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1. Introduction

1 With the emergence of climate change (IPCC, 2021) and the need for cities to initiate mitigation and adaptation strategies (Rosenzweig et al. , 2018), the topic of climate is gaining a prominent place in urban planning. France follows the international regulatory evolution and implements a progressive territorialization of climate and energy policies. Starting from global objectives, actions have been implemented from regional to local scales and have had strong implications in town planning. From the

Inter-ministerial Mission for the Greenhouse Effect which in 2000 drew up the first National Program for the Fight against Climate Change to the present day, a succession of Plans and laws have made it possible to structure energy and climate policies at the local scale (see Hidalgo, 2022 for a historical perspective).

2 Thus, following recent legislative developments, the integration of climate and energy issues is required in the spatial planning tools of local authorities (the Territorial Coherence Scheme – Schéma de Cohérence Territoriale - SCOT, and the Local Masterplan - Plan Local d'Urbanisme - PLU) or through compatibility links with dedicated tools such as the Climate Plans – Plan Climat Air Energie Territoriale – PCAET. These plans introduced the obligation, for cities with more than 50000 inhabitants in 2012 and more than 20000 inhabitants in 2018, to establish environmental diagnoses and actions to integrate mitigation and adaptation to climate change. Consequently, the content of the environmental reports in these documents is evolving to better account for the dual objective of establishing climate mitigation and adaptation policies at the local scale (Lambert et *al*., 2019). However, in the Environmental Assessment, the mitigation and adaptation components do not have the same methodological framework. Carbon assessments are, for example, required by sector of activity in order to identify actions to reduce greenhouse gas emissions, while nothing is imposed concerning the adaptation component.

3 Concerning the adaptation to the risk of extreme temperatures in urban areas, this seems consistent with the pace of methodological development for producing spatial knowledge at these fine scales in France (Hidalgo, 2022). Between 2015 and 2020, the research consortium around the ANR-MApUCE and ADEME-PAENDORA projects implemented new methods for producing data describing the urban surface (Bocher et al, 2018; Tornay et al. 2017), which makes it possible to produce microclimatic simulations for any city in France (Gardes et al. 2020). Those research projects represented a pivotal moment in the production of urban and climate data through research with the production of numerical simulations for a group of fifty French cities.

4 In the context previously introduced, the research question addressed here can be summarized as follows *"Given that the regulatory framework requires French local authorities to take summer comfort issues into account in urban planning and that tools for modeling the urban atmosphere are available at sufficient spatial resolutions :*

- *Is it possible, through an interdisciplinary action research approach, to co-construct a methodological proposition for mapping the urban climate for summer comfort management ?*
- *What formatting is required for this diagnosis to be incorporated into a French urban planning document?*
- *What climate information should be put forward and, in what stages of the urban planning document, can this information be used?*

5 The following paper proposes a demonstration on how to use the available geographic and climatic data to map the urban climate to address summer comfort management in France. It also shows how the collaboration with the local authorities of Toulouse Metropole and the local urban agency allowed translation of the spatial climatic information into recommendations for urban planners and developers.

2. Theoretical framework and originality of this study

6 By observing what is happening in countries that have already conducted studies on applied urban climatology, it is possible to identify a common point: the use of cartographic representations that makes it possible to spatialize the atmospheric information on the scale of the concerned territory. For nearly three decades, researchers in urban climatology have embarked on—often in partnership with urban planning actors—the development of climate maps to enrich the environmental aspect of territorial diagnoses and to guide, alongside other elements, the planning process. Despite having appeared under various names based on the countries and scales addressed, today these initiatives tend to converge under the generic name of Urban Climatic Maps (UC-Maps) (Ng and Ren, 2015).

7 UC-Maps represent both a microclimatic diagnoses tool for urban areas and a regulatory translation tool for identified issues. Japan can be cited as one of the most advanced countries in this field, with climate maps of urban environments (Tanaka et al., 2009) having been developed for several cities (Kobe, Osaka, Yokohama, and Sakai). China has also been extensively working on this topic in the past few years. Even though the methodologies used are specific to each local context, climate maps of urban environments consist of two types of maps: "climate analysis maps" and "recommendations maps," corresponding to two planning scales, that of the city (1:10,000) and that of the district (1:2,500). In Europe, Germany is leading the way in experiments in this field because its regulatory context is highly favorable to considering the environment in urban planning. Several cities in the Ruhr region, e.g., Berlin and Stuttgart, have adopted climate maps according to differentiated models (climate analysis maps, synthetic functions maps, or digital environmental atlases) to guide their urban planning (Baumüller, 2008; Welsh, 2015). More recently, the techniques used in Japan and Germany have spread internationally, notably to Hong Kong (Urban Climatic Map and Standards for Wind Environment - Feasibility Study, 2006), the Netherlands (in Arnhem, Burghardt et al., 2010), Spain (in Bilbao, Acero, 2012), and many other geographic contexts (e.g., Iran, Sweden, Switzerland, Norway, Greece, Poland, Brazil, and Thailand).

8 The broad outlines of the content of these maps have tended to normalize despite necessary adjustments to local climatic, cultural, economic, and urban contexts. The VDI 3787 guidelines, published for the first time in 1997 by the Association of German Engineers, have become an international benchmark in this field[1]. Finally, a recent publication titled "The Urban Climatic Map, A Methodology for Sustainable Urban Planning" (Ng and Ren, 2015) has contributed to the international dissemination of these mapping tools by formulating the scientific and technical bases of the tools and by explaining methods for linking meteorological information, planning, land use, topography, and vegetation data.

9 Different methodological approaches exist for the production of a microclimatic diagnosis. From a thematic point of view, some approaches are more "thermal stress" oriented, such as the one developed in Tokyo (Ashie et al., 2015), while others are "ventilation and air quality" oriented, emphasizing dynamic potential and wind information. This is often the case in German cities, where air pollution problems are more important and frequent than issues of high heat stress. In Hong Kong, microclimatic diagnoses focus on summer comfort and both heat stress and ventilation

aspects are explored with respect to the pronounced topography and the proximity to the sea (Urban Climatic Map and Standards for Wind Environment - Feasibility Study, 2006[2]). With regard to the used data, cities in countries where this tool has traditionally been developed have benefited from measurement campaigns within the framework of dedicated research programs or have permanent atmospheric networks. This allows approaches seeking to establish statistical links between microclimatic conditions, land use and urban morphology. The characterization of the urbanized and topographic surfaces, therefore, gains a predominant importance in this type of analysis. In Germany, for example, land cover is generally the only data used to obtain a classification of the physical spaces in different "climatopes" representing areas with supposedly distinct local climates (VDI 3787 guidelines). The temperature or thermal stress data are then used to characterize these areas. Wind data is used to define ventilation corridors, fresh air production zones, and wind blockage zones. Conversely, in Hong Kong, because of its complex urban morphology in terms of the density and height of its buildings, other parameters such as the building volume come into play (Urban Climatic Map and Standards for Wind Environment - Feasibility Study, 2006).

10 The use of UC-Maps in France is new and the research here presented is inspired by this line of international work. The goal of this study is to propose methods to represent the climate information that, in our experience, appear to be adapted to the climate issues and regulatory frameworks of French cities. Accordingly, several methodological choices were made. The first choice was to focus on the thermal stress issue. Depending on the geographical location and topography, there is great climatic variability within French territories. Several climatic regimes can be identified, including oceanic, Mediterranean, semi-continental, and mountainous climates, as well as mixed regimes of these climates (Joly et al., 2010). Cities in southern France have milder climates, which can lead to heat stress during both day and night periods. This situation of high thermal stress is also observed in continental cities, located in the east and north of France. From the perspective of long-term climate change, the minimum and maximum temperatures will likely increase in France, as well as the frequency, duration, and intensity of heat wave episodes throughout the year, particularly in the Mediterranean Basin. The medium- and long-term evolution of other atmospheric parameters, such as rainfall or wind, is uncertain (ONERC, 2018). Following the logic of a rigorous transfer of scientific knowledge to the operational level, it seems relevant to start by integrating knowledge of the most reliable climatic hazards, which positions the issue of thermal stress as a natural choice for this first experiment. This choice is further reinforced by the fact that there is public awareness of this problem following the heat wave of 2003 and other heat waves that have very closely followed one another in recent years. Indeed, severe heat waves have occurred almost every year in France since 2015[3] with important health impacts (Pascal et al., 2019; Ung et al., 2019). The second choice was to offer tools to improve the implementation of local urban climate management policies in a generic methodological approach applicable at the national level. Climate management and adaptation programs and measures to be put in place in the following years must obviously be adapted to the realities of each field and co-produced with local actors. A certain generality is sought here primarily through technical aspects concerning the cartographic methods, climate data translation, and visualization tools from the sphere of the data producers (researchers and design offices) to that of operational use. The third choice was to take advantage of numerical simulation capacities of French research teams proposing to define recommendations map directly

from atmospheric informations combined with local operational expertise. This proposition is new compared to other studies where the information of urban surface has a predominant weight. Atmospheric modeling data allow wide and homogeneous access to information concerning air temperature, thermal stress, and wind. This information applies to a wide range of meteorological situations and uses a physical representation of atmospheric dynamics, which is not possible with the statistical approaches used, for example, in Germany or Hong Kong, which assume that the microclimatic conditions of the urban environment are essentially driven by the surface. This is true for very calm and windless atmospheric situations but has limits for strong wind or transitional situations, as well as for cities subject to mountain or coastal breezes. In this sense, modeling data provide a powerful tool that allows systemic (surface–atmosphere) microclimatic diagnoses. The urban database produced during the project facilitates both numerical simulations, and the interpretation and understanding of surface impacts on the surrounding atmosphere. The land use information makes it possible to understand the contours of the urban heat island, and the height and contiguity of the built elements allow for the identification of barriers to wind or, conversely, potential acceleration paths.

11 Another important point of the study was that the **c**o-construction with urban actors was part of the methodological cartographic proposition. Indeed, a strong choice of the project was to develop the proposed methodology with the urban actors in charge of the last PLU redaction, that is to say with the local authorities of Toulouse Metropole and the urban planning agency Aua/T. The methodology entailed to collaborate with them in three steps. A first phase over 3 years (2015–2018) consisted of a follow-up to the work meetings of the Climate–Energy group during the development of the PLU for Toulouse, a scientific analysis of the climate information, and the production of the cartographic elements. A second phase consisted of a series of meetings to prepare and conduct two workshops to co-develop recommendations with the services of the Toulouse Metropole in charge of urban planning, urban development and design, and urban environment. These workshops brought together approximately 20 agents, each representing around 10 departments (e.g., the Climate Plan, Urban Planning Department, housing and land operations directorate, DEE, Town Planning Department - SPU, Town Planning Department - SAE, Green Spaces Department, Urban Prospective, Management of Aquatic Environments and Flood Prevention, Mobility Network Management, and Toulouse Aerospace Project). Finally, in the period between 2018 and 2019, three workshops on geographic visualization were organized with the French GEO-VISU working group, a group of French cartographers. These workshops focused on resolving obstacles in the representation of data in cartography/geomatics and contributing to semiology with respect to urban and climatic localized data collection, processing, analysis, and representation.

3. Data presentation

3.1 Study area

12 The Toulouse Metropole is situated in Southwest France, has a population exceeding 750,000, and is organized into 37 municipalities (Figure 1) that cover ~118 km² (~16 km from north to south and ~12 km from west to east). The population density is ~1600 inhabitants/km², making the Toulouse Metropole one of the most sprawling cities in

France. The population of the metropolitan region has been increasing significantly, with more than 8,000 new inhabitants per year over the last 20 years. The topography of this area is relatively flat, ranging from 102 m to 273 m above sea level and is mostly influenced by the tributary valleys of the Garonne River. Because of its large distance from the ocean and flat terrain, cooling benefits from sea and valley breezes are very limited. Toulouse has a degraded oceanic climate, meaning that it presents a stark seasonal contrast. In summertime, there are usually large daily temperature variations accompanied by mild northwest or southwest winds. Even though the daily temperature usually fluctuates between 15°C in the early morning and 30°C in the afternoon, extreme heat wave periods with temperatures reaching 40°C frequently occur.

Figure 1. Locations of the main toponyms cited in this study.

3.2 Supporting data types

13 Three types of data were used. Urban data describing the urban surface was obtained via the automatic treatment of indicators describing the urban fabric and land use (Bocher et al., 2018; Hidalgo et al. 2018). Two categories of climatic information were selected to describe the climate of the Toulouse area. The first refers to the characterization of the meteorological situations experienced by the citizens of Toulouse called Local Weather Types (LWT, Hidalgo and Jougla, 2018). The second refers to the spatialized microclimate data from numerical simulations. Spatialized climate data were derived during a typical year in Toulouse via numerical modeling using the atmospheric Meso-NH (Lac et al., 2018) and surface SURFEX (Masson et al., 2013) models. The meteorological data of this typical year correspond to the period between March 2004 and February 2005 and are associated with the CAPITOUL field

campaign (Masson et al., 2008), which provides sufficient measurements to assess the quality of the simulations (Kwok et al., 2019). The atmospheric fields cover the entire territory of the Toulouse Metropole. The horizontal (250 m) and temporal (one map per hour) resolutions allow the spatial and temporal variations of the climatic variables in the territory to be detected. Finally, socio-demographic data from INSEE 2015 grid and BD Sirene 2016, as well as local data on equipment, vegetation, and land use in the Toulouse Metropole.

3.3 Data post-processing

14 The atmospheric information accessible via numerical simulations is very rich in terms of the quantity of variables, availability of time steps, and vertical levels. Based on the team meeting discussions, three types of atmospheric information were used to build the analysis maps : firstly, the level of daytime thermal stress, characterized by the Universal Thermal Climate Index[4] (UTCI) indicator at a height of 2 meters above the ground, strongly affects the comfort of city dwellers and makes air conditioning essential in many sectoral activities. Secondly, the influence of the city on the air temperature during the night at a height 2 meters above the ground, characterized by the intensity of the urban heat island (UHI), influences the capacity of buildings to cool down during the night rest hours and therefore affects the health of inhabitants. Finally, the aeraulic conditions 10 meters above the canopy, wind direction and intensity, make it possible to identify areas favorable to natural ventilation and areas with a ventilation deficit.

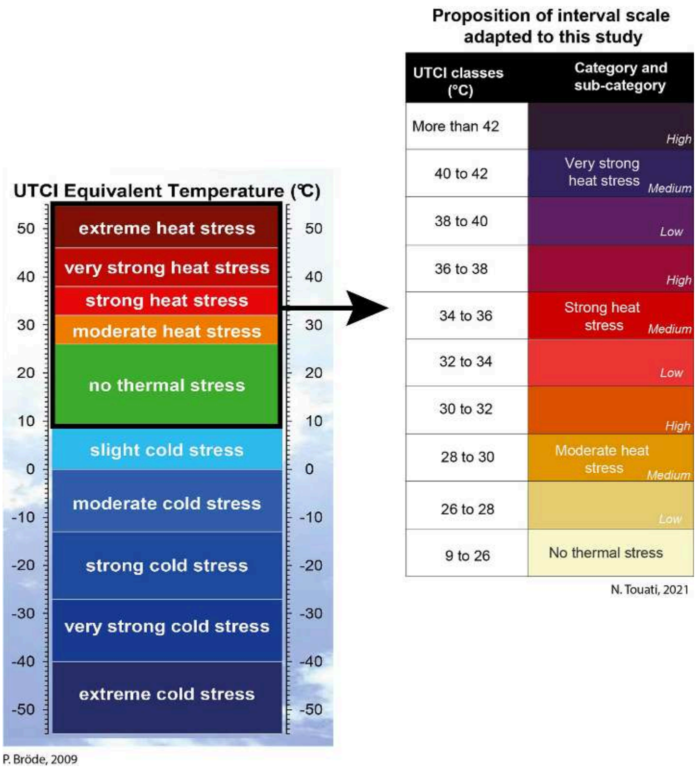
15 The numerical simulations produced a map for each meteorological variable at an hourly time step, i.e., in total, 8670 maps were generated. During discussions with local authorities, it was decided to focus on three types of meteorological situations (LWTs 7, 8, and 9) for summertime. This made reducing the amount of data to be processed and presented, possible. These three situations represent, for the simulated typical year, 85% of summer days with occurrence frequencies of 24 days (26%), 37 days (40%), and 18 days (20%) for LWTs 7, 8, and 9, respectively. Even though the diurnal dynamics were analyzed, two four-hour time slots were ultimately retained: late afternoon (5–8 pm local time) and night (3–6 am local time).

16 Several statistical treatments are possible to identify city areas with different microclimatic behaviors. The choice was made to calculate the most frequent level per pixel for a given type of weather situation and time slot to identify areas that are particularly sensitive to climatic hazards. Here, we are interested in thermal and wind effects. We call these areas *persistence areas.*

17 The classification levels used for each atmospheric field are as follows: UTCI is an international standard produced as part of the COST 730 action[5] that proposes a classification of values between the thermal stress levels of “extreme cold” and “extreme hot” (Figure 2, left). Because the intervals of this standard are very broad, to maintain a certain spatial variability, it is proposed in this study to subdivide each of the levels corresponding to thermal stresses from “moderate” to “very strong” into three subcategories: low, medium, and high (Figure 2, right). The collaboration with cartographers made us understand that a color legend in warm tones, and not from blue to red as usual in atmospheric sciences, was more suitable for an application in urban planning. For the UHI intensity, one-degree interval categories were created. For

the wind, three analyses were performed. As with the previous indicators, categories were considered for Duo using the wind direction and wind speed from the first level of the MESO-NH atmospheric model located 10 m above the canopy. These categories vary every 30° for the wind direction (e.g., N, NE, E, and SE) and are based on the Beaufort scale categories for the wind speed (i.e., 1.5, 3.3, 5.4, 10.7, 13.8, 17.1, and 24.4 m s^{-1}). Using the same source data, the spatial discontinuities of the mean wind speed per pixel were also calculated (Appendix 1) to highlight areas were the wind speed varies rapidly. Finally, the velocity ratio (wind speed at 2 meters above the ground/wind speed at 10 meters above the canopy) was also analyzed to depict areas with high and low ventilation potentials.

Figure 2. Interval scale for the Universal Thermal Climate Index (UTCI) in terms of the heat stress. Interval scale proposed by the COST 730 action (right; UTCI, 2003). Proposed interval scale used in this study (left).



4. Results: proposition of UC-Maps for Toulouse

18 In UC-Maps, the first level is that of the microclimatic diagnosis. This level gathers the meteorology, land use, topography, and vegetation information, according to which their relationships and effects on wind and thermal comfort are spatially analyzed and assessed. This diagnosis is, therefore, based on a set of maps commonly called “analysis maps” (“cartes d'analyse thématiques” is here proposed for use in French) and is superimposed with planning elements (e.g., green and blue corridors and urban zoning). Analysis maps should make it possible to identify a certain number of areas at risk from a microclimatic point of view. From a thermal point of view, areas at risk need to be depicted in terms of the daily heat stress level and/or the nighttime urban heat island intensity. This is correlated with the typologies of the urban areas,

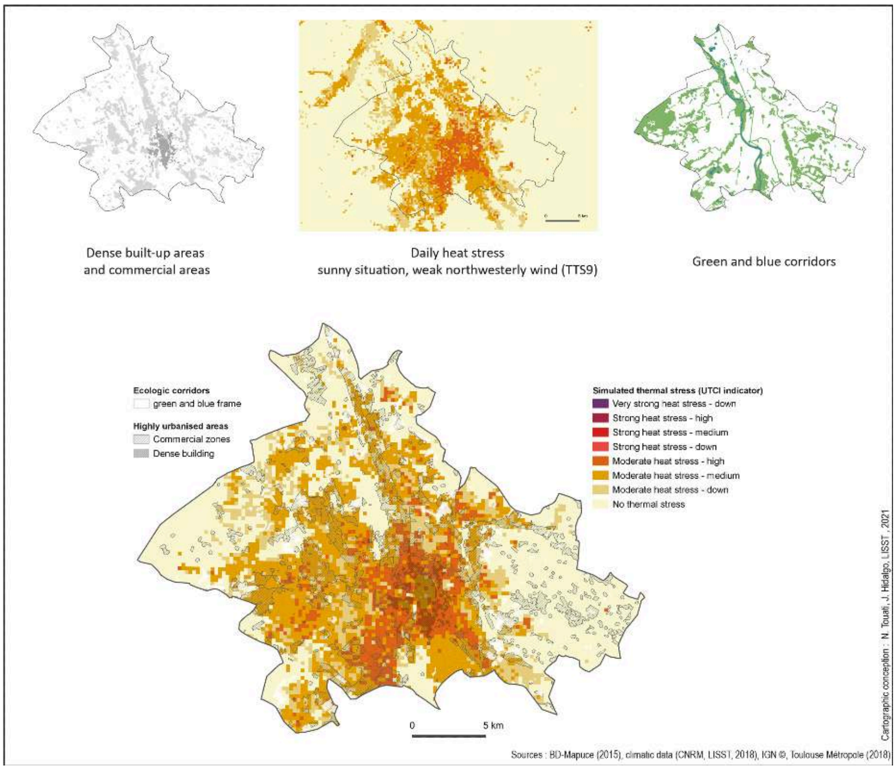
according to their density or urban structure; temperature-regulating spaces, such as water bodies and vegetation; and commercial and/or activity areas, which often have highly impervious surfaces and include the intense use of air conditioning. From an aeraulic point of view, it is necessary to identify predominant wind corridors, areas generating mountain breezes, areas producing fresh air (e.g., vegetation and water) or hot air (e.g., mineral-rich areas or areas with air conditioning use), and areas that block the wind (VDI 3787 guidelines). The second level allows for a regulatory translation that provides general strategic and practical orientations in urban planning to improve the thermal and wind environment based on the microclimatic diagnosis and practical constraints. This translation hinges on a “recommendations map” however, we propose using the name “cartes des zones à enjeux” in French, or “maps of strategic areas,” because the cartographic format itself is not adapted to communicate recommendations. Recommendations are often contained in guidelines that are complementary to the previous set of maps and that precisely and extensively present the proposed measures.

4.1 Thematic analysis maps for daytime conditions

4.1.1 Thermal analysis for daytime conditions

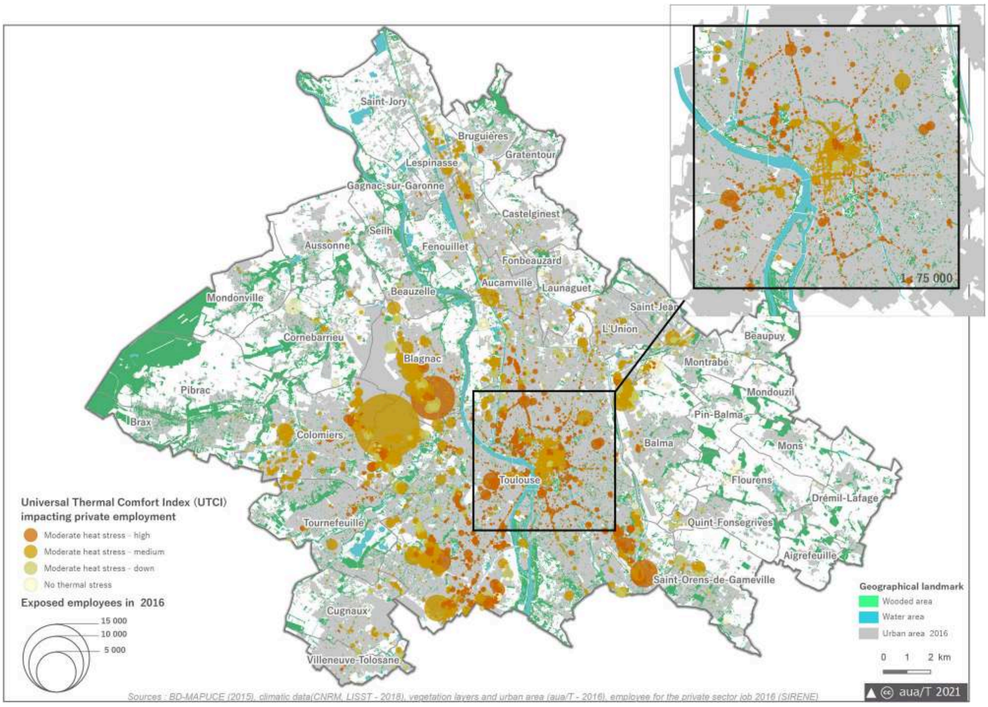
19 When the human body is submitted to extreme weather conditions, such as hot weather, several health impacts are possible. Depending on factors such as age, sex, and length of exposure, the body will be more or less able to cope with a given situation. A thermal comfort indicator is often used to characterize the thermal stress levels that a body may be exposed to in terms of moderate, strong, or very strong heat stress. According to these gradations, specific precautions should be considered, such as drinking, resting, or staying in the shade. The UTCI indicator is used here to characterize the thermal environment of Toulouse during the daytime. The thematic analysis maps for this indicator (Figure 3 and Appendix 2) allowed previous results observed in an air temperature analysis of the CAPITOUL campaign to be confirmed (Hidalgo et al., 2008; Pigeon et al., 2008), that is, during the day the areas with higher UTCI levels are not located in the dense historical core but rather in the immediate suburbs called *faubourgs* (e.g., Saint Michel, Saint Cyprian, Minimes, and Bonnefoy, Figure 1). The medieval historical core, called the *octogone*, experiences lower thermal stress by one or two levels compared with the surrounding districts. This relatively cool island effect is particularly remarkable for LWT 8. What is new compared with previous studies is the analysis of the commercial and activity areas. These areas also present significant thermal stress levels during the day. However, this effect depends on the location of the area, for example, areas located in the Garonne Valley north of the metropolitan area exhibit particularly high levels of heat stress. This effect is particularly visible on the LWT 7 map (Appendix 2).

Figure 3. Analysis map for the heat stress indicator, UTCI, during the day from numerical simulations for the typical meteorological situation, LWT 9, most favorable to the formation of a strong urban heat island (UHI) in summer.



20 Even if the *octogone* appears to be shielded from a thermal stress point of view compared with other areas, it still represents a sensitive point when analyzing the climatic information in terms of population exposure. The choice was made to analyze the UTCI intensity levels and the areas of private employment because they correspond to areas where a large segment of the population is located during the day (Figure 4). This allowed areas of activity that presented both strong exposure and the presence of people to be targeted. From this perspective, the city center of Toulouse remains a strategic area in addition to the major centers of activity (e.g., Blagnac and Colomiers in the east where the Airbus industry is located, Basso Cambo in the southeast, and Le Palays in the southwest) and areas along the main roads where a number of businesses and shops are concentrated, primarily on Route d'Espagne and D820, both of which follow the Garonne Valley to the southeast and north, respectively.

Figure 4. Exposure map for private employment with respect to the daytime heat stress level

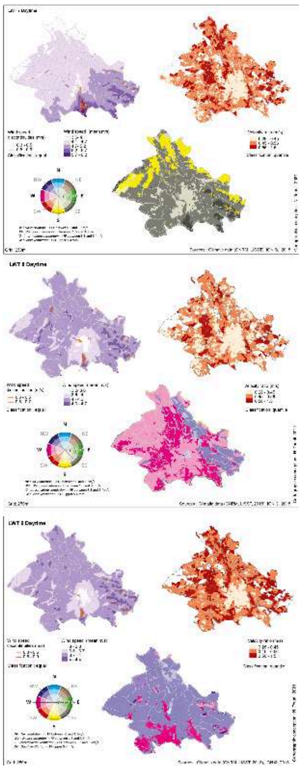


4.1.2 Aeraulic analysis for daytime conditions

21 The predominant winds in this region are from the southeast and the northwest. The Garonne River and its valley, which have a very similar orientation, channel the wind under strong wind conditions. Conversely, under light wind conditions, the wind stagnates, especially in the city center, because of the roughness of the buildings, and downstream in the valley areas. The objective here is to better understand the spatial variability of the wind related to the topography and the presence of vegetation, buildings, or infrastructure. The three analyzed LWTs coincide in terms of their daytime high thermal conditions but have different wind characteristics (Figures 5). For each panel in Figure 5, the spatial discontinuities in the mean wind speed are presented on the left, the velocity ratio is presented on the upper right, and the frequency analysis of the Duo wind direction and wind speed is presented on the lower right.

- LWT 7 is a situation with a predominant southeasterly wind that turns south in the northern part of the metropolitan area. The spatial discontinuity map superimposed on the mean wind speed at 10 meters above the ground indicates that the latter decreases by 50% between the outskirts and the city center (Figure 5a left, level of mean wind speed between 3.6 m s^{-1} and 4.1 m s^{-1}). The same is true for the Bouconne forest located to the west and the municipalities of Saint-Jory and Bruguières located in the north. The mean wind speed varies from 6.3 m s^{-1} in the countryside (Pech David located to the south and the Coteaux hills located to the east) to 3.5 m s^{-1} in the city center. In the east, stronger winds are observed on the ridges with pronounced spatial discontinuities at the ridge–valley boundary. The frequency analysis (Figure 5a lower right) shows an area of weak wind in the city center and of greater extension and higher spatial variability than is shown by an averaging approach and confirms the low values of the wind speed over the Bouconne forest and the municipalities in the north, Saint-Jory and Bruguières, and in the outer part of the metropolitan area in the east. The velocity ratio (Figure 5 upper right) clearly shows the city center (*octogone* and *faubourgs*) effect with a decrease of 60–80% in the wind speed between the first canopy level (situated in urban areas at 30 to 40 meters above the surface) and a height of 2 meters. Areas with good ventilation potential can be identified to the west of the city center in the municipalities of Blagnac and Colomiers coinciding with the Airbus industrial zone, to the southeast coinciding with the ridges, and to the southwest coinciding with the first terrace of the Garonne River.

Figure 5. Thematic analysis maps for the wind during the daytime for LWT 7, LWT 8 and LWT 9: spatial discontinuities in the mean wind speed (left), velocity ratio (upper right), and frequency analysis of the Duo wind direction and wind speed (lower right).



- LWTs 8 and 9 are situations in which the predominant wind comes from the northwest or even from the west over certain areas; however, LWT 8 generally presents higher intensities (FF_{max} ~ 4.7 m s^{-1} and FF_{min} ~ 3.2 m s^{-1}) than LWT 9 (FF_{max} ~ 4.4 m s^{-1} and FF_{min} ~ 3 m s^{-1}). The area with light wind has a concentric shape with two differentiated zones, shown in white and light purple, corresponding approximately to the *octogone* and *faubourgs*. Under these meteorological conditions, the Coteaux hills located in the southeast are downstream of the predominant flow. The ridges and valleys continue to represent privileged ventilation corridors for the downstream territory; however, the intensity of the wind is lower because the flow first passes through the urbanized areas. This is particularly evident in the valleys (shown in light purple in the mean wind speed map).

22 The wind data from those numerical simulations do not allow for the identification of mountain breezes (fresh and clean air coming down from the hills) or rural breezes (also called urban breezes), even if previous studies of the second phenomenon exist indicating the possibility of developing a daytime breeze situation under LWT 9 (Hidalgo et al., 2008a, 2008b). The spatial resolution of the urban and climatic data manipulated here also does not allow the impact on the wind of infrastructure

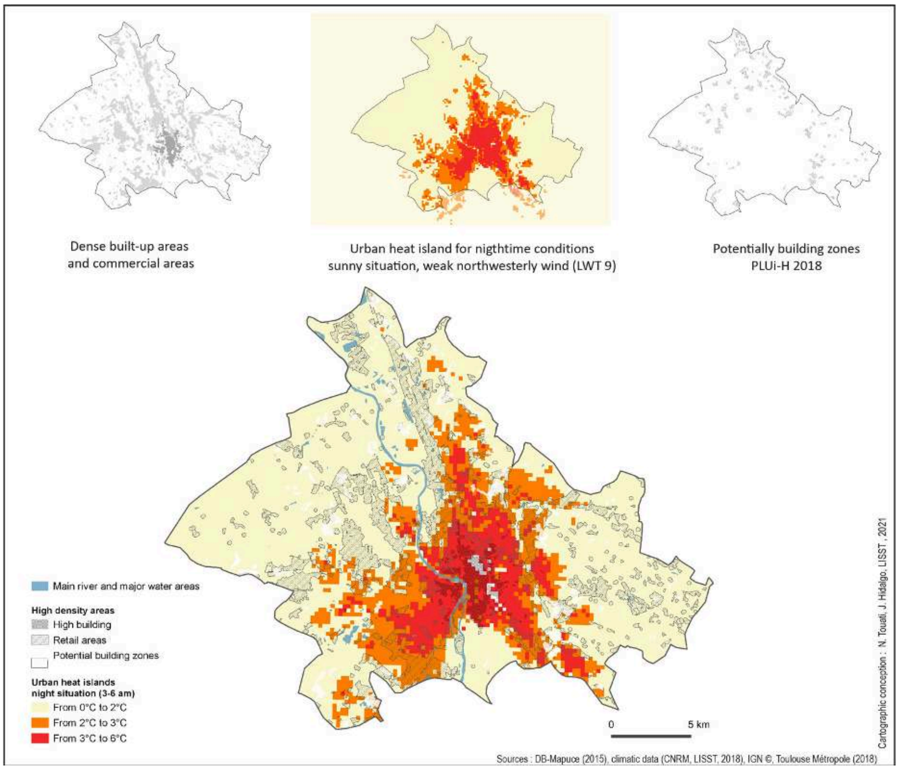
elements, such as major traffic lanes or dikes in the Garonne River, to be studied. Even though we cannot characterize such elements quantitatively, we know that they can constitute ventilation corridors (the ring road and the motorway primarily canalize chemically and thermally polluted air at times of heavy traffic) and that they can block air masses, e.g., the noise barrier of the ring road in the lower part of Pech David.

4.2 Thematic analysis maps for nighttime conditions

4.2.1 Thermal analysis for nighttime conditions

23 Under the most favorable meteorological situation for UHI development (LWT 9), the contribution of urbanization to the nighttime air temperature in the Toulouse city center exceeds 3°C for most of this area (octogone and faubourgs) (Figure 6).

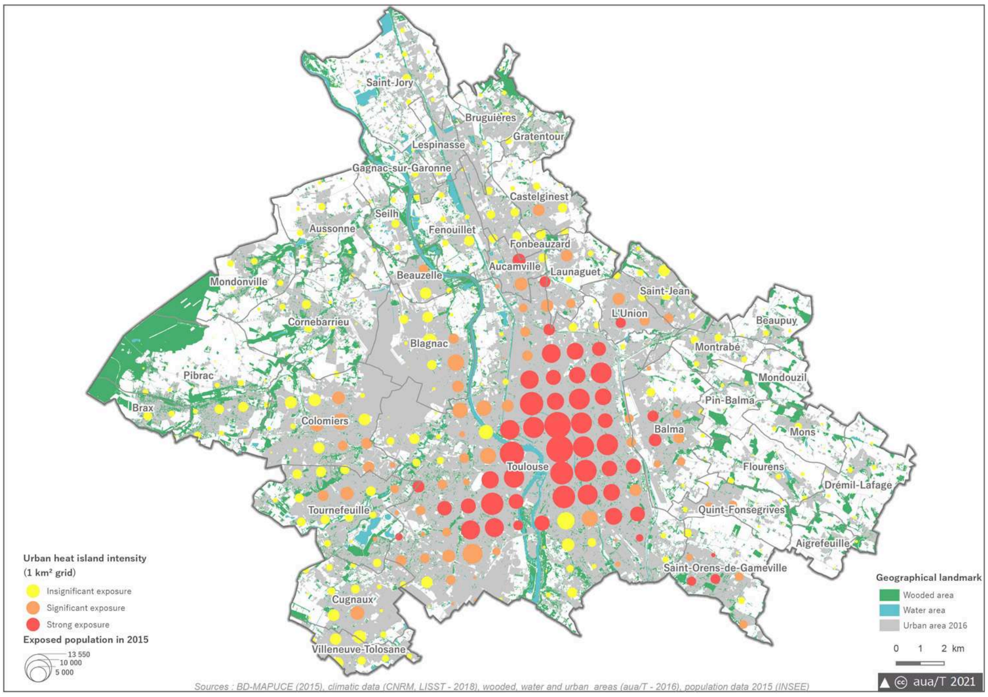
Figure 6: Analysis map of the UHI indicator using numerical simulations of the typical meteorological situation most favorable to the formation of this phenomenon in summer (LWT 9).



24 The UHI intensity can reach +6°C in areas situated west of the *octogone* (between Boulevard Antoine Carnot and Boulevard de la Gare); this is mostly due to the advection by the main background wind of hot air from the *octogone* to the west. This effect is difficult for the general public to understand when the map is provided without an accompanying interpretation by a climatology expert. For this reason, it was decided to create a single exposure class from +3°C up to the maximum UHI intensity. The intensity varies depending not only on the meteorological situation but also on the spatial extent (Appendix 3). Areas exposed to a nocturnal UHI of over +3°C vary from ~30 km^2 under LWT 9 to ~10 km^2 and ~0 km^2 under LWTs 8 and 7, respectively. The exposure of the municipalities adjacent to Toulouse (Launaget, L'Union, Balma, and Saint Orens to the east and Blagnac, Colomiers, Tournefeuille, and Cugnaux to the west)

to high temperature levels is less than that in the municipality of Toulouse in terms of spatial extent; however, the impact of urbanization on the air temperature is nonetheless non-negligible over large areas (shown in orange in Figure 6). These are areas that can quickly transition to high exposure levels. In this study, we call them *switchover zones* (“*zones à basculement*” in French), for which particular attention is required in terms of urban planning, especially because many new areas are now open to urbanization north, east, and southeast of the metropolitan area. Figure 7 indicates that the population density and the UHI intensity are highly correlated. The intra-ring area is the most populated and the most exposed to the nocturnal UHI, in addition to the town centers of the municipalities adjacent to Toulouse, where the majority of the municipal population is concentrated. The reasons for the high UHI exposure of these territories are multiple: they contain the most impervious surfaces in the metropolitan area, urban forms are the most liable to UHIs, and the activities or housing in these areas evacuate the most heat (e.g., via air conditioning).

Figure 7. Map showing the population density and the nocturnal UHI exposure levels for LWT 9, corresponding to a sunny summertime situation with light wind coming from the west to northwest.



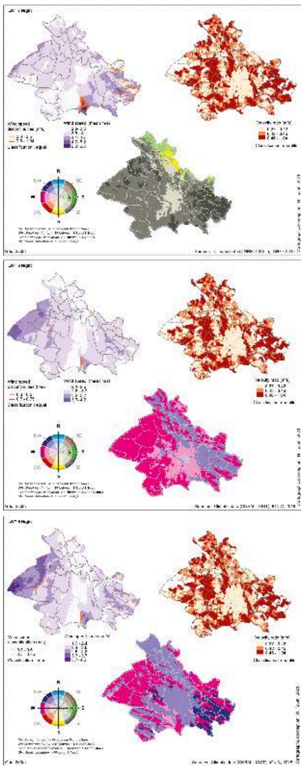
25 The territory also includes some natural thermoregulatory elements. Wooded masses, while having a limited presence in the city center, play an important role in thermal regulation at the micro-local scale (a few tens of meters) through the effects of shading and evapotranspiration. From previous studies (Kwok et al., 2019), we know that, at night, these wooded areas are 2°C cooler than surrounding built-up areas. In the previously mentioned municipalities situated near Toulouse, this difference in air temperature is only approximately 0.5°C despite the higher presence of vegetation. Regarding large water bodies, the Garonne River and the canals both play a thermal regulatory role and act as clean air ventilation corridors. At night during the summer, the water temperature approaches the air temperature and therefore does not contribute to lowering the air temperature. The role of thermal regulation is instead

fulfilled by the presence of trees and vegetation rather than evaporation. Evaporation lowers the temperature in a very localized way; however, high air humidity can increase the feeling of heat stress. Proximity to large bodies of water is, therefore, a double-edged sword at night.

4.2.2 Aeraulic analysis for nighttime conditions

26 Figure 8 shows that, for LWT 7 (Figure 8a), the wind direction rotates slightly to the east in the northern area and, for LWT 9 (Figure 8c), to the northwest in the southern area, while the LWT 8 (Figure 8c) wind direction remains stable. In general terms, the wind speed intensity at night decreases relative to the daytime conditions. LWT 9 presents the weakest intensities with 1.5 m s^{-1} in weaker areas of the city center and 4.2 m s^{-1} in the most ventilated rural areas. The frequency analysis shows that the Garonne River remains a ventilation corridor relative to the city center (wind speeds between 3.3 m s^{-1} and 5.4 m s^{-1}), even though these are weak values when compared with those of more ventilated areas located to the northwest and southeast. During the day, the area of light wind is concentric and its spatial extent corresponds to the *octogone* and *faubourgs*. During the night, the area of light wind stretches across the Garonne Valley, taking the shape of a vertical banana. The wind is also slowed to the west over the towns of Colomiers and Tournefeuille, likely because of the roughness of the urbanized surface.

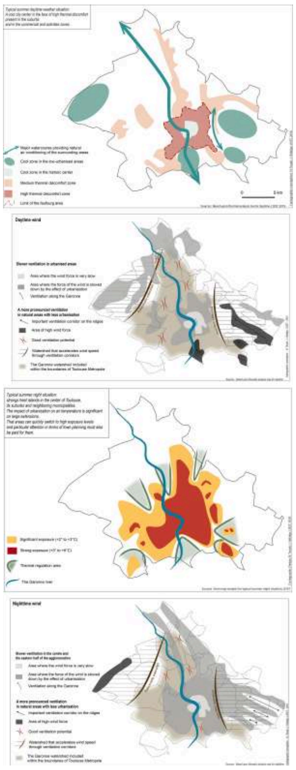
Figure 8. Thematic analysis maps of the nighttime wind for (a) LWT 7, (b) LWT 8, and (c) LWT 9, showing spatial discontinuities in the mean wind speed (left), the velocity ratio (upper right), and the frequency analysis for the Duo wind direction and wind speed (lower right).



4.3 Maps of strategic areas

27 Based on the thematic analysis maps, it is possible to differentiate at risk sectors according to microclimatic behaviors that require special attention in terms of urban planning (Figure 9).

Figure 9. Maps of strategic areas based on the daytime thermal stress and wind and the nighttime UHI and wind.



- **The historic center** (*octogone*)**:** This central area behaves like a cool island during the day because its narrow streets provide shade in the morning and prevent street, facade, and ground materials from overheating in the late afternoon. However, this configuration prevents satisfactory cooling at night and promotes an intense nocturnal heat island. Squares with mineral surfaces exposed to sun (e.g., Capitole and Esquirol) are an exception during the day, with higher heat stress levels than those found in the adjacent, more shaded streets. From an urban planning perspective, it would be interesting to preserve this island effect of natural cooling during the day, to minimize the heating of public spaces that exhibit high-level thermal stress, and to promote access to natural ventilation in these central areas.
- **The *faubourgs*:** The districts of the city center called *faubourgs* (e.g., Saint Cyprien, Saint Michel, Minimes, and Bonnefoy) present the highest levels of thermal stress in the city center because of the roadways and exposed walls. At night, these areas experience faster cooling than areas in the *octogone*. However, their central position within an extended agglomeration means that these suburbs remain exposed to a strong UHI effect. From an urban development perspective, it would be favorable to promote pedestrian comfort as much as possible, to minimize solar gains inside buildings to guarantee good nighttime comfort, to minimize the heating of public spaces with a high level of thermal stress, and to promote the natural ventilation of outdoor spaces.

- **City centers of municipalities adjacent to Toulouse:** Contrary to expectations, the town centers of these municipalities also contribute significantly (more than +3°C) to the UHI of the agglomeration. We propose particular attention be paid to the *switchover zones* that surround these city centers and already have UHI values between +2°C and +3°C. From an urban planning perspective, it is necessary to reduce the UHI intensity of the city center to reduce the extension of these *switchover zones* and to reinforce the green and blue corridors and ventilation corridors.
- **Commercial and activity areas:** These areas present high levels of thermal stress during the day because of the lack of shading, strong waterproofing of the ground, and high rates of air conditioning. At night, activity zones with strong nighttime human activities (e.g., production and logistics) and/or those located in the Garonne Valley (in particular those located southwest and north of the city center) have strong exposure to the UHI. Here, objectives would be to reduce both the use of active air conditioning systems and the extent of waterproofed areas.

28 Regulating spaces are areas that help preserve climatic comfort via shading, evapotranspiration, or ventilation. At a fine territorial scale, this corresponds to green and blue corridors and large parks (e.g., the Bouconne forest, Pech David, and Ramier Island), non-urbanized open spaces, and reliefs of any type, the most pronounced of which are potentially capable of causing breeze phenomena (e.g., the Coteaux hills and the Pech David promontory) or of channeling the predominant wind (e.g., the tributary valleys of the Garonne River, Ariège in the south and Hers in the northeast, and the hills of Montaudran and Jolimont).

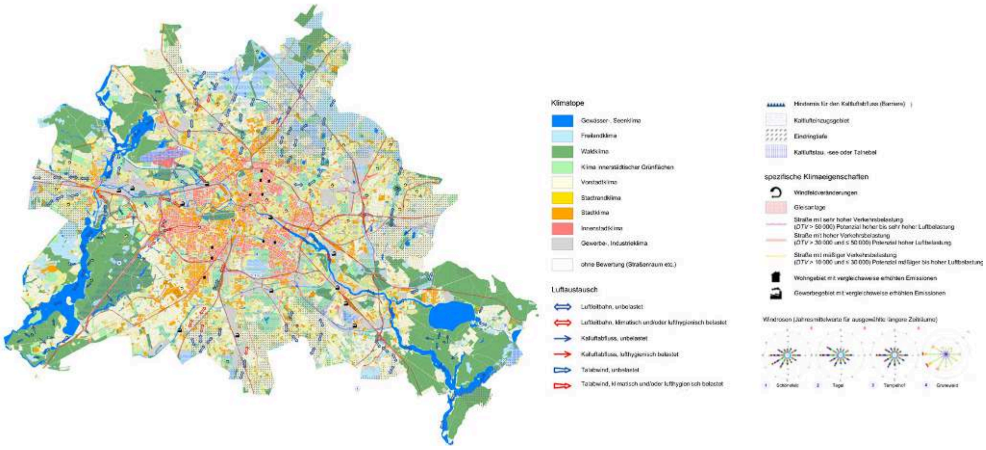
29 Previous maps and specific recommendations in terms of urban planning were collected in a set of recommendation guidelines edited by the local authorities of the Toulouse Metropole for its internal services and urban developers/promoters entitled "Taking into account the climate in the construction of tomorrow's metropolis"[6]. This set of guidelines is composed of five sections. In the first two sections, several keys to a theoretical understanding of global and local climatic issues, as well as a microclimatic diagnosis of the territory, are presented. Detailed recommendations are organized in a third section according to adaptation levers (e.g., vegetation, shade, urban forms, urban materials and surfaces, and water management) and the previously presented geographical sectors (i.e., the historic center, the *faubourgs*, the city centers of the municipalities adjacent to Toulouse, the commercial and activity areas, and actions at the metropolitan scale). There is a section presenting the monitoring tools used to study the urban climate of Toulouse, in particular, the urban atmospheric network composed of ~70 meteorological stations (Dumas et al., 2021). Finally, a list of 14 questions associated with the urban microclimate, and prerequisites to any development or urban planning project closes the Guideline.

5. Discussion of the graphic semiology for the UC-Maps

30 Cartographic representations strongly depend on the disciplinary background of the researchers involved in the data analysis and cartographic development. Urban climatologists in Germany have been working on this subject since the 1970s and have actively contributed to international dissemination in terms of methodologies and standards. Accordingly, the VDI 3787 directives published by the Association of German

Engineers in 1997 and subsequently updated in 2015 have become an international benchmark in the field of urban climate maps that has inspired many other cities and researchers around the world (Ng and Ren, 2015). If we take the UC-Map of Berlin as a European example (Figure 10), we can categorize the arrangement of information into two large groups: representations of the urban morphology according to its typology (the city center in red, town in orange and yellow, and commercial areas in grey) and representations of the temperature and air exchanges (arrows).

Figure 10. Climate analysis of Berlin (general view, scale 1:265,000; source: Senate Department for Urban Development and the Environment, Environmental Atlas). For a detailed legend please consult VDI 3787, pg31.



31 The same colors are used to highlight areas of high heat intensities and fairly dense or very mineralized urban areas. The colors orange/red/gray are used to indicate UHIs and correspond to the city center (red), other urban areas (orange), and commercial and industrial areas (gray). The wind speed and direction are represented by arrows, dots, and wind roses. Like many other urban planning maps, the coverage and spatial resolution of the climate and urban information are adapted to the scale of the urban planning exercise. From regional to city maps, this scale ranges from 1:100,000 to 1:5,000. The difficulty lies in adjustments between data at the correct spatial resolution and the correct spatial coverage. The very dense graphic representation and the superposition of visual variables to qualify strategic areas from a microclimatic point of view do not correspond to French cartographic standards in operational urban planning. The MApUCE project therefore included an important focus on graphic semiology for urban climate spatial representations.

5.1 Visualization choices for the thematic analysis climate maps of Toulouse

32 The climatic map design phase took place after several working sessions involving urban climatologists, urban geographers, and cartographers from both the institutional partners (the Toulouse Metropole Environment Department, the Urban Regulation Department, and Aua/T) and from the GEO-VISU research collective. The development of this type of multi-thematic map involves a significant amount of complexity, which is often encountered in the process of map production to support local authorities in territorial management. Various studies (Fairbairn, 2006; Jegou, 2012) have shown that

the complexity of a map is measured through the articulation of two types of complexity. First, readers are confronted with the visual and functional complexity of the map. The readers carefully read the map, observing the shapes, textures, and colors. Then, by interpreting the symbols and comparing them to their knowledge and goals, the readers move on to the intellectual and functional complexity of the map. When producing a thematic map, these two types of complexity do not follow a linear progression but are interwoven with each other resulting in a map whose main function is to correctly and easily communicate information. It is therefore important, when the information to be represented is dense, to support readers in the construction and visual perception they have of this geographic or climatic information.

33 For Toulouse, we proposed a visual organization used in the urban planning agency that has proven to provide a good understanding of geographic information. The composition of the UTCI and UHI analysis maps (Figures 3 and 6, respectively) follows three layer maps that show the data required for the final map. This makes it possible to more precisely discern the overall form of the spatial information, which could otherwise be difficult to read with the superimposition of multiple types of data. In Figure 3, three types of data are shown: the dense built-up area, the thermal stress levels during daytime, and the green and blue corridors. Below, a synthesis map superimposes these three data types whose graphic semiology is changed compared with their representations in the individual layer maps. Green corridors, generally shown in green, are depicted in white with a transparency effect to be more readable in the superposition. Highly urbanized areas are divided into two classes: commercial areas in light gray and dense buildings in dark gray. Sparse urban areas are not shown here because they do not represent a strategic area from an artificial surface point of view. However, sparsely built-up areas that contribute to the thermal regulation zones appear in the representation of the green and blue corridors. Finally, the heat stress is divided into three major classes (no heat stress, moderate heat stress, and high heat stress), one of which (moderate heat stress) includes intensity subclasses (low, medium, and high). Three colors close to the same colorimetric spectrum are used for the heat stress: a beige gradient for the absence of heat stress, a red gradient for moderate heat stress, and a purple gradient for high heat stress. The UHI thematic analysis map (Figure 6) is mostly based on the same organization and semiology. The three layer maps required for the final map are shown individually: there are regions with dense built-up areas and commercial areas, the nighttime UHI data, and potential areas for future urbanization as noted in the Master Plan. A color gradient (from red to yellow-ocher) indicates the UHI intensities grouped into three classes for the nighttime conditions (3 am–6 am local time): from 0°C to 2°C (yellow-ocher), from 2°C to 3°C (orange), and from 3°C to 6°C (red). Bright yellow was not used because this color exceeds the level of our colorimetric perception.

5.2 Visualization choices for the maps of the strategic areas

34 The proposed maps (Figure 9) are at the interface between a mapped descriptive representation of the geographic information and a sketch-diagram that is an explanatory and educational representation of the geographic information. The objective of this type of representation is to present a map offering an efficient spatial synthesis of areas of interest to show the importance of thermal stress, UHI

phenomena, or wind conditions. For the UHI, the representation revolves around two pieces of information: the UHI exposure level in degrees Celsius and the thermal regulation zones (e.g., relief, vegetation, and effects of the Garonne River). Such a map is accompanied by an explanatory insert that complements the graphic information with a textual description. The thermal stress map includes four important pieces of information from the thematic map: the effect of the Garonne and Hers-Mort rivers, which ensure natural air cooling of the surrounding areas; the cool zones in sparsely urbanized areas (e.g., the Bouconne forest and Pech David); and the areas of discomfort and freshness in urban spaces, where the extent of the area of high discomfort corresponds to the limit of the suburban area.

35 This type of representation is based on the researcher's expertise and follows, in this sense, the content of the thematic analysis maps while incorporating local urban entities such as the *octogone*, *faubourgs*, or centers of the peripheral municipalities. For the sake of efficiency and support for the implementation of a recommendation guideline, such a map cannot be presented alone. Its construction is based on some important elements: the sketch-diagram should build in the analysis maps diagnostic, the size of the composition must be large enough to show the strategic areas; the legend, which is the most important element of the composition, needs to guide the reader through a clear organization of the major elements; and finally, it seems important to accompany the map with a written description so that the whole is as autonomous as possible.

6. Final Discussion

36 Nowadays in France we have modeling tools and data on land use and description of the urban surface that are sufficiently detailed to create geographical and spatial microclimatic diagnoses (of heat stress, urban heat island, ventilation). This is important so that any city can, if it has the will, address the issue of adapting to rising temperatures in its territory.

37 Drawing on the international experience of countries such as Germany, China and Japan, in this paper we propose a methodological protocol for the production of climate maps tested in and for Toulouse, as well as a reflection on the graphic semiology adopted on this occasion. These maps constitute both a microclimatic diagnostic tool for the urban territory and a potential method to provide a regulatory translation of the issues identified (a recommendations map) able to compensate for the absence or weakness of quantitative and/or spatialized approaches to the urban microclimate in urban planning exercises in French cities.

38 From a methodological point of view, several propositions are new contributions to the field, such as the nature of the strategic areas identification, directly from numerical modeling instead of surface information discussed in section 3.2, and the description of several meteorological situations (LWT approach) that allows to catch all the atmospheric complexity, in particular related to wind conditions. Finally, the frequency approach in the spatial analysis (section 3.3), instead of the mean average, has the advantage of being easy to communicate to stakeholders and the public. Indeed, it is easier to understand that the most frequent situation matters. A phenomenon that often occurs in the targeted areas will have more impact than information based on average data that is not actually experienced. This approach also makes it possible to

maintain more spatial heterogeneity than an averaging approach, which spatially smooths the data. This strategy, based on the LWT approach, and the identification of persistence areas, was key to communicating the climate diagnosis in an understandable way to our operational collaborators. This study also aims to make a first contribution on the reflexion about how to represent and visualize the climate data. For that, cartographers from operational and research spheres were implicated in the process. The originality of the Toulouse Metropole climate maps, compared to those found in the cited literature, relates to the use of organization in layer maps, a fairly frequent mode of representation in French urban planning mapping. These maps gradually lead the reader to understand the synthesis map, bringing together all the data necessary for its construction. The synthesis map does not always use the colors of the layer maps; however, the reader can quickly identify the shapes seen in previous maps and incorporate that information. These layer maps together therefore have a stronger visual impact than that of a complex legend as discussed in section 5.

39 It is appropriate to question the conditions and limitations of the replicability of this protocol for other French cities. Surveys carried out with the network of urban planning agencies of the FNAU[7] in 2015 as part of the MApUCE project, and then in 2020 as part of the PAENDORA project, indicate that the integration of climate and energy issues into urban planning remains an important issue for most urban planning professionals. Despite the availability at the national level of both broader and more precise urban, climate, and energy data (resulting in particular from recently facilitated access in the form of open data), these professionals continue to encounter difficulties in dealing with and integrating these data into projects they are leading or participating in. The lack of directly exploitable data and the absence of simple tools and accessible methods are the main issues reported, which translate concretely into various problems, including a scarcity of georeferenced data, unsuitable resolution, heterogeneity of the data, restricted access, and irregular updates. Inadequate or lacking in-house skills are combined with a lack of knowledge concerning the tools available (including the MApUCE Orbisgis database, which still has limited visibility), making it difficult to incorporate research methodology studies that are still not sufficiently established and have not been systematized.

40 Not all territories considering the impact of climate hazards have partnerships with expert climate researchers nor do they necessarily have strong in-house expertise in this area, even if an increase in the climate skills of urban actors has been observed. The Toulouse experiment is unique in this regard in that there is an established partnership spanning several years between the community and a multidisciplinary research team. Even though these conditions are not systematically replicable, existing or future research groups could incorporate the findings of this study and offer similar expertise within the framework of their relationships with local authorities.

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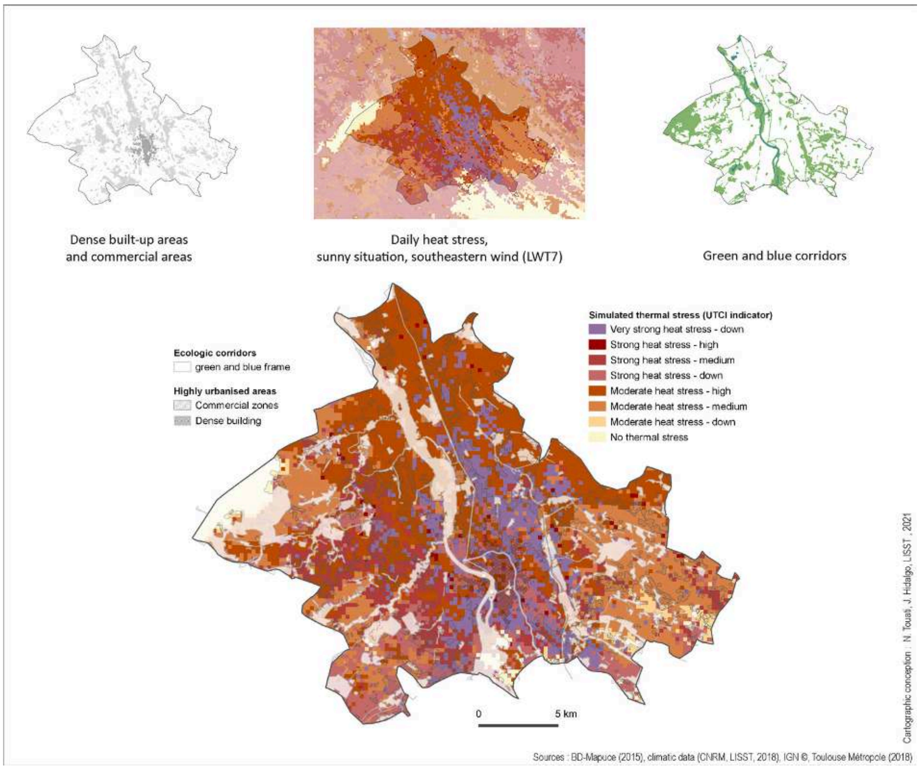
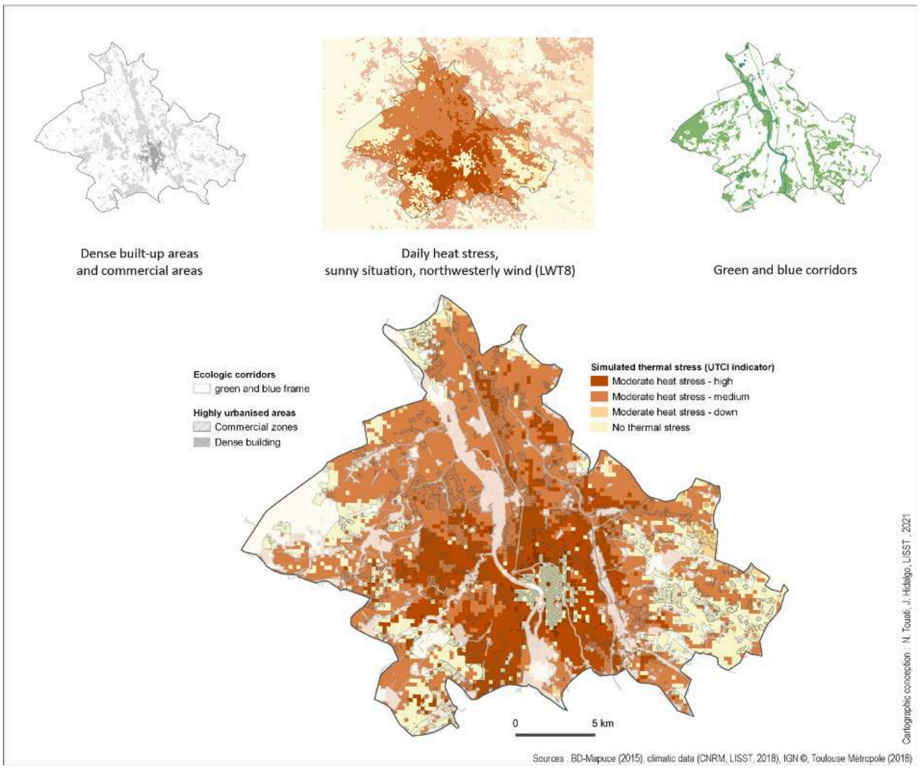
APPENDIXES

Appendix 1: Spatial discontinuities of the mean wind speed

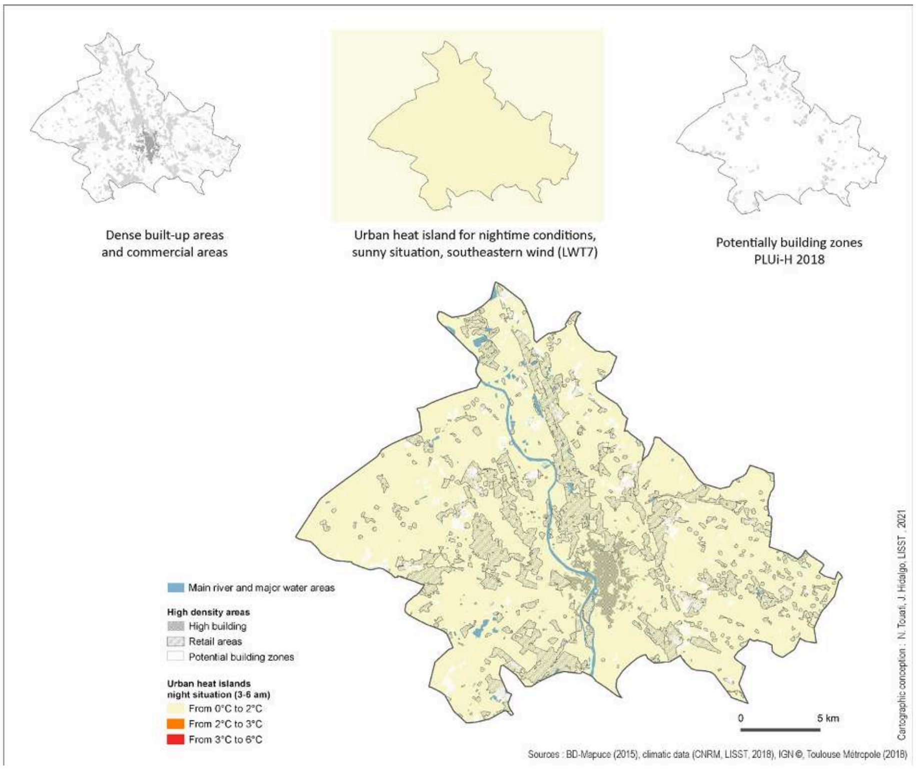
In geography and thematic analyses, spatial discontinuities are defined as the separation between two adjacent units. This concept was first mentioned by Roger Brunet in 1967 but was also discussed and developed by other geographers (Hubert, 1993; Gay, 1995; François and Grasland, 1997). For this study in the context of the atmospheric data, the representation of discontinuities is based on one continuous indicator, the wind speed in meters per second. First, the localization and measurement of disparities between classes was calculated using the R package “Cartography” developed by Lambert and Giraud. For each border, the ratio or the difference of the polygon values was calculated on both sides. In this case, the calculated discontinuities are “static,” i.e., a rupture in space due to local and durable phenomena. Such discontinuities may also be related to anthropic phenomena such as urbanization or urban spread. The values to be represented are continuous (meters per second) and are represented using a color gradient (from orange to red).

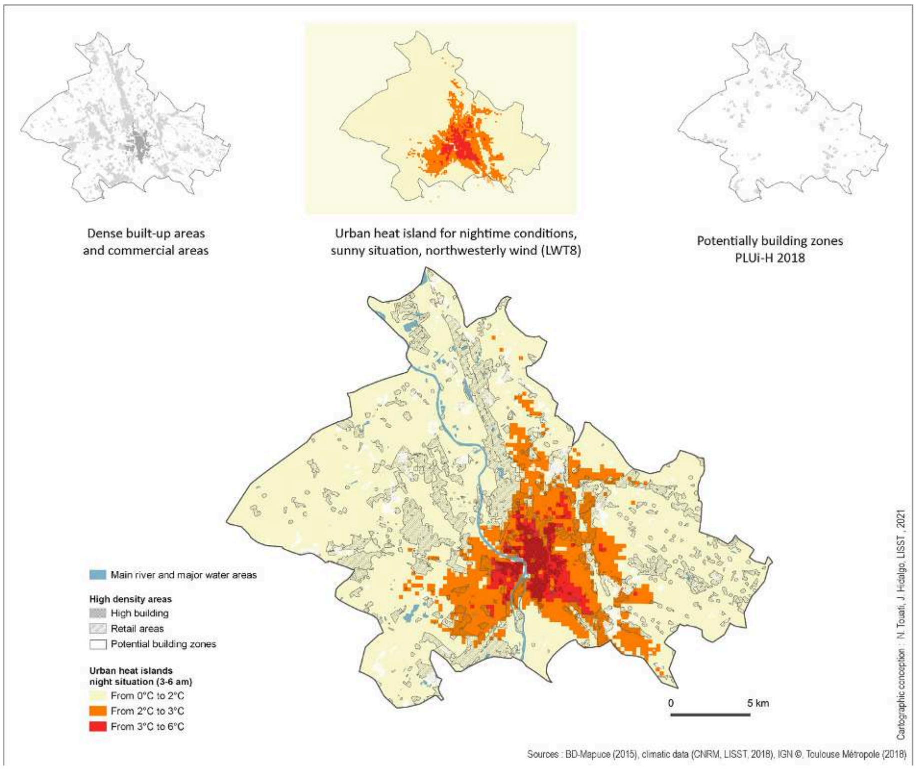
Appendix 2: Thermal stress analysis maps for local weather types 7 and 8





Appendix 3: Analysis maps for the nighttime urban heat island for local weather types 7 and 8





NOTES

1. « The standard describes how to present and to evaluate climatologically relevant facts for cities in maps. Further, it specifies how to use the deduced planning recommendation maps. On local and regional levels these maps are basically for zoning plans and for local development plans. In times of climate change and environmental justice these maps gain more importance. The scope of this standard extends from urban to regional planning. This standard supports the user to evaluate the thermal and air quality situation and the effects of planning and development measures. » https://www.vdi.eu/nc/guidelines/vdi_3787_blatt_1-umweltmeteorologie_klima_und_lufthygienekarten_fuer_staedte_und_regionen_/)

2. https://www.researchgate.net/publication/283806656_Final_Report_of_Hong_Kong_Urban_Climatic_Map_and_Standards_for_Wind_Environment-_Feasibility_Study

3. http://www.meteofrance.fr/climat-passe-et-futur/impacts-du-changement-climatique-sur-les-phenomenes-hydrometeorologiques/changement-climatique-et-canicules

4. http://www.utci.org/

5. http://www.utci.org/cost.php

6. https://www.toulouse-metropole.fr/documents/10180/26954502/Guide_ICU_priseencompteclimaturbain+2021.pdf/d71ceaa2-8839-4c83-8669-cdc85545b675

7. The National Federation of Town Planning Agencies (La Fédération Nationale des Agences d'Urbanisme) is an association that structures and coordinates a network of the approximately 50 town planning agencies present in France.

ABSTRACTS

In France, the integration of climate and energy issues in the spatial planning tools of local authorities is compulsory for cities with more than 20000 inhabitants. Through the example of Toulouse Metropole, the interdisciplinary work here presented make use of the available geographic and climatic data to perform spatial microclimatic diagnostics and its translation into recommendations to address thermal summer comfort. Analysis maps and strategic maps for daytime and night time are presented for thermal and aeraulic analysis taking advantage of available numerical simulations at 250x250 m, one year of duration and local weather type classifications. A three years long collaboration with the local authority and the urban agency allowed the co-construction of the cartographic protocol and the publication of an Atlas as well as a set of guidelines. Collaboration with a network of French cartographers allowed original propositions on graphic semiology as visual organization, the choice of urban and geographical information to be combined with the climatic information or a proposition of a new UTCI colorimetric spectrum.

L'intégration des enjeux climatiques et énergétiques dans les outils de planification du territoire en France est obligatoire pour les villes de plus de 20 000 habitants. A travers l'exemple de Toulouse Métropole, les travaux interdisciplinaires ici présentés s'appuient sur les données géographiques et climatiques disponibles pour réaliser un diagnostic spatial microclimatique et sa traduction en recommandations pour aborder le confort thermique d'été. Des cartes d'analyse et des cartes stratégiques pour le jour et la nuit sont présentées pour l'analyse thermique et aéraulique en tirant parti des simulations numériques disponibles à 250x250 m d'une durée d'un an et d'une classification des types de temps locaux. Une collaboration de trois ans avec la collectivité et l'agence d'urbanisme a permis la co-construction du protocole cartographique et la publication d'un Atlas et d'un guide à destination des chefs de projet et promoteurs privés. La collaboration avec un réseau de cartographes français a permis des propositions originales sur la sémiologie graphique, sur l'organisation visuelle, le choix d'informations urbaines et géographiques à combiner avec les informations climatiques ou la proposition d'un nouveau spectre colorimétrique pour l'indicateur de stress thermique UTCI.

INDEX

Mots-clés: visualisation climatique, aménagement du territoire, cartographie appliquée, cartes climatiques de l'environnement urbain, îlot de chaleur urbain
Keywords: climate visualization, territorial planning, applied cartography, urban climatic maps, urban heat island

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