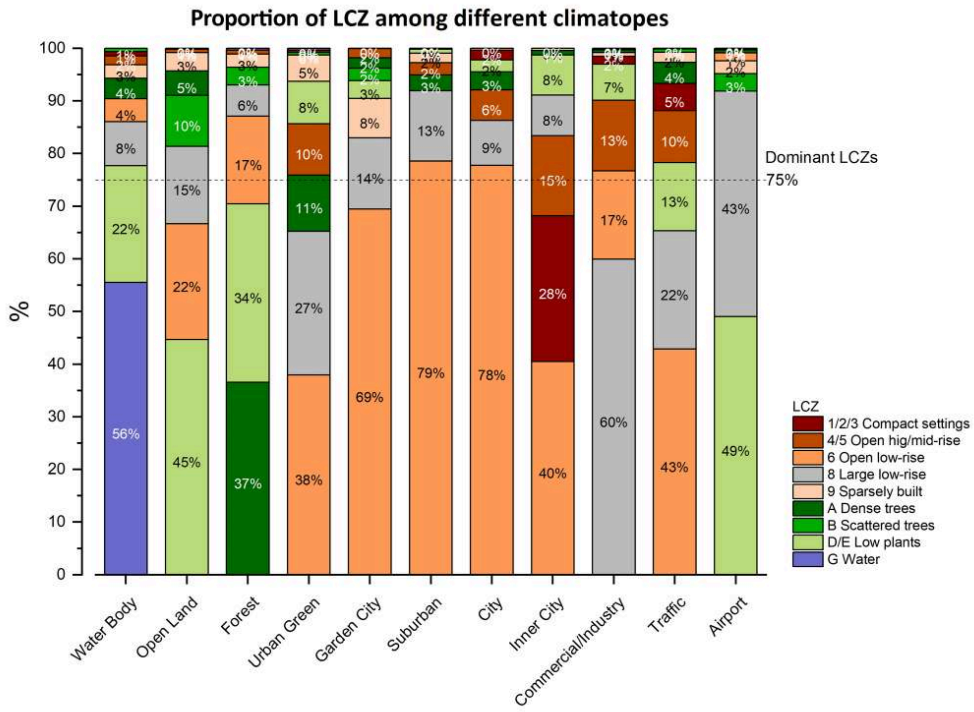
17 Figure 9 presents the hybrid Climatope-LCZ map resulting from the integration of the climatope and LCZ classifications. Proportions of correlated spatial areas of less than 0.05% are difficult to identify and are intentionally left blank on the map. According to the spatial area correlation between the climatopes and the LCZs, each climatope is composed of multiple LCZs of various amounts. For example, the City climatope has a maximum level of intersection with Open Low-rise (LCZ 6, 15.71%), followed by the Open Land climatope's intersection with Low Plants (LCZ D/E, 15.16%). Compact settings (LCZ 1/2/3) are primarily distributed in the Inner City climatope (1.32%), as well as in the City climatopes and the Traffic climate condition. Open High/Mid-rises (LCZ 4/5) are present more frequently in the Commercial/Industry and City climatopes. Large Low-rise (LCZ 8), featuring large low-rise structures, is primarily found in the Commercial/Industry (7.45%) and Open Land (4.99%) climatopes. The vegetated Dense and scattered trees (LCZs A and B) are predominantly located in the Forest (2.45%) and Open Land (1.58%) climatopes, respectively.

Figure 7. Hybrid Climatope-LCZ map and spatial area correlations between the climatopes and the LCZs. LCZ 1/2/3 is Compact settings; LCZ 4/5 is Open High/Mid-rises; LCZ 6 is Open Low-rise; LCZ 8 is Large Low-rise; LCZ 9 is Sparsely Built; LCZ A is Dense Trees; LCZ B is Scattered Trees; LCZ D/E is Low Plants; LCZ G is Water.



18 The proportion of LCZs in each climatope is illustrated in Figure 10. The predominant LCZs in each climatope are defined as the cumulated percentage over 75% (shown by the dashed line) sorted from largest to smallest component. The Garden City, Suburban and City climatopes indicate a single dominant LCZ, Open Low-rises (LCZ 6). The Inner City climatope is dominated by all types of built-up LCZs (1 to 6). Such a multi-LCZ-dominated situation also exists in greenery climatopes such as the Open Land, Forest, and Urban Green climatopes, which primarily consist of Dense Trees, Low Plants, Open and Large Low-rises (LCZs A, D/E, 6, and 8). The specific local climate conditions are dominated by Open, Large Low-rises, and Low Plants (LCZs 6, 8, and D/E).

Figure 8. Percentage of LCZs in the different climatopes.

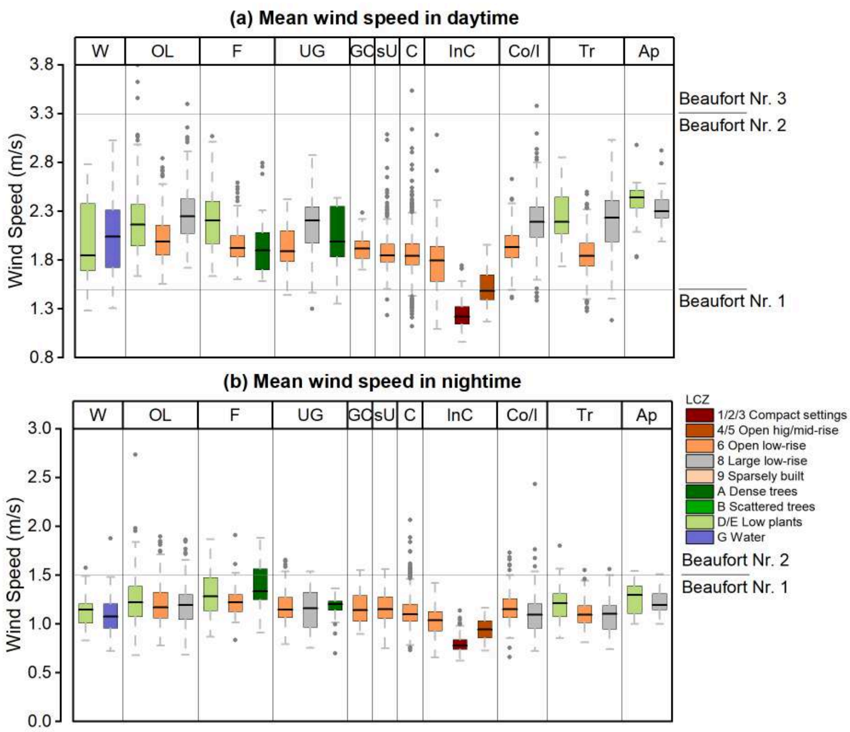


3.4 Wind and thermal characteristics

3.4.1 Wind environment

19 As shown in Figure 11, Toulouse Metropole has a very steady and calm wind environment. At night, the *ff* values in the different climatopes vary within a limited range, from approximately 0.6 m s^{-1} to 1.5 m s^{-1} and nearly all of the climatopes have a Beaufort force of 1. The daytime *ff* values primarily correspond to a Beaufort force of 2. The wind speed in the Traffic and Airport climate conditions demonstrate the best ventilation performance, especially in the Low Plants and Large Low-rise (LCZs D/E and 8). Conversely, the wind environment in the Inner City climatope is the weakest.

Figure 9. Distribution of the mean wind speed at a height of 2 m in the dominant LCZs: (a) in the daytime and (b) at night. Abbreviations of the climatopes are as follows: W: Water Body, OL: Open Land, F: Forest, UG: Urban Garden, GC: Garden City, sU: Suburban, C: City, InC: Inner City, Co/I: Commercial/Industry, Tr: Traffic, and Ap: Airport.



3.4.2 Thermal characteristics

20 As shown in Figure 12, the overall pattern of T_{air} is very similar for the three studied time periods. The Commercial/Industry climatope and the Traffic climate condition are warmer during the daytime, while at night, the Compact Settings and Open High/Mid-rises (LCZ 1/2/3 and 4/5) in inner city are hotter than the other LCZs. The lowest T_{air} value is found in the Forest climatope during the daytime but shifts to the Open Land climatope at night. Regarding the T_{mrt} (Figure 13), the range patterns of T_{mrt} present significant differences between the daytime and nighttime periods. The overall T_{mrt} in the early afternoon is approximately 5–8°C hotter than that in the late afternoon because the solar radiation diminishes during the late afternoon. The IQRs of all the climatopes are very narrow, only 49–52°C in the early afternoon and 43–47.5°C in the late afternoon, except for Compact Settings (LCZ 1/2/3) in the Inner City climatope and Dense Trees (LCZ A) in the Forest climatope. During the night, the built-up climatopes retain high T_{mrt}; conversely, the upper quartiles of the other LCZs are below 15°C.

3.4.3 Thermal stress

21 The frequencies of thermal stress occurrence according to the simulated UTCI in the three studied periods are presented in Figure 14. The climatope and LCZ combinations are represented as the climatope abbreviation linked with the suffix of the LCZ using a "+" symbol, e.g., OL+6 indicates LCZ 6 in the Open Land climatope. The Toulouse Metropole has non-negligible thermal stress problems under typical summer

conditions, especially in the Inner City climatope and Traffic climate condition in the early afternoon. Open High/Mid-rises (LCZ 4/5) in the Inner City climatope experiences the highest severe heat stress with only 14.7% of its area having no thermal stress, followed by Compact Settings (LCZ 1/2/3) in the Inner City climatope (23.6%). The combination of vegetated LCZs and greenery climatopes have a greater chance for “no thermal stress,” indicating a better thermal environment.

Figure 10. Distributions of the modeled air temperature, T_{air}, 2 m above ground for different climatopes during the three time periods: (a) early afternoon, (b) late afternoon, and (c) night. Abbreviations of the climatopes are as follows: W: Water Body, OL: Open Land, F: Forest, UG: Urban Garden, GC: Garden City, sU: Suburban, C: City, InC: Inner City, Co/I: Commercial/Industry, Tr: Traffic, and Ap: Airport.

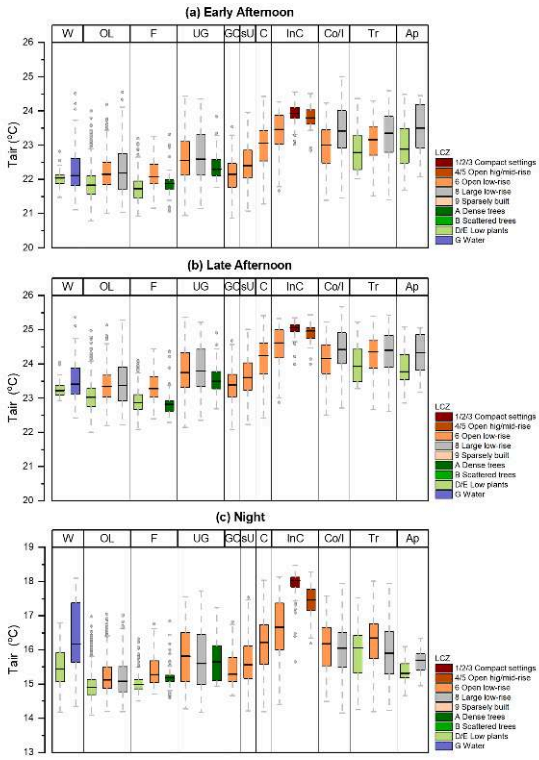


Figure 11. Distributions of the modeled mean radiant temperature, T_{mrt}, 2 m above ground for the different climatopes during the three time periods: (a) early afternoon, (b) late afternoon, and (c) night. Abbreviations of the climatopes are as follows: W: Water Body, OL: Open Land, F: Forest, UG: Urban Garden, GC: Garden City, sU: Suburban, C: City, InC: Inner City, Co/I: Commercial/Industry, Tr: Traffic, and Ap: Airport.

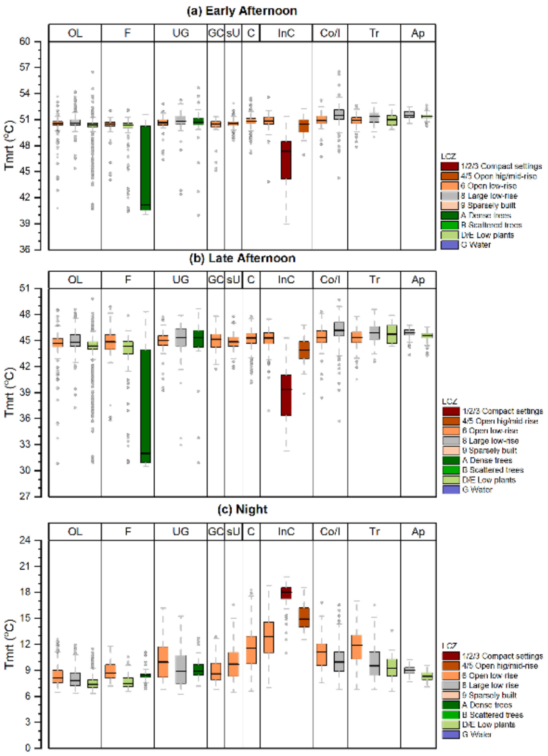
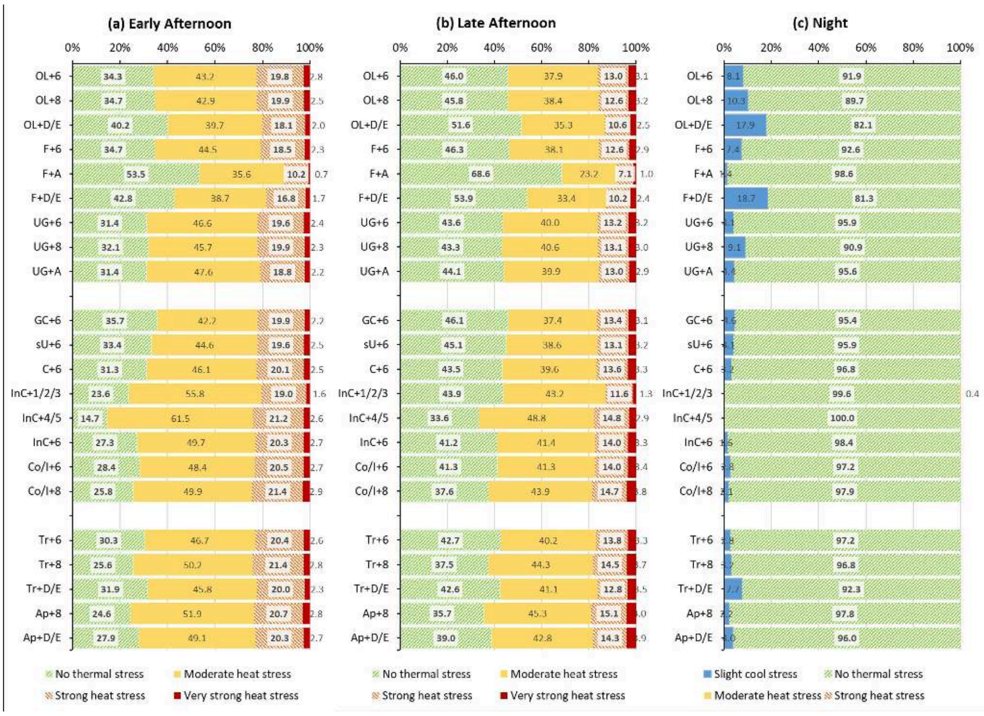


Figure 12. Frequencies of thermal stress occurrence evaluated by the modeled Universal Thermal Climate Index (UTCI) in different LCZs and climatopes during the three time periods: (a) early afternoon, (b) late afternoon, and (c) night. The investigated area is given as the abbreviation of the climatope plus the LCZ classification. Abbreviations of the climatopes are as follows: W: Water Body, OL: Open Land, F: Forest, UG: Urban Garden, GC: Garden City, sU: Suburban, C: City, InC: Inner City, Co/I: Commercial/Industry, Tr: Traffic, and Ap: Airport. Regarding LCZ, LCZ 1/2/3 is Compact settings; LCZ 4/5 is Open High/Mid-rises; LCZ 6 is Open Low-rise; LCZ 8 is Large Low-rise; LCZ 9 is Sparsely Built; LCZ A is Dense Trees; LCZ B is Scattered Trees; LCZ D/E is Low Plants; LCZ G is Water.

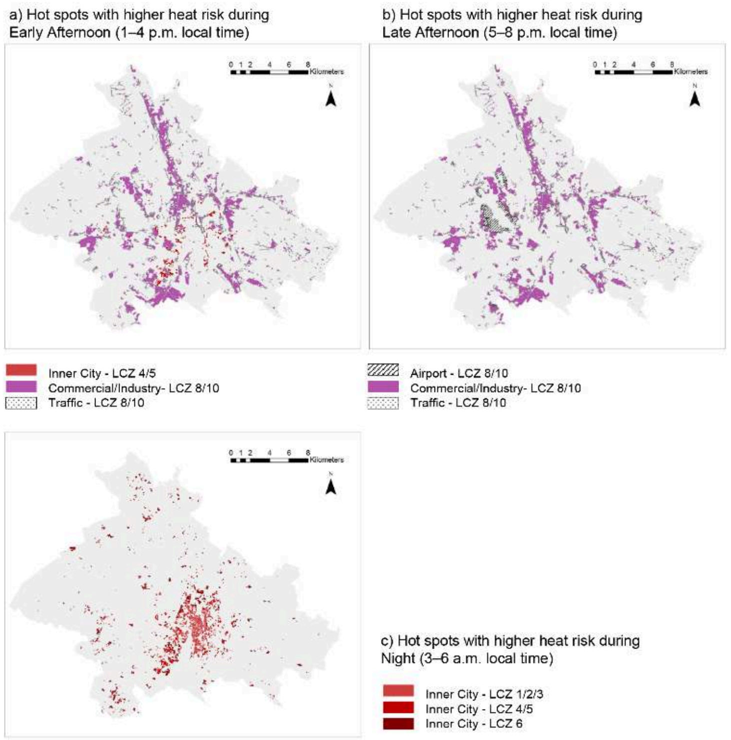


4. Discussion

4.1 Morphological and meteorological information in hybrid Climatope-LCZ map

22 After synthesizing climatopes map with LCZs, the most significant mutual benefit is that more detailed urban morphological and meteorological characters are integrated together for targeting hot spot physical exposure precisely. As shown in Figure 13, during daytime, namely Early and Late Afternoon, the hot spots are detected out due to their higher frequencies with strong heat stress. During nighttime, the areas in Inner City with both compact and open setting are always illustrating higher air temperature than others.

Figure 13. Hot spots with heat risk during different period, a) Early Afternoon, b) Late Afternoon and c) Night.



23 In the initial UC-AnMap, a climatope only represent a uniform climate condition. Now, the area with the different climatic issues can be targeted respectively. For instance, the Compact Settings (LCZ 1/2/3) of Inner City climatope shows both the worst wind environment, while the most intensive thermal stress is found in Open High/Mid-rise (LCZ 4/5). Müller, Kuttler and Barlag (2013) in Germany, Milošević et al. (2016) in Serbia, and Unger, Skarbit and Gal (2018) in Hungary have reported that the urban morphology with open setting suffers from severe thermal issues, followed by compact settings, because of reduced shading from buildings.

24 Regarding LCZ scheme, the heterogeneous thermal load that resulted from building occupancy and location in the same LCZ can be also identified. For example, the composition of LCZs in Garden City, Suburban, and City climatopes are quite similar, thus their present closing wind environments as well. However, the variabilities of their T_{air} and T_{mrt} values are determined by their distance from the city center, i.e., from Garden City to City climatopes, which is evidence for the classification of climatopes succeeded in differentiating thermal loads across built-up area.

25 Based on this mutual benefit, the planning recommendations for improving urban climate can be more targeted or practical. Taking natural climatopes and specific climate areas as cases, their majority LCZs are Low Plants and Large Low-rise (LCZ D/E and 8), which are considered pleasant wind environment during daytime and less thermal stress in nighttime. Among them, the Forest climatope and the Airport climate condition are regarded as important ventilation corridors for introducing prevailing wind to cool down the city at night, because they are located at the most frequent wind directions, LWT-9 is westerly and northwesterly as annual prevailing wind (Hidalgo and Jougla 2018). Therefore, different actions can be proposed for preserving low roughness

and enhancing cool sources at the natural and built-up LCZ, respectively (Ren et al. 2018). Though the T_{air} in Water Body climatope was observed surprisingly high at night, the cooling effect from evaporation and ventilation potential are still valuable as reported in Theeuwes, Solcerová and Steeneveld (2013), Steeneveld et al. (2014). Therefore, some measures for guiding the layout of plant are necessary for creating wind channel in the area of Low Plants (D/E) near Water Body climatopes.

4.2 Urban climate planning recommendations for LCZs

26 The Table 5 is generated for Toulouse Metropole by adding the dominant LCZ information in a climatope from the hybrid map with planning recommendations following the VDI 3787-Part 1 (2015) based on spatial and climatic characteristics analyzed in Results. It is a reference for planners or decision-makers to understand corresponding relations between climatopes and LCZs. Furthermore, the urban climate planning recommendations for the LCZs in Toulouse Metropole can be proposed (Table 6). The General Characteristics column summarizes the primary locations and environmental performance of the LCZs. Central Toulouse consists of buildings with both compact and open settings; these areas suffer from a weak wind environment, intense UHI, and severe thermal stress, as discussed in Section 3.4. Therefore, mitigation actions are recommended and are essential for both classifications. Effective measures include reducing heat gain and emissions from buildings, increasing greenery, shading facilities, and avoiding dense building developments. In addition, linking open spaces plays a significant role in introducing fresh and cooling air into these city districts. Even though large low-rise settings are dispersed around the outskirts of the Toulouse city center and only present moderate thermal stress under LWT-9 conditions, some mitigation actions are still encouraged. Only a few areas in Toulouse are sparsely built-up areas in which there is no heat stress in the daytime. It is suggested that the other LCZs occupied by vegetation, such as trees, grass, and water, in the outskirt areas of the Toulouse Metropole be preserved as cooling sources for the urban climate or used as potential air corridors.

Table 5. Linking the planning recommendations of climatopes from VDI 3787-Part 1 (2015) with their dominant LCZs.

Climatopes/ Climate Conditions	**Dominant LCZ**	**Planning** Recommendations
Water Body	G	Avoid dense structures that obstruct the shoreline.
	D/E	
Open Land	D/E	Possibilities for afforestation and settlement in accordance with the local climate conditions; however, observe the importance of these areas for large-scale air exchange (e.g., in suburban locations) and preserve their cold air production potential.
	6 & 9	
	8/10	
Forest	A	Maintain and extend as far as compatible with the local climate (consider obstacles to cold air drainage). Function for adjacent areas with higher air pollution levels: protective function for air pollution control (air regeneration).

	D/E	
	6	
Urban Green Space	6	Maintain and link as far as possible. Maintain or aim at low-density housing (to facilitate air exchange).
	8/10	
	A	
Garden City	6 & 8/10	Avoid further sealing, consolidation possible. Aim for low-emission power supply.
Suburban		Especially in these climatopes, the link between green spaces and open land needs to be maintained or created. Avoid tall, enclosed building structures and developments closing off the surrounding areas. Aim for low-emission power supply.
City		Removal of sealed surfaces, replacement of buildings in interior parts of city blocks by decorative plants. Avoid high traffic density in narrow street canyons, aim for traffic reduction and low-emission power supply.
Inner City	4/5 &6	See City climatope. Give priority to low-emission power supply.
	1/2/3	
Commercial/ Industry	8/10	Roof and facade greening, car park greening, planting of areas, greenage links, removal of sealed surfaces, maintain or create permeable structures for ventilation, restriction to low-emission enterprises, and low-emission power supply, e.g., district heating.
	4/5 & 6	
Traffic	D/E	Potential wind corridor and air pollution sources, keep free of sources and increase roughness in case of different uses.
	8/10	
	4/5 & 6	
Airport	D/E	Potential air ventilation corridor.
	8/10	

Table 6. Urban climate planning recommendations for each LCZ in Toulouse basing on VDI 3787-Part 1 (2015).

LCZs	General Characteristics	Planning Recommendations

Compact Settings 1/2/3	Compact built-up areas with moderate to strong heat stress in the daytime. Mainly located in the core areas of the Toulouse city center. Because of their compact settings and narrow streets, heat can be trapped in the daytime and released slowly at night. Furthermore, very limited greenery and vegetated spaces can be found in these areas. Heat stress can be kept at moderate to strong levels throughout most of the daytime (before sunset) under typical clear summer conditions; however, under heatwave conditions, the overall heat stress can worsen and reach strong or even very strong levels.	Mitigation actions are recommended and essential. Effective measures include: • prevent heat from being stored in buildings, street canyons, pavement, and rooftops; • reduce anthropogenic heat from commercial areas; • increase greening on rooftops, on building façades, and at pedestrian level; • increase reflectance of rooftops; • increase water features; • respect and link open spaces; • create urban oases; and • provide canopy and shading devices.
Open Settings 4/5 and 6	Open built-up areas with moderate to strong heat stress in the daytime. Mainly located in both the Toulouse city center and metropolitan areas. Includes large clusters of villages and new towns. Overall heat stress can be kept at moderate to strong levels throughout most of the daytime (before sunset) under typical clear summer conditions; however, under heatwave conditions, the overall heat stress can worsen and reach strong or even very strong levels.	Mitigation actions are recommended and necessary. Effective measures include: • avoid dense building developments; • prevent heat from being stored in buildings; • fully respect open space and greenery areas in-between buildings; • increase greening, especially green belts, street trees, and medium green parks; • create vegetated open spaces and green parks; • increase reflectance of rooftops; • link open spaces; • provide canopy and shading devices; and • adopt high albedo materials.

Large Low-rise Settings 8/10	Large low-rise built-up areas with no heat stress to strong heat stress in the daytime. Mainly located in the outskirt areas of the Toulouse city center with limited greenery. Such areas consist of industrial warehouses, shopping malls, and villages. Because of the large open spaces in-between buildings, stored heat can be released to the air quickly at night. Overall heat stress can vary from negligible to strong levels under typical clear summer conditions; however, under heatwave conditions, the overall heat stress can worsen and reach strong or very strong levels.	Some mitigation actions are encouraged where possible. Further development is possible but should be carefully planned. Effective measures include: • avoid dense building developments; • prevent heat from being stored in buildings; • create more open space and greenery areas in-between buildings; • increase greening, especially green belts and medium–large green parks; • create vegetated open spaces and green parks; and • adopt high albedo materials.
Sparsely Built-up Areas 9	Sparsely built-up areas with no heat stress to strong heat stress in the daytime. Scattered locations in the Toulouse Metropole region, primarily consisting of arable, grazing, or meadow land with low sealing levels. Because these areas are next to large open spaces and vegetated areas, stored heat can be quickly released to the air at night. Overall heat stress can vary from negligible to strong levels under typical clear summer conditions; however, under heatwave conditions, the overall heat stress can worsen and reach strong or very strong levels.	Preserve and enhance. Further development is possible but should be carefully planned and dense building developments should be avoided. These areas should be carefully used, especially as potential air corridors, and linked to built-up areas to enable the transfer of cool and fresh air.
Trees A/B	Woodland and tree-planted areas with no heat stress to strong heat stress in the daytime. Scattered locations in the Toulouse Metropole region.	Preserve and enhance. Increase green belts and woodlands if possible and link them to built-up areas to enable the transfer of cool and fresh air.
Grass/ Shrubs D/E	Grass and shrub areas with no heat stress to strong heat stress in the daytime. Mainly located in the outskirt areas of the Toulouse Metropole.	Preserve and maintain. Further development is possible but should be carefully planned. These areas should be carefully used especially as potential air corridors.
Water Bodies G	Garonne River, scattered lakes, and water bodies with no heat stress to strong heat stress in the daytime. Large water bodies can provide an evaporative cooling effect to the surrounding areas. Given its low surface roughness, the Garonne River serves as a major air corridor for the Toulouse city center.	Preserve. Waterfront areas should be carefully planned with respect to the breeze and wind from large water bodies.

4.3 Implementations

27 In an era of public concern for high-quality urban living, sustainable climatic spatial planning is one of the most important tasks and challenges facing city planners and policymakers. Unprecedented challenges include comprehensively understanding the interrelationship between modern urbanization and urban climatic conditions and establishing a reasonable urban planning system from the perspective of sustainable development. Therefore, incorporating climatic and environmental information into urban planning practices and ecological city construction is crucial to ensure that science-based planning provides healthier, more sustainable, and more comfortable living conditions. In the process of urban planning, the working hierarchy ranges from the macroscale to the microscale. Combining UC-AnMap and LCZs can offer appropriate urban climatic planning recommendations according to the different working objects. Using a UC-AnMap, local planners and policymakers can obtain a comprehensive understanding of the urban climatic-environmental conditions at the regional or city level. An LCZ map is better for quantitative analyses for UHI- and morphology-related studies at the urban or district scale. Using hybrid Climatope-LCZ map, hot spots with heat risk in a climatope can be targeted and mitigation strategies can be promoted for the relevant LCZs based on the features of the climatope or land use policies. Therefore, Table 5 and Table 6 can be cooperatively adopted by planners or practitioners to crosscheck specific spatial information and climatic planning recommendations when dealing with projects on different scales.

4.4 Limitations

28 Some limitations in this study are worth to be noted. Firstly, the urban morphology in the Toulouse Metropole is relatively in low dense and homogeneous compared to Asian or American cities. Only a mild change in the building morphology and density occurs from rural to urban areas; this results in a similar composition of LCZs in the built-up climatopes. Conversely, in Hangzhou, China, large urban areas are densely covered by Compact Settings (LCZ 1/2/3) and Open High-rise (LCZ 4)(Ren et al. 2016). In Hong Kong, Open High and Mid-rises (LCZ 4/5, 54.8% and 24.6%, respectively) are the dominant LCZ types(Zheng et al. 2018). Meanwhile, some LCZ classifications were excluded in the case study because of the limitations of the database. Therefore, the spatial correlation between the climatopes and LCZs might lack representativeness. Secondly, the resolution of the wind and thermal environment simulations was 250 m × 250 m. It is difficult to indicate microclimatic characteristics, such as roads and scattered buildings, in climatopes with spatial scales smaller than this resolution. Lastly, the proposed planning recommendations for LCZs are relative general and theoretical, which are only proposed for linking the urban structure and potential actions with the strong limit to not be territorialized. The specific strategies and corresponding impacts to develop more practical guidance were developed in Hidalgo et al. paper recently submitted to this same journal.

5. Conclusions

29 This study compared and synergized the UCMap system based on VDI 3787-Part 1 with the LCZ scheme to point out their potential mutual benefits by taking Toulouse Metropole as a case study. The weather information from numeric simulation in typical summer conditions (LWT-9) was employed as evidence for analyzing the microclimatic performance accompanied with the hybrid Climatope-LCZ map. Some mutual benefits are summarized. Firstly, the hybrid Climatope-LCZ map demonstrates more detailed heterogeneous characteristics about urban morphology and urban climate in climatopes. Meanwhile, the various thermal loads within a LCZ are identified by linking with climatopes spatially. Therefore, hot spots with heat risks are easily detected on the hybrid Climatope-LCZ map. Finally, based on the above findings and guidelines from the VDI 3787-Part 1 (2015), the urban climatic planning recommendations for the LCZs in the Toulouse Metropole were generated, presenting the potential of this method to support planning practitioners or decision-makers in comprehensibly understanding scientific information concerning urban climate and in proposing effective measures for mitigation in response to the challenges posed by future climate change.

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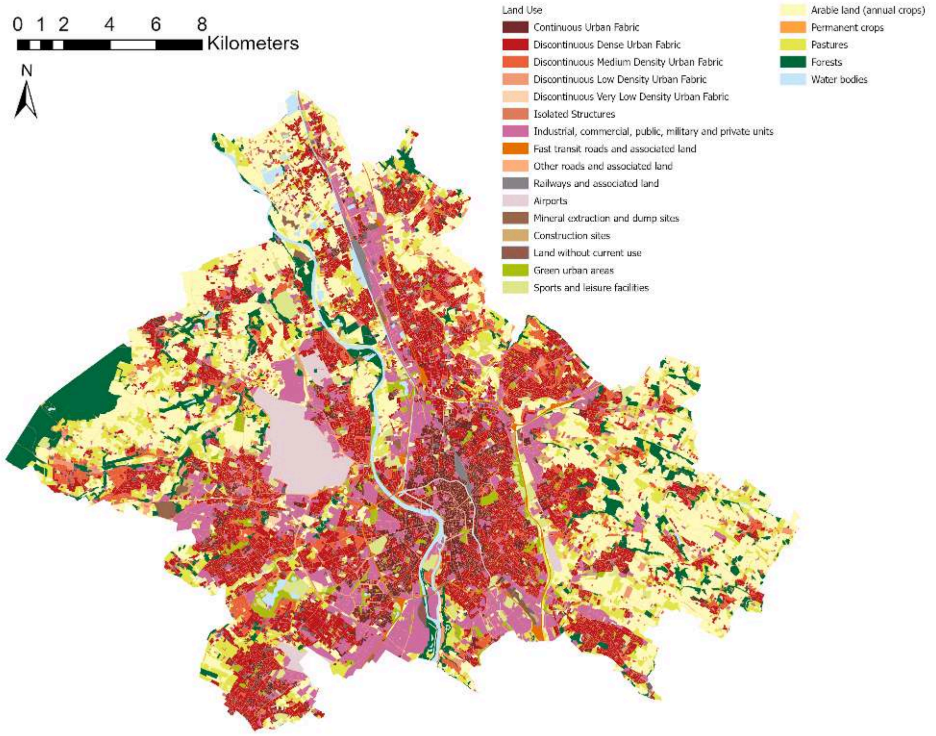
APPENDIXES

A1. Data collection

The land use data were extracted from the 2012 Urban Atlas produced by the European Environment Agency under the framework of the Copernicus Land Monitoring Service (European Environment 2012). The Urban Atlas dataset for the Toulouse Metropole distinguishes 21 land use types, 16 of which are artificial surfaces dominantly influenced by human activities, as shown in Figure S1. The morphological data were derived from the MApUCE morphological database (Bocher et al. 2018), which includes 27 morphological indicators at the building scale, 9 at the block scale, and 28 at the reference spatial unit (RSU) scale (Plumejeaud-Perreau et al. 2015). An RSU corresponds to an urban islet, i.e., blocks surrounded by roads. The urban vegetation data were retrieved from SPOT 6 satellite images at 1.5-m resolution using the methodology and software developed by Crombette et al. (2014). The categories “trees and bushes,” “grass,” and “no vegetation” can be distinguished.

Figure S1. Land use in the Toulouse Metropole according to the Urban Atlas data (European Environment 2012).



A2. Climatope classification

The initial UC-AnMap in this study was classified in accordance with VDI 3787-Part 1. Because the relatively flat topography in the Toulouse Metropole has a limited influence on the regional climate, land use is the predominant factor for recognizing specific climatopes with homogeneous thermal and dynamic conditions. On this basis, climatopes with similar, uniform, small-scale, and near-ground local climate conditions were derived from land use types, such as water, forest, and settlement. Then, the classification of the climatopes was refined to account for density and impervious surface coverage; the spatial relationships between neighboring climatopes were also considered. Because of the lack of air quality-related information, the designation of pollutants released near ground level, especially by traffic facilities and activities, were simplified to typical transportation-related land use types. Consequently, transportation lines and facilities, primarily airports, railway lines, and fast transit or other roads, are simply listed to represent possible specific climatic and air quality conditions. Apart from the Airport climate condition, the other three specific climate conditions were merged into a single group, i.e., the Traffic climate condition, to simplify the analysis.

A3. LCZ classification

The LCZ map of the Toulouse Metropole applied in this study was first presented in Hidalgo et al. (2019) and was constructed under a vector-based GIS framework.

Morphological data were employed to classify the LCZs using information concerning the land cover composition (e.g., water, roads, and vegetation) and building characteristics at the RSU scale. The classifications of the built-up LCZs were based on seven building indicators extracted from the Toulouse administrative and topographic database (Bocher et al. 2018). These indicators are the building density, building typology, dominant typology of buildings within an RSU, mean building height, average and median minimum distance between buildings, and number of buildings. As a semi-automatic statistical method, K-means was introduced to distinguish the thresholds of the indicators to classify the urban polygons into different LCZ groups. Polygons were classified as Water Bodies (LCZ G) or Paved Surfaces (LCZ E) if their corresponding fractions of water or roads, respectively, were over 50% in the RSU. Vegetated LCZs, e.g., Dense Trees (LCZ A), Scattered Trees (LCZ B), and Low Plants (LCZ D), were calculated from high-resolution SPOT 6 image data. Heavy Industry (LCZ 10), Bush/Scrub (LCZ C), and Bare Soil (LCZ F) were difficult to classify because of data limitations; therefore, these three classifications were excluded from this study. To ensure that the sample sizes of the LCZs were sufficiently large for thermal analyses, Compact Settings (LCZ 1/2/3), Open High/Mid-rises (LCZ 4/5), and Low Plants (LCZ D/E) were grouped according to their similar thermal characteristics and their physical proximities to each other (Kwok et al. 2019).

A4. Hybrid Climatope-LCZ map

A hybrid Climatope-LCZ map was generated by joining the climatope and LCZ layers based on their spatial locations. The results were stored in a new shapefile layer, each polygon of which has two attributes: a climatope type and an LCZ type. The joint spatial results are composed of subdivisions of climatope–LCZ types, which provides new information indicating both the land use and the building morphology. Taking area as the basic quantized criteria, it is possible to recognize dominant building morphology and land cover types in each climatope, or simultaneously, the predominant land uses and human activities in each LCZ.

A5. Meteorological analysis

Hidalgo and Jougla (2018) defined 11 local weather types (LWTs) in Toulouse. One of the summertime weather types, LWT-9, which occurred most frequently in the weather records from 1998 to 2008, is the focus of this study. LWT-9 features high temperatures (that can reach 40°C), a strong nocturnal UHI effect, and weak winds typically blowing from the northwest or west. In total, 18 days demonstrating LWT-9 conditions in June, July, and August of 2004 were investigated. The city-wide spatial coverage of the meteorological variables, including the wind speed (*ff*), air temperature (T_{air}), mean radiant temperature (T_{mrt}), and Universal Thermal Climate Index (UTCI) at a height of 2 m above ground for the Toulouse Metropole were retrieved from a simulation of a mesoscale atmospheric model, i.e., Meso-NH (Lac et al. 2018) coupled with SURFEX (Masson et al. 2013). All the wind and thermal data were acquired from Kwok et al. (2019), in which the thermal characteristics of the LCZs in the Toulouse Metropole are compared in detail. The results of the model simulation are available at a resolution of 250 m; each grid can be regarded as having a point at its centroid with the *ff*, T_{air}, T_{mrt}, and UTCI values. To conduct the urban thermal climatic analysis, the attributions of both the climatope and the LCZ of these points were assigned by geographically joining the grids with a VDI-based Urban Climatic Analysis Map and an LCZ map.

A5.1 Wind environment

The wind environment analysis was primarily based on the scalar average wind speed during the late afternoon (5–8 p.m. local time) and night (3–6 a.m. local time) to represent the daytime and nighttime wind environments for the LWT-9 conditions, respectively. *ff* at 2 m was calculated in the Town Energy Balance model with the Surface Boundary Layer scheme (Masson et al. 2013) by taking into account the drag force due to the buildings and the vertical turbulent momentum transport. To better understand the wind environment of the Toulouse Metropole, we used the Beaufort wind force scale, which is a classic tool for measuring the wind force effect; it was first invented by Admiral Sir Frances Beaufort for use at sea and was later revised to estimate wind speeds on land in the early 1980s. Table S1 shows part of the modern Beaufort wind force scale, describing the wind speed ranges and related effects (Penwarden 1973).

Table S1. Effects of the wind force according to the Beaufort scale (Penwarden 1973).

Beaufort Number	**Speed(m s^{-1})**	**Effects**
0, 1	0.0–1.5	Calm, no noticeable wind.
2	1.6–3.3	Wind felt on face.
3	3.4–5.4	Wind extends light flag. Hair is disturbed. Clothing flaps.

A5.2 Thermal environment

To discuss the diurnal variations of the thermal environment, three time periods were defined: early afternoon (1–4 p.m. local time), late afternoon (5–8 p.m. local time), and night (3–6 a.m. local time). Because the nighttime weather conditions are heavily influenced by the daytime conditions of the previous day, the nighttime conditions were defined for the night following a defined LWT-9 day. T_{air} is one of the most universal indicators for assessing the UHI intensity. T_{mrt} is a popular indicator measuring the human energy balance and exchange with the near environment (Ashrae 2013, Kántor and Unger 2011). The averages of T_{air} and T_{mrt} during the three periods were compared in this study. UTCI is employed to reflect human physiological reactions to the outdoor thermal environment (Bröde et al. 2012). Different UTCI ranges can be linked to thermal stress categories, inferring different thermal comfort levels, as shown in Table S2 (Błażejczyk et al. 2013). The hourly UTCI values at a point during a selected four-hour period were pooled together for all LWT-9 conditions (i.e., 72 values for each point for the 18 days) to analyze the proportions of the different stress categories. The Water Body climatope was not included in the T_{mrt} and UTCI analyses because there are no people living in such areas.

Table S2. Universal Thermal Climate Index (UTCI) categorized in terms of the thermal stress (Błażejczyk et al. 2013).

UTCI Range	**Stress Category**
38–46°C	Very strong heat stress
32–38°C	Strong heat stress
26–32°C	Moderate heat stress
9–26°C	No thermal stress
0–9°C	Slight cold stress

ABSTRACTS

The urban climatic map (UCMap) is an urban climate information tool for planning purpose commonly used in German-speaking countries while local climate zone (LCZ) scheme is developed to link the characteristics urban climate and urban morphology at the city level world widely. These two frameworks differ with each other on the aspect of data sources, classification standards, and planning implementation. This study explores the potential of integrating these two complementary frameworks to identify problematic hot spots and propose some generic urban planning recommendations according to current urban climate standards. To address this issue, the Toulouse Metropole area is taken as a case study; a hybrid Climatope-LCZ map is derived by synthetizing the classification of climatopes, based on the German standard (VDI 3787-Part 1), and LCZs at equivalent spatial positions. Furthermore, the simulated meteorological data about wind and thermal environments of Toulouse Metropole during typical summer season are introduced as evidence for analyzing the mutual benefits on urban climate study and application. According to the results, both the heterogeneous urban geometric characteristics and urban climatic issues within a climatope are well identified spatially by the corresponding composition of LCZ. Likewise, the differences of thermal stress between climatopes but in the same LCZ are also clearly illustrated. Lastly, a list of urban climatic planning recommendations for LCZs is proposed followed by the guidelines in VDI 3787-Part 1. This study proves that hybrid Climatope-LCZ map offers more detailed urban climate information to planners or decision-makers than classic urban climate map framework.

La carte climatique urbaine (UCMap) est un outil d'information sur le climat urbain à des fins de planification, couramment utilisé dans les pays germanophones, tandis que le schéma des zones climatiques locales (LCZ) est développé pour relier les caractéristiques du climat urbain et de la morphologie urbaine au niveau de la ville dans le monde entier. Ces deux cadres diffèrent l'un de l'autre en ce qui concerne les sources de données, les normes de classification et la mise en œuvre de la planification. Cette étude explore le potentiel d'intégration de ces deux cadres complémentaires afin d'identifier les points chauds problématiques et de proposer des recommandations d'urbanisme génériques selon les normes actuelles du climat urbain. Pour aborder cette question, la région de Toulouse Métropole est prise comme étude de cas ; une carte hybride Climatope-LCZ est dérivée en synthétisant la classification des climatopes, basée sur la norme allemande (VDI 3787-Part 1), et les LCZs à des positions spatiales équivalentes. En outre, les données météorologiques simulées sur les environnements éoliens et thermiques de Toulouse Métropole pendant une saison estivale typique sont introduites comme preuve pour analyser les avantages mutuels sur l'étude et l'application du climat urbain. D'après les résultats, les caractéristiques géométriques urbaines hétérogènes et les problèmes de climat urbain au sein d'un climatope sont bien identifiés spatialement par la composition correspondante de la LCZ. De même, les différences de stress thermique entre les climatopes mais dans la même LCZ sont également clairement illustrées. Enfin, une liste de recommandations de planification climatique urbaine pour les LCZ est proposée, suivie par les directives de la VDI 3787-Partie 1. Cette étude prouve que la carte hybride Climatope-LCZ offre des informations climatiques urbaines plus détaillées aux planificateurs ou aux décideurs que le cadre classique des cartes climatiques urbaines.

La carta climática urbana (UCMap) es una herramienta de información sobre el clima urbano con fines de planificación y frecuentemente utilizada en los países de habla alemana, mientras que el esquema de Zonas climáticas locales (LCZ) vincula las características del clima urbano y la morfología urbana a nivel de ciudad en todo el mundo. Estos dos marcos difieren entre sí en las fuentes de datos, las normas de clasificación y la implementación de la planificación. Este estudio explora el potencial de integrar estos dos enfoques identificando los nudos críticos y proponiendo recomendaciones generales de planificación urbana según los estándares climáticos urbanos actuales. Para abordar lo anterior, se consideró el caso de estudio la región metropolitana de Toulouse, en la cual se deriva un mapa híbrido Climatope-LCZ para sintetizar la clasificación de climatopos basada en el estándar alemán (VDI 3787-Parte 1) y LCZ en posiciones espaciales equivalentes. Además, se presentan datos meteorológicos simulados sobre los entornos eólicos y térmicos de la región metropolitana de Toulouse durante una estación típica de verano como evidencia para analizar los beneficios mutuos en el estudio y la aplicación del clima urbano. Los resultados expresan que las características geométricas urbanas heterogéneas y los problemas climáticos urbanos al interior de un climatopo están espacialmente bien identificados por la composición correspondiente de las LCZ. Además, se ilustran claramente las diferencias en el estrés térmico entre climatopos pero en una misma LCZ. Finalmente, se propone una lista de recomendaciones de planificación climática urbana para LCZ, según las pautas de VDI 3787-Parte 1. Este estudio demuestra que la carta híbrida Climatope-LCZ ofrece una información climática urbana más detallada para planificadores o tomadores de decisión que los clásicos mapas climáticos urbanos.

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