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1. Introduction

1 Urban areas are particularly sensitive to climate issues. Urbanization results in the artificialization of surfaces, which has a strong influence on living conditions, particularly in terms of public health, energy consumption, and the thermal degradation of urban spaces. Accordingly, land-use modifications, urban roughness, and anthropogenic activities in cities modify the local climate, generating a so-called urban microclimate (Oke and Aigbavboa, 2017). This modification is evident in all meteorological variables; however, in terms of the temperature, this change results in the formation of an urban heat island (UHI), specially during nigth-time. Local microclimatic issues combine with larger scale climate evolution to create composite risks during heat wave episodes. Indeed, UHIs likely enhance the negative impacts of heat waves in urban areas (Li and Bou-Zeid, 2013). This makes adaptation to climate change a new challenge for cities worldwide, regardless of their location or size.

2 Cities in economically developed countries are making efforts to integrate climate issues into urban planning and development; such efforts include the development of cartographic analysis tools (Hidalgo et al., 2018). For cities situated in developing countries, here referred to as southern cities,[1] it is sometimes difficult to make adaptation a priority in urban planning, given the multitude of traditional urban challenges being faced by these cities, including massive poverty and high population growth. The consideration of climate adaptation in urban practices is further hampered by the rapid and informal growth of such cities, as well as the lack of climatic expertise within urban planning services. This is primarily due to a notable lack of urban and climatic data in these regions and the inadequacy of the available financial and human resources (Emmanuel, 2005).

3 It is therefore crucial to explore adjustments to the specific contexts of some of the solutions and tools designed in northern cities for use in southern cities. Recently, urban climatic maps have been developed in several cities worldwide, such as Kassel in Germany and Arnhem in the Netherlands (Ng and Ren, 2015; Ren et al., 2011). In collaboration with the local authority, such cartographic tools allow both a microclimatic diagnosis of an urban territory to be obtained and recommendations for subsequent regulatory translations of the identified issues to be proposed. In addition, the entire process of co-producing climatic knowledge can constitute an important lever to insert climate adaptation agendas into urban policies (Mhedbhi, 2021). This can be particularly important in southern cities such as Tunis in Tunisia, where there is a real lack of easily understandable diagnostics in terms of urban climatology.

4 The Urban Climatic Map (UCMap) framework generally consists of two main components (Ren et al., 2011). First, an ensemble of maps allows the physical state of the urban climatic environment to be diagnosed by considering the topography, urban morphology, land use, and local climate data of the study area. The combination of these data enables a spatialized study of their effects on thermal comfort and/or air temperature and the identification of different homogeneous areas from a microclimatic point of view. In general, this set of maps is called an Urban Climatic Analysis Map (UC-AnMap). Second, based on the analysis obtained using the UC-AnMap, guidelines can be proposed for urban planning and development scenarios. Similar areas are grouped into homogeneous zones for which recommendations are formulated to better adapt them to the climatic constraints to which they are exposed. The challenge is to consider the territorialization of the proposed recommendations. This requires close collaboration with local urban actors to effectively inform them of the urban microclimatic conditions so that they can account for them in planning projects in their territories. In general, this synthetic map is called the Urban Climatic Recommendation Map but here we will use the terminology of strategic maps as defined for Toulouse by Hidalgo et al. (2022).

5 There are two different approaches to developing UCMaps, the choice of which is modulated, essentially, by the researcher's area of expertise. The first approach relies primarily on urban data (land use and urban morphology data) to project the potential impacts of an urban surface on its surrounding atmosphere. This approach has been historically used by researchers with a background in architecture and/or geography, mainly through atmospheric observations and geographic information system (GIS) techniques such as those used by the German, Japanese, or Hong Kong research groups (Ng and Ren, 2015). This approach is based on the classification of the urban surface

using different methods considering the topography of the study area, the urban morphology, the land use combined with climatic data, and a heat stress indicator. The combination of these data allows a spatialized study of their effects on thermal comfort to be conducted, through the classification of the urban space into different climatopes. [2] This approach assumes that microclimatic conditions are primarily surface driven. In recent years, through interdisciplinary collaborations with atmospheric modelers, a second approach has emerged that relies more on meteorological parameters (e.g., air temperature, heat stress indicators, and wind) to identify strategic areas. In this method, the topographic and urban surface information is mobilized both upstream, as input data in numerical simulations, and downstream, to understand the microclimatic phenomena. This approach permits the diverse local weather situations to be explored (Hidalgo and Jougla, 2018) when considering recommendations. The spatial resolution of the identified homogeneous areas is coarser than that used with the climatope approach. This approach is therefore complementary to the climatope approach because it allows an intermediate stage in which it is possible to identify strategic areas that have a meaning and a precise interlocutor from the point of view of local territorial management (Hidalgo et al., 2022).

6 Some southern cities have already developed their own climatic maps; these include two Brazilian cities, Salvador (Andrade et al., 2015) and Campinas (Shimomura et al., 2015), Manizales in Colombia (Roncancio and Stewart, submitted), and Ho Chi Minh City in Vietnam (Katzschner and Burghardt, 2015). In general, such studies focus on heat stress and urban ventilation; these issues are very important in tropical and subtropical regions because the air quality and environmental thermal comfort strongly depend on the ventilation patterns. In these study cases, the climatope approach was adopted. In the case of Campinas, the methodological approach used a large set of data, including the physical characteristics of the land occupation and a topographic description combined with the climatic conditions (e.g., air temperature, humidity, and wind speed and direction). Using computational fluid dynamics models and GIS tools, a decrease in the wind speed with urban growth was demonstrated. In Manizales, the climatic analysis was based on a rich meteorological weather station network that enabled the identification of valley breezes, which constitute a natural source of cooling for the city. For Salvador, other observational strategies and mobile measurements were used to identify the thermal comfort conditions along four transects through the city.

7 On the African continent, as far as we know, no city has developed its own UCMap. This paper therefore focuses on the Greater Metropolitan area of Tunis in North Africa to test the adaptability of the approach developed for Toulouse of combining urban data and mesoscale numerical simulations to identify and map strategic areas for intervention. The study was developed in the framework of a PhD research project and is the result of a collaboration between French laboratories and the local Urban Planning Agency in Tunis (AUGT). The urban climatic maps developed in this study are based on numerical simulations using an atmospheric model of a heat-wave event that occurred in Tunis in July 2019.

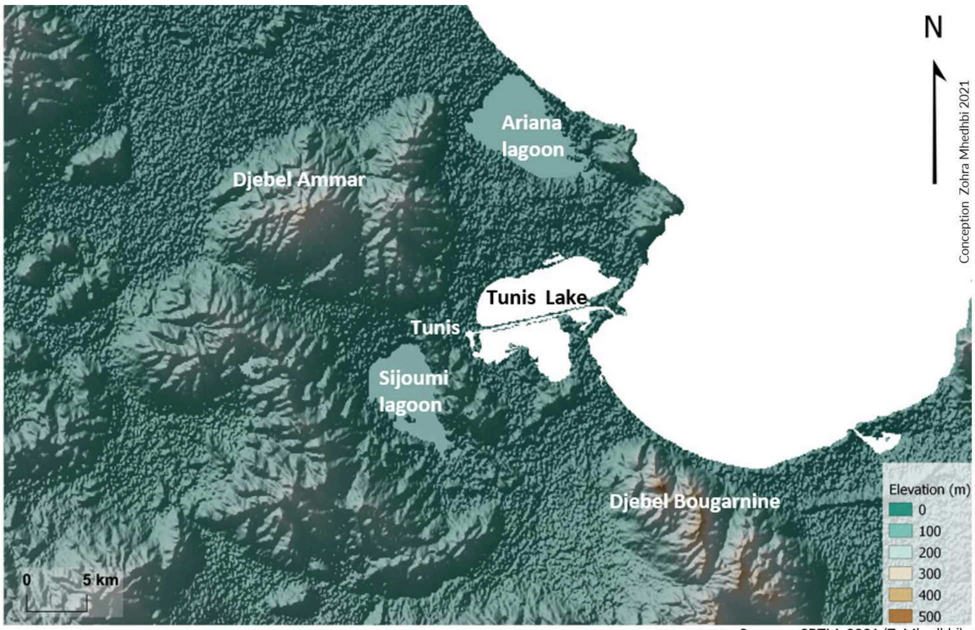
2. Tunis as a case study of an African city

8 Tunis is the capital of Tunisia. It is located along the coast of the Mediterranean Sea. In terms of climate, the greater metropolitan area of Tunis belongs to the Mediterranean

Basin, which has been identified by climatologists as a “hot spot for climate change” (Giorgi, 2006). Climate models indicate a clear increase in temperature that should continue throughout the 21st century, likely at a rate higher than the estimated global average (Agoumi, 2003). The region of Tunis has experienced several exceptional weather events in recent years. During the 2003 heat wave, the city experienced a period of 59 consecutive days with maximum temperatures above 35°C. In September of the same year, the city experienced a cumulative rainfall of 186 mm in 24 h, which is high compared to the annual average rainfall of approximately 456 mm $year^{-1}$ (World Bank, 2011).

9 The Greater Metropolitan area of Tunis covers a surface area of approximately 2560 km^2 and has a population of approximately 2.6 million inhabitants. This region presents a complex environment consisting of basins, plains, lakes, lagoons,[3] and a gulf that is over 200 km long. This region occupies a low coastal plain that is dotted with hills. The highest reliefs are Djebel Boukornine in the southeast (507 m) and Djebel Ammar in the northwest (325 m) (Figure 1).

Figure 1. Main geomorphologic characteristics of the Tunis region.



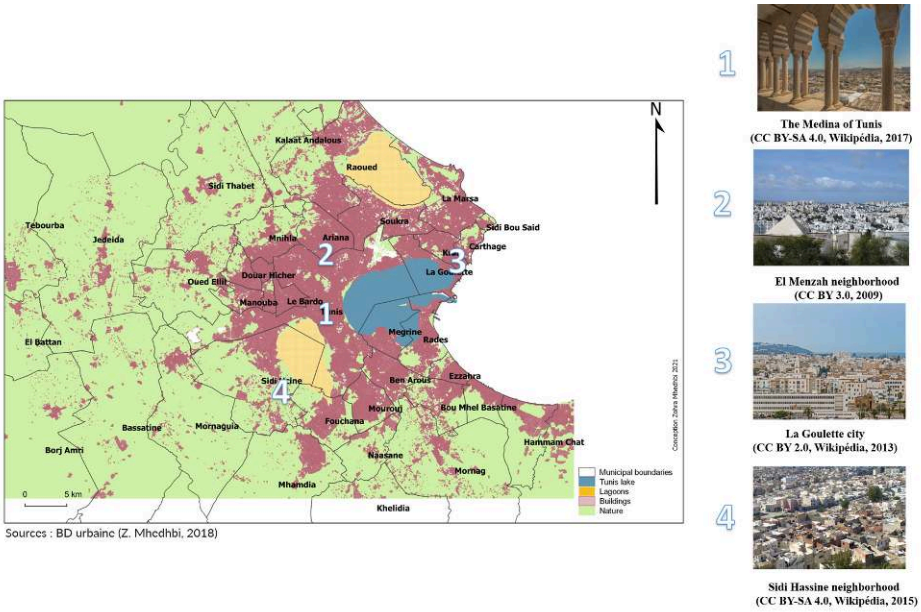
Sources : SRTM, 2021 (Z. Mhedhbi)

10 Administratively, this region is divided into four provinces (Tunis, Ariana, Manouba, and Ben Arous). The territory is composed of 38 communes (Figure 2); however, there is no institution working at the metropolitan level. The AUGT, a technical body, is the only operational actor working at the regional scale. It is a corollary of the central power, working under the supervision of the Ministry of Equipment, Housing, and Land Management. Accordingly, it is this ministry that has legal authority in terms of planning and urban development at all levels via its regional delegations. Local authorities are just beginning to implement the decentralization process following the 2011 revolution; however, this process is not yet effective. Therefore, these authorities have a poor level of participation in decision-making processes.

11 The urban structure of the city is organized around the medina and the colonial city (Figure 2). The medina was built in the 7th century. This urban complex contains a very

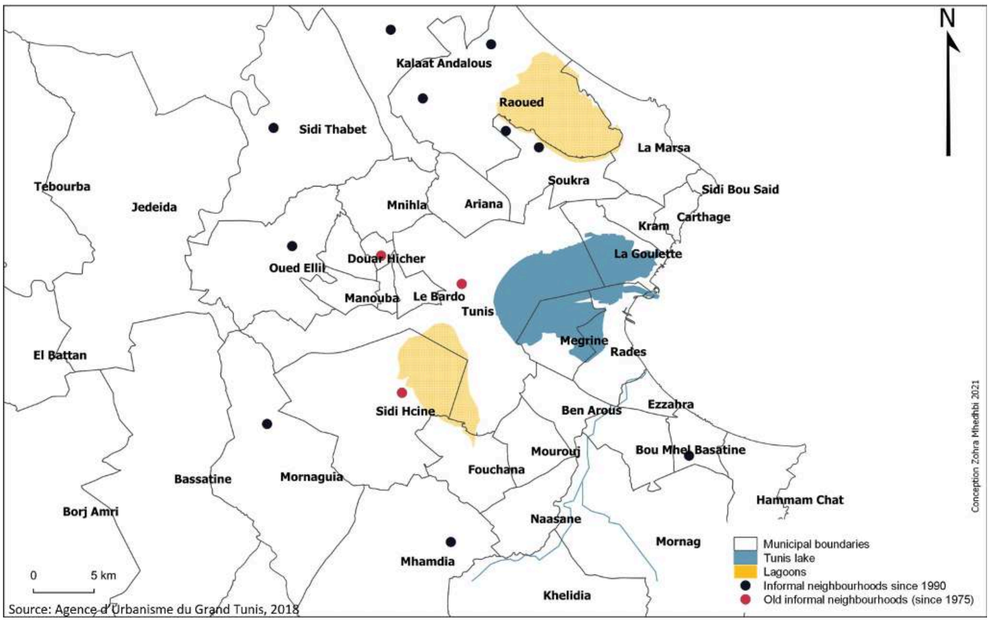
rich architectural heritage, composed of religious buildings of utmost importance and multiple monuments of Arab-Muslim architecture. A northern zone, characterized by a high standard of housing, benefits from a good local network of dynamic urban centers in the districts of El Manar and El Menzah, with fairly commercial areas. The northeastern zone next to traditional central municipalities (e.g., La Goulette and La Marsa) benefits from contributions from the projecting banks of the lake. The southern zone, renowned for its industrial functions, remains without a regional urban center, despite its old central network (e.g., Hammam-Lif and Radès). The western zone is marked by informal urbanization such as the Sidi Hacine neighborhood.

Figure 2. Land use map and examples of districts making up the urban structure of Tunis.



12 Given the demographic and economic growth in the greater metropolitan area of Tunis, both regulated and informal urban sprawl have developed. Unplanned urbanization produces vulnerable urban spaces because these districts are often located in flood-prone areas, built with precarious materials, and are less well served by infrastructure and services than regulated districts (Legros, 2003). In the absence of effective building controls, the city has tended to expand at the expense of the surrounding agricultural plains. The buildings have spread out over hills that were previously cultivated and wooded (Barthel, 2003). The urban fabric of these informal settlements generally takes the form of clustered neighborhoods characterized by contiguous housing and the existence of a few informal businesses created by inhabitants (Figure 3). According to AUGT experts,[4] this is the most common form of informal urbanization. It is also common for informal housing to develop around major roads with better access to urban centers.

Figure 3. Informal neighborhoods in Tunis, adapted from the local Urban Planning Agency of the greater metropolitan area of Tunis.



13 In addition to this issue of major informal urbanization, there are multiple obstacles in Tunis hindering the emergence of climate issues in urban planning. First, this region is characterized by a lack of data necessary to describe urban surfaces. Even when such data exist, they are scattered among different administrations and are difficult to access, even for research purposes. Indeed, Tunisian institutions, both academic and professional, are currently facing a shortage of urban data stemming from a lack of financial and human resources, as well as the dispersal of data production efforts in different organizations. Each institution works on the construction of its own database without coordination or consolidation of the produced data.

3. Methodology

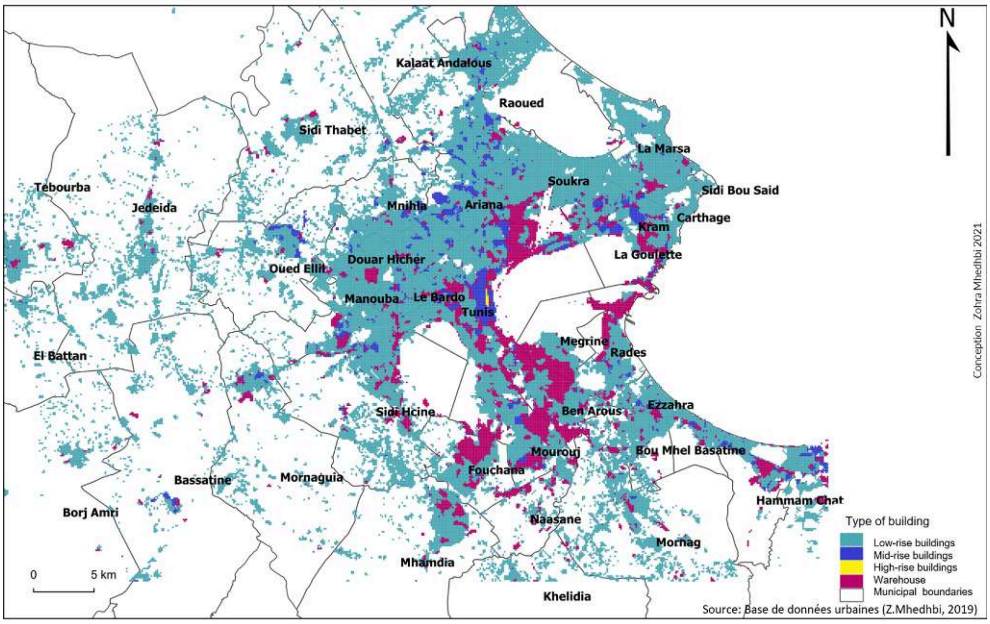
14 The UCMap of Tunis was built based on the daytime and nighttime thermal conditions during a heat-wave event in July 2019; this event is thought to be representative of the meteorological conditions relevant to urban heat issues. Numerical simulations using a mesoscale atmospheric model provided the fine-scale spatial and temporal meteorological information. Given the significant lack of urban data in Tunis, it was necessary to develop an ad hoc urban database to provide the necessary surface input parameters for the climatic simulations.

3.1 Urban database

15 The construction of the urban database of the Greater Metropolitan area of Tunis heavily relied on local climate zone (LCZ) typologies (Stewart and Oke, 2012). The combined use of the LCZ classifications and other data, such as open source data (Open Street Map; Mooney and Minghini, 2017), data collected from AUGT, and the results of remote-sensing processing to detect the different vegetation strata, allowed us to build a land use database. In addition to the land use data, architectural and morphological

characteristics of the territory were also required for the climate modeling step. Accordingly, a social media questionnaire was designed to collect architectural data on the basis of voluntary citizen participation. This questionnaire focused on the following architectural parameters: the height of buildings, roof types, building materials, and window descriptions (Mhedhbi et al., 2019). This work contributes to the methods proposed to collect World Database and Access Portal Tools (WUDAPT) Level 1 (Ching et al., 2019) architectural data in any city worldwide and, more particularly, in cities where there is a real lack of data, such as southern cities. More generally, the willingness to use financially accessible data and tools has the advantage of making the method easily reproducible in other territories. Figure 4 shows an example of the building typology in the greater metropolitan area of Tunis, one of the indicators that was constructed based on a combination of the questionnaire responses and scientific literature. Low-rise buildings are dominant in the Tunis metropolitan area. Mid-rise buildings are primarily located around the Lake of Tunis and northwest of the agglomeration. The purple regions in the figure correspond to industrial zones and are primarily located around the Lake of Tunis. The urban database contains information concerning the land use (vegetation, buildings, and water), building morphology (typology, building use, construction period, and other indicators describing the building form), and the described architectural details. The methodology is extensively described in Mhedhbi (2021).

Figure 4. Building typology in the greater metropolitan area of Tunis (from Mhedhbi, 2021).



3.2 Urban microclimate simulation

16 The microclimate simulation relies on the mesoscale atmospheric model Meso-NH (Lac et al., 2018; Lafore et al., 1998). This atmospheric model represents all the atmospheric variables (e.g., air temperature, humidity, wind, pressure, and clouds) and their interactions in a three-dimensional grid mesh. The vertical resolution varies from 10 m near the ground to 500 m in the upper atmosphere at an altitude of 18 km. There are 60

layers in total. The horizontal resolution ranges from 8 km for the entire western Mediterranean Basin to 125 m for the greater metropolitan area of Tunis. This enables simulations of the atmosphere at a resolution relevant to urban planning needs.

17 Below the atmospheric grid meshes, it is necessary to represent the various surfaces (sea, lakes, countryside, and city) and their impacts on the overlying atmosphere (through energy and water vapor exchanges and the decrease in the wind speed due to friction at the surface). This is done using the numerical surface scheme SURFEX (Masson et al., 2013), which describes all four different types of surfaces and their interactions with the underlaying atmosphere. It is essential with a coastal city such as Tunis to consider interactions with the sea and the surrounding topography to properly simulate the local microclimate. The Town Energy Balance model developed by Masson (2000) was used for the urbanized areas. The model was further refined with respect to different urban processes: a surface boundary scheme was used to derive climatic variable profiles within the urban canyons (Hamdi and Masson, 2008) and a better description of interactions between the urban vegetation and artificial surfaces was included (Lemonsu et al., 2012).

18 The simulation concerns a seven-day heat wave event that took place between July 7th and July 13th, 2019. The period between July 9th and July 13th was used for the climatic analysis to allow the model sufficient time to reach atmospheric stabilization (a two-day spin-up period).

3.3 Cartographic work

19 The numerical simulation provided the parameters of interest for the urban climatic diagnosis, such as the air temperature, the Urban Thermal Climate Index (UTCI; Bröde et al., 2012), and the wind speed. These parameters were stored at an hourly frequency in the urban canopy at a height of 2 m. The other parameters, such as the wind direction, are available at a specific height (10 m) above the urban canopy.

20 The UC-AnMap focused on the daytime and nighttime thermal stress analysis, and the following phenomena were characterized: the daytime maximum heat stress period, sea-breeze development, and nighttime UHI. The UTCI, air temperature at 2 m, and wind speed and direction were analyzed for the daytime and nighttime periods using a frequency approach. The most frequent level of a parameter per pixel was calculated to obtain a single map for each phenomenon. Because the UTCI values were within the range of the moderate to extreme heat stress levels, and to obtain an easily identifiable spatial variability, we did not adopt the scale of the standard produced in the framework of a European Cooperation in Science and Technology (COST) Action, which has fairly wide classification ranges for the cartographic work; this scale was only used for the qualitative analysis (http://www.utci.org/cost.php). Instead, the levels of thermal stress were subdivided from high to very high into three categories: low, medium, and high, following the work done in Toulouse by Hidalgo et al. (2022).

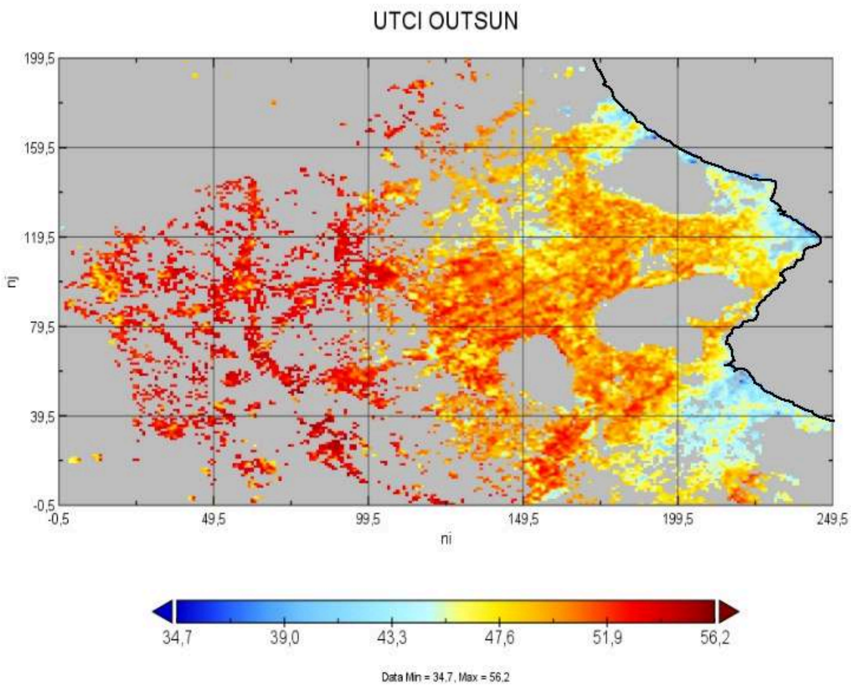
4. Results

4.1 Description of a hot day in Tunis

21 Because little variation was noted for all the parameters between the different days of the heat wave, July 9th, 2019, was chosen as the representative day and was used to characterize the temporal evolution of the microclimatic phenomena on a typical day of this heat wave. All times are given in local time.

22 The simulated microclimatic conditions show that the air temperature increased during the morning and that the diurnal heat stress reached a value of approximately 46°C at 9 a.m., which corresponds to the extreme heat stress level according to the UTCI scale. The UTCI value continued to increase to a maximum of 56.2°C at 2 p.m. (Figure 5). The heat stress level remained extreme until 5 p.m. (45.9°C), and then around 8–9 p.m., it decreased to 32.9°C, which corresponds to a moderate level of heat stress.

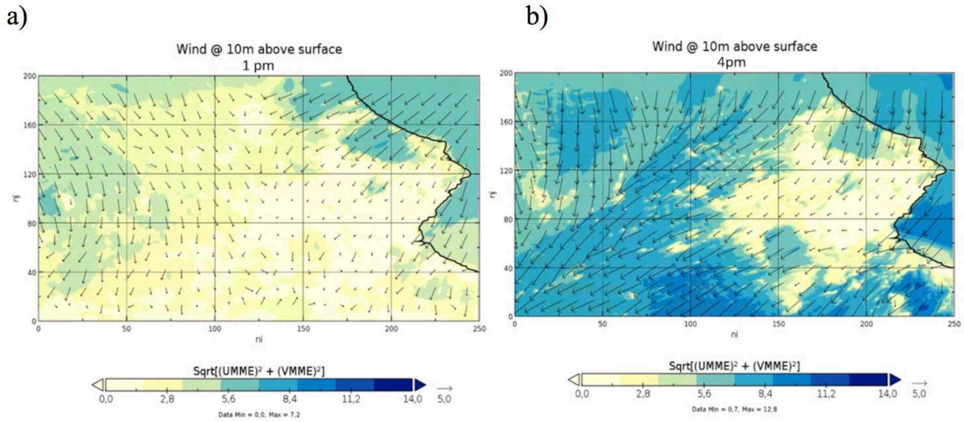
Figure 5. Map of the Urban Thermal Climate Index (UTCI) for July 9, 2019, for a person outside in the sun at 2 p.m. local time (Simulations, de Munck, 2020).



23 During this diurnal thermal dynamic, the air above the land heats and rises. Because the land is warmer than the neighboring water, the air that was situated at low levels on land is replaced by cooler air coming from the sea. As the sea breeze penetrates inland, it has an important influence on the microclimate (Masson et al., 2020). The establishment of the sea breeze on the coast usually results in a change in the wind direction at the surface, associated with an increase in the wind speed, a decrease in the temperature, and an increase in the relative humidity. This is what was observed during the atmospheric simulation. The sea breeze started around 12–1 p.m. (Figure 6a) and strengthened a few hours later, cooling the air (and reducing the heat stress) in the mid-afternoon. At 4 p.m., the highest wind speeds were over the sea (~8 m s^{-1}) and

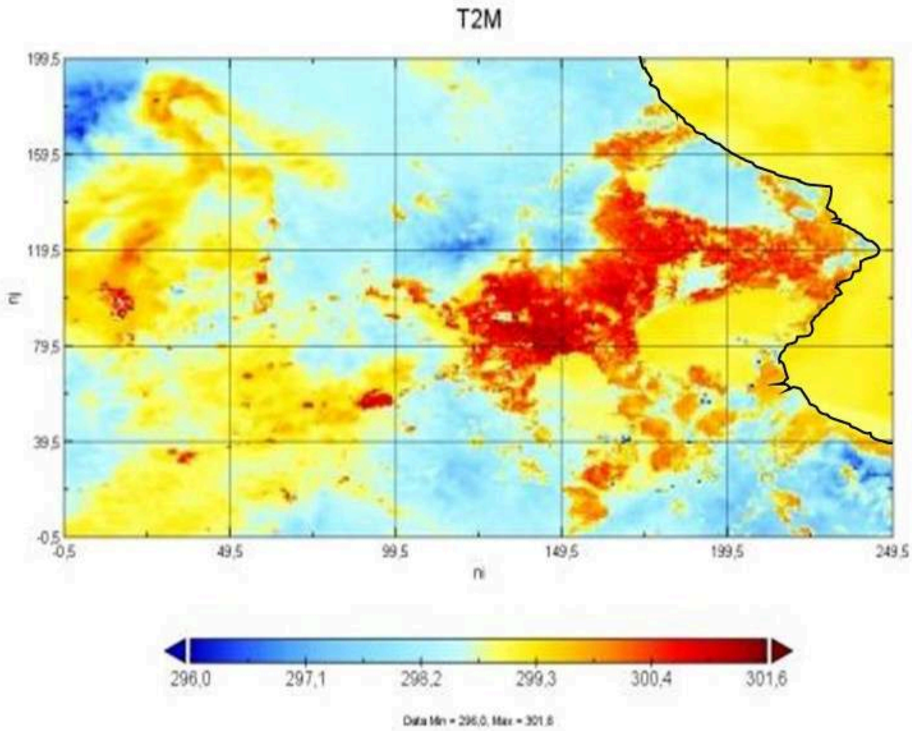
then over all the land forms located in the northwest and southeast of the domain (8–12 m s^{-1}). Conversely, the wind was significantly lower over the urbanized areas (<3 m s^{-1}) (Figure 6b) throughout the day. The sea breeze began to weaken from 10 p.m. onward but did not give way to an onshore breeze during the night of July 9th–10th.

Figure 6. Wind speed and direction at 10 m above the canopy for July 9th at (a) 1 p.m. and (b) 4 p.m (Simulations, de Munck, 2020).



24 During the night of July 9th–10th, 2019, a UHI developed. At 4 a.m., the impact of the urbanized areas was clearly visible on the 2-m air temperature and the temperature difference with the surrounding rural land was identifiable and had an intensity of 4.5°C (Figure 7).

Figure 7. Air temperature at 4 a.m. local time for the night of July 9th–10th, 2019 (Simulations, de Munck, 2020).



25 For the rest of the heat wave period (July 10th–13th) the daily dynamics of all the variables were very similar. Starting at 11 a.m., the UTCI started to reach values corresponding to an extreme heat level (above 46°C) and then reached its peak at 1 p.m. The heat stress remained strong until 8 p.m. The simulation also shows daily sea breezes, which were established around midday. The strength of these breezes reached a maximum value (8–9 m s^{-1}) around 2–3 p.m. In the urbanized areas, very weak winds were identified throughout the entire day (<1.4 m s^{-1}), which can be explained by the impact of the surface roughness on the wind at 10 m above the canopy. The UHI developed between 3 a.m. and 4–5 a.m.

26 The analysis of the Tunis microclimate simulation results was divided into time slots that can be used as input for the statistical analysis underlying the Tunis UCMaps development. The time slots are summarized in Table 1.

Table 1. Daytime and nighttime time slots selected for the Urban Thermal Climate Index (UTCI) and urban heat island (UHI) analysis maps.

Day in 2019	**UTCI**	**Sea breeze**	**UHI resulting from the previous day**
July 9th	1, 2, 3, 4 p.m.	2, 3, 4, 5 p.m.	
July 10th	**11 a.m., 12, 1, 2 p.m.**	**2, 3, 4, 5 p.m.**	**4, 5, 6 a.m.**
July 11th	11 a.m., 12, 1, 2 p.m.	2, 3, 4, 5 p.m.	4, 5 a.m.
July 12th	12, 1, 2, 3 p.m.	2, 3, 4, 5 p.m.	3, 4, 5 a.m.
July 13th	12, 1, 2, 3 p.m.	1, 2, 3, 4 p.m.	2, 3, 4 a.m.

4.2 Urban climatic maps for the greater metropolitan area of Tunis

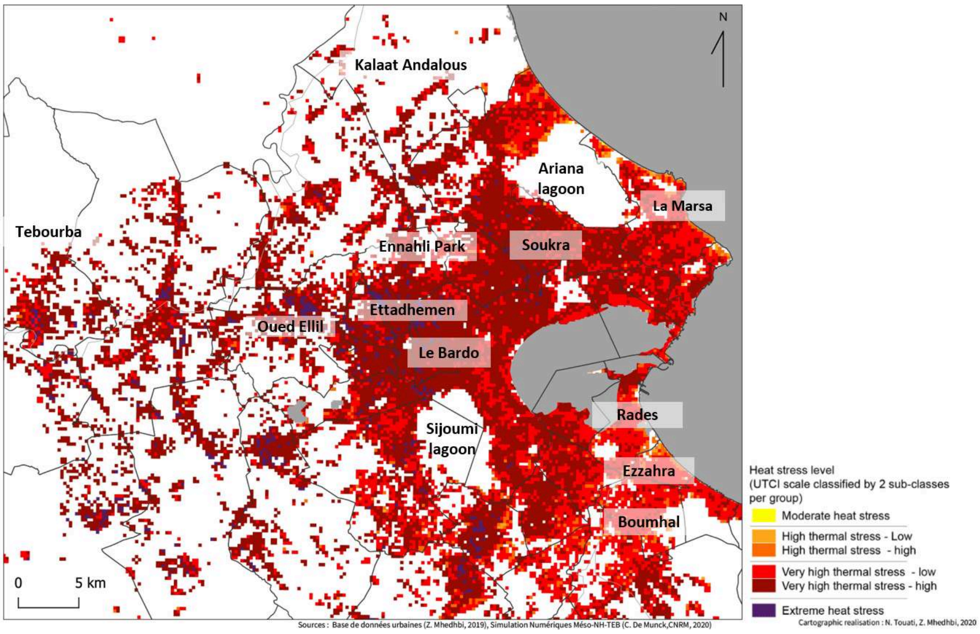
27 The cartographic work was conducted by differentiating between the daytime and nighttime analyses. Based on the results of the previously presented microclimatic analysis, a single map per parameter for each day of the heat wave was obtained via a statistical analysis. Because this study focuses on the thermal conditions, the choice was made to qualify the breeze through its effect on the UTCI and not through an analysis map specific to the wind field. For the nighttime conditions, an analysis map was produced for the UHI.

4.2.1 Analysis maps for the daytime conditions

28 Examining the map corresponding to the maximum UTCI time slots (Figure 8), it was noticed that the thermal stress corresponds to very high to extreme levels north of the Sijoumi Lagoon, especially in the communes of Bardo and Ettadhamen. This level of heat stress was also identified on the southwestern side of the Ariana Lagoon. This residential area straddles the cities of Soukra and Raoued, where the building density is high and the lack of vegetation is remarkable. The UTCI map shows a lower level of heat stress for the coastal municipalities, where the UTCI level varies between very high and moderate stress levels. This effect is even more visible south of the Tunis

agglomeration (in the municipalities of Radès, Ezzahra, and Bou Mhel), where the proximity to the sea is combined with the effect of vegetation, provided primarily by the Radès Forest and the relief of Djebel Boukornine. Northwest of the town of Ariana, the thermal stress also corresponds to a level of medium-high to low-high heat, showing the effect of Ennahli Park.

Figure 8. Map of the UTCI stress levels in the sun marked with the names of significant locations.



29 A cross-analysis of the UTCI analysis map (Figure 8) and the urban surface characteristics (Figures 1 and 2) indicates that the zones of extreme heat stress correspond to the following areas:

- Residential areas with very high density and very little vegetation (e.g., northwest of the Tunis region in the center of Tebourba, in the dense district of Oued Elil, and in the district of Ettadhamen, excepting very dense areas where the streets are in the shade, such as in the medina, where it is relatively cool);
- Commercial areas, such as the one located north of the Tunis region (south of the Kaalet Andalous commune); and
- Industrial zones, such as that of Fouchana south of the Sijoumi Lagoon or those of El Omran El Alaa located near dense residential areas.

30 The analysis of the sea breeze was made using two UTCI maps. The first UTCI map corresponds to the period before the sea breeze was established (Figure 8), and the second map corresponds to the time slots when the breeze was at its maximum (Figure 9). With the establishment of the sea breeze, a decrease in the level of heat stress is evident, especially on the coastline of the greater metropolitan area of Tunis. The communes of La Marsa, Kram, La Goulette, Rades, Ezzahra, and Boumhal experience a cooling effect. Nevertheless, the level of heat stress remains high (moderate heat/very high heat) in these coastal municipalities (Figure 9). Indeed, heat stress in the sun is primarily related to the solar radiation component of UTCI. As a result, it can remain extreme for a very long time even if the air is cooled by the effect of a breeze. Figure 10 allows a better evaluation of the spatial sea-breeze effect on the level of thermal stress.

Figure 9. UTCI analysis map for the greater metropolitan area of Tunis after the establishment of the sea breeze.

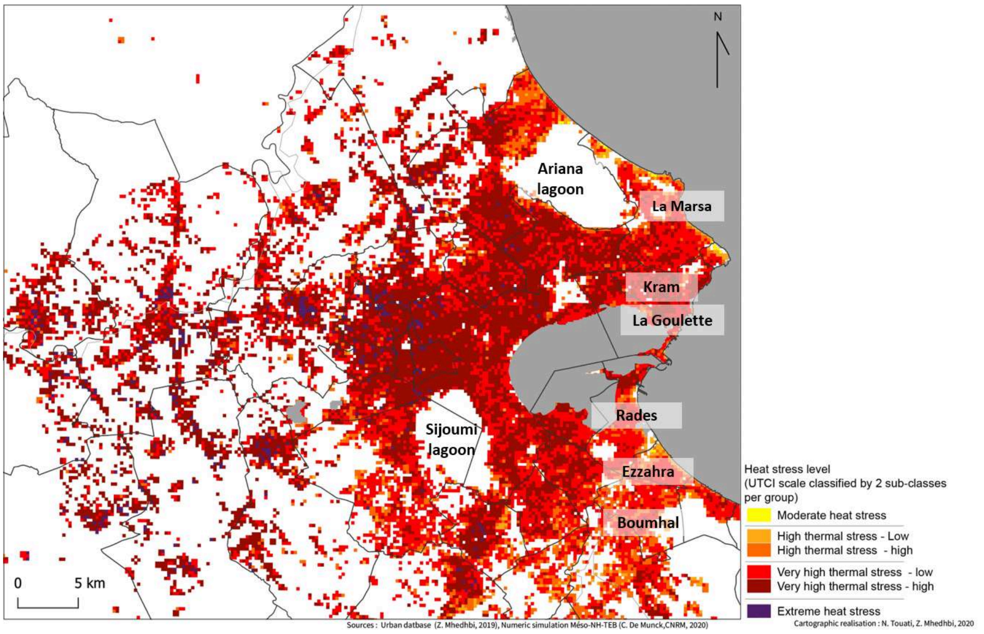
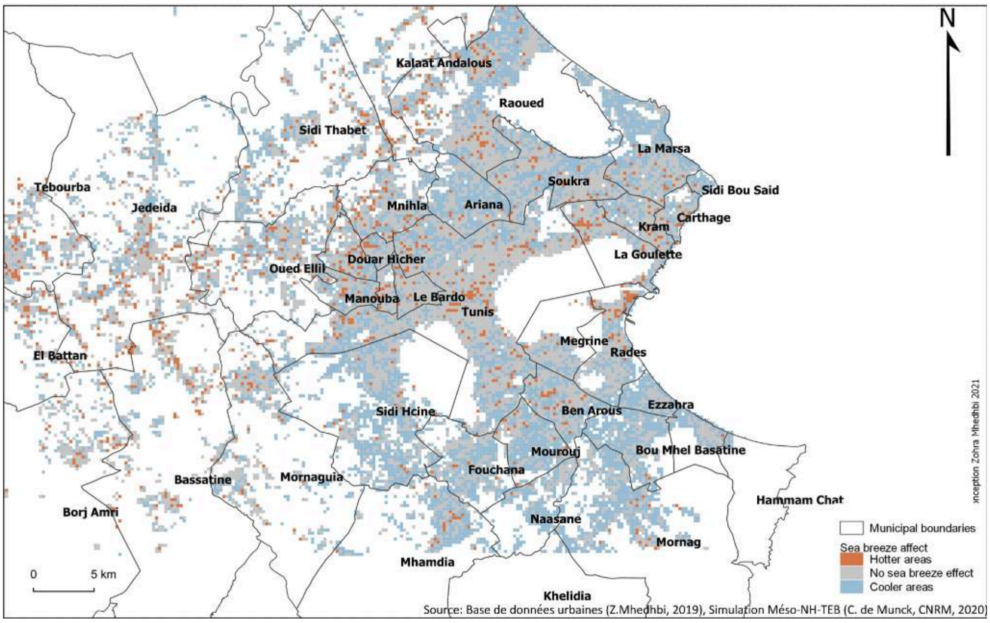


Figure 10. Effect of the sea breeze on the Tunis agglomeration.



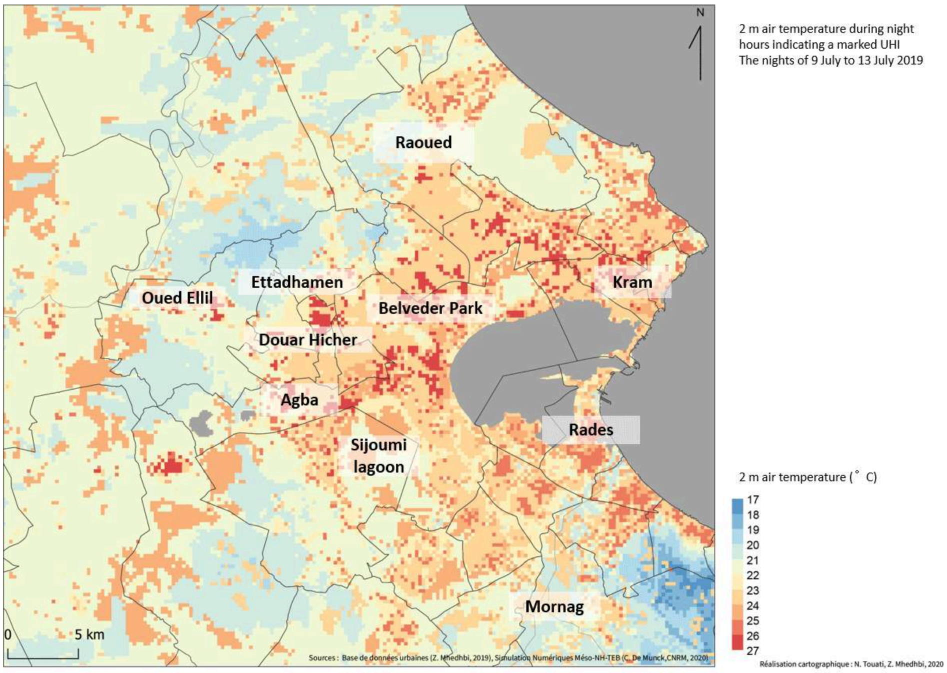
31 The difference between the UTCI prior to the breeze and the UTCI after the breeze is established indicates a clear cooling effect on the coastline. Areas in gray, corresponding to the densest urban spots, are not impacted by the breeze because of their high roughness. Note that the Lake of Tunis, which consists of a coastal lagoon with an average depth of 1 m (Ben Charrada, 1988), does not play the role of a ventilation corridor to cool the city center. The most striking effect of the sea breeze remains in the areas northeast of the Ariana Lagoon, where the effect of the sea breeze is combined with the surrounding countryside vegetation. This effect is also observable

southeast of the region near the Radès Forest and Djebel Boukornine, as well as in the residential areas of Menzah, where the urban density is relatively low.

4.2.2 Analysis maps for the nighttime conditions

32 A frequency analysis of the air temperature at a height of 2 m was conducted. A first "classic" representation based on an interval of 1°C with colors ranging from blue to red was produced for the microclimatic analysis phase (Figure 11). In a second step, to facilitate communication with the urban agency, a specific study concerning the graphics semiology was undertaken to retain only three classes for the urban heat exposure. The first class extends from 17°C to 23°C, at which UHI exposure is negligible, followed by a narrow interval between 23°C and 25°C corresponding to the definition of warm tropical nights (Wei and Sun, 2007), and a third level of over 25°C, where the exposure, increased by the UHI, is considered high.

Figure 11. Nighttime UHI analysis map established at an interval of 1°C.



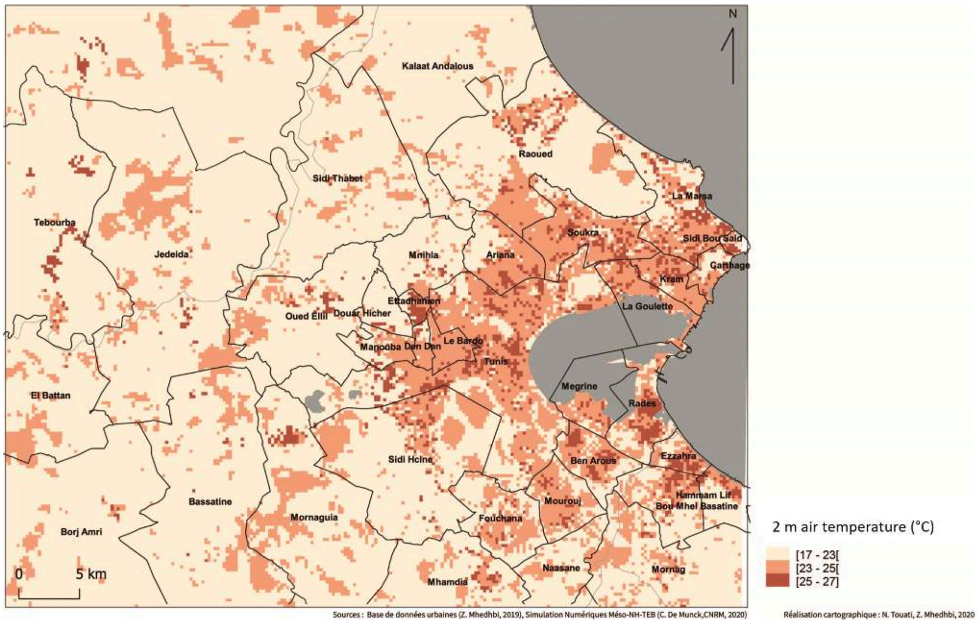
33 As shown in Figure 11, the highest air temperatures are primarily located in dense and informal (non-regulatory) neighborhoods in the region, such as Oued Ellil, Ettadhamen, and Douar Hicher in the northwest. In the northeast, the neighborhood called 10th December (Kram's city) is the most marked by the UHI. A nocturnal urban signal corresponding to the informal district of El Agba can also be seen northwest of Sebkha Sijoumi.

34 The 2-m air temperature map (Figure 12) shows significantly homogeneous forms with a temperature gradient between 23°C and 25°C. This temperature gradient corresponds to informal settlements that have been built progressively along the roads. Another typology of non-regulatory neighborhoods is present in the form of scattered buildings on agricultural land. This includes non-agglomerated constructions that are spread out over the northern plains, for example, in Raoued, and in the south in Mornag. These

buildings are identifiable on the 2-m air temperature map (Figure 11) in the form of isolated or grouped pixels in very small numbers.

35 The relatively cool areas correspond to urban parks, such as Belvedere Park and Ennahli Park, or urban forests, such as the Radès Forest or that in Sijoumi. These less-hot areas may also correspond to reliefs such as Djebl Ammar in the northwest and Djebl Bougarnin in the southeast.

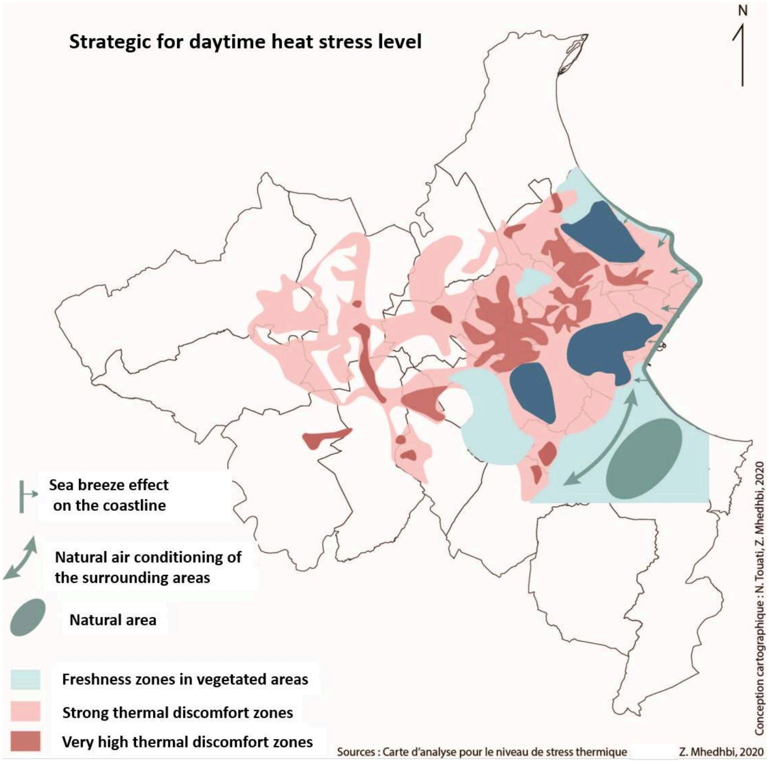
Figure 12. Nighttime UHI analysis map designed for communication with local urban agencies.



4.2.3 Strategic maps

36 Using these analyses and interweaving the temperature at 2 m with the description of the land use and the UTCI map with the land use, two strategic maps for the UTCI (Figure 13) and the UHI (Figure 14) are proposed.

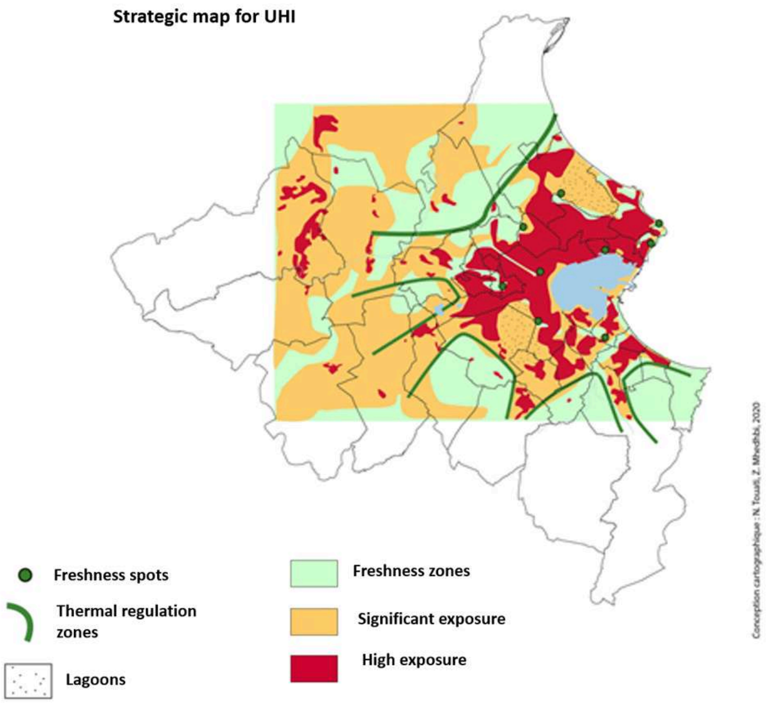
Figure 13. Strategic map for the daytime heat stress level.



37 On the daytime heat stress level strategic map (Figure 13), the zones corresponding to very strong thermal discomfort follow the density of the built-up areas in the non-coastal municipalities. However, the coastal communities benefit from the sea-breeze effect. This effect is shown on this strategic map by small arrows coming from the sea and pointing toward the land. Because the urbanization follows major roads, areas of high thermal discomfort also tend to follow the same arteries. On this map, the light pink areas correspond to tipping zones where the thermal stress could easily go from strong to very strong if the agglomeration continues to expand without accounting for the problem of daytime thermal comfort. In the southeast Tunis region, the natural areas shown on the map can act as thermal regulatory zones; such areas correspond to the Radès Forest and Djebel Boukornine.

38 On the strategic map of the nighttime UHI (Figure 14), the red zones represent regions with strong exposure, which correspond to strongly urbanized environments. The zones drawn in yellow–orange are areas with significant exposure. These areas correspond to tipping zones that could easily switch to hotter zones if the territorial projects of local stakeholders do not consider the UHI as a component in urban development. The cool spots correspond to urban parks and urban forests, which operate as cool islands.

Figure 14. Strategic map for the UHI.



Source: Carte d'analyse de l'ilot de chaleur urbain , Z.Mhedhbi 2020

39 These strategic maps can play two major roles.

40 In the first role, they can be used as translation tools that allow researchers to explain their expertise to stakeholders. This translation can be useful for urban planning exercises. These maps can also serve as a mediation tool allowing different social spheres (researchers, technicians, and elected officials, some of whom are non-specialists) to communicate about climate issues in relation to urban planning without difficulty. The mobilization of these strategic maps as mediation objects was useful to produce a common understanding between the researchers and actors in the case of Tunis.

41 In the second role, they can provide guidance to urban-planning actors to formulate territorial-specific recommendations. For example, urban planners should preserve urban parks and forests to provide cool islands (Figure 14). In areas with significant exposure, vegetation is important and ventilation corridors need to be maintained. In the most exposed areas, if there is no way to implement green areas, action can at least be oriented toward the appearance and colors of buildings to regulate the albedo. Traditionally, buildings in Tunis were all white; however, in recent years, in an effort to copy the occidental style, many buildings have been constructed with large windows and in dark colors. Urban development plans can therefore provide recommendations to improve the urban climate. Work on urban-planning documents constitutes a continuation of this research in collaboration with urban-planning actors in Tunis, with the aim of integrating the most relevant climate information into their documents.

Conclusions

42 In a context of a lack of urban and climatic data, it may be difficult to produce territorial-specific climatic expertise that is useful to local authorities. To overcome this lack of data, this paper proposed several methodological adjustments to the cartographic approach developed by an interdisciplinary research team in the city of Toulouse, France, to be compatible with the context of a southern city such as Tunis. It is important to note the gap between these two contexts. In Toulouse, there is an abundance of data and a regulatory framework for urban planning that is increasingly cognizant of climate issues. In Tunis, urban actors are caught up in priorities (e.g., poverty and informal urbanization) other than climate issues and they work within the context of a shortage of data. To reduce this gap, at least technologically, multiple data collection and processing strategies are required. Urban data were collected from different sources; for example, the Open Street Map database allowed road infrastructure data to be collected and remote-sensing processing was applied to acquire missing data such as vegetation cover. Accordingly, different sources of data were mobilized, which required GIS treatments to be applied with various methods to convert these data into the form of useful indicators for climate modeling. As a further step, a Google Form questionnaire was created. This form was accessible on all devices with no installation required and was shared via Facebook in groups with motivated participants, such as those belonging to associations working on environmental issues. The aim was to collect morphological and architectural parameters. It was also necessary to modify the choice of meteorological situations. For Toulouse, an approach using local weather types was applied. This approach requires a series of hourly data with a duration of at least 10 years for all parameters: air temperature, wind direction and strength, specific humidity, and precipitation. The Tunisian National Institute of Meteorology charged too much for these data, which led us to abandon an analysis by weather type and to focus on a heat-wave period.

43 Together, these adjustments made it possible to produce an urban database that was then used to describe the surface of the Greater Metropolitan area of Tunis for a numerical simulation of its microclimate during a heat wave in 2019. The microclimatic simulation results show three phenomena characterizing a typical hot day in Tunis: high levels of heat stress that develop from the early morning, sea-breeze development in the early afternoon, and a well-developed nocturnal UHI. A statistical analysis of the simulation outputs provided the basis for establishing UC-AnMaps for the diurnal heat stress and the UHI. Some initial lessons for the Tunisian territory were identified. First, the coastal municipalities are the least affected by daytime and nighttime heat stresses. Second, the most affected neighborhoods are dense and informal neighborhoods, such as Ettahdamen and Oued Lil in the northwest Tunis region. Based on these UC-AnMaps, which are generally interpreted with a focus on the exposure gradient, a strategic map was proposed to highlight areas in the territory with significant issues. This strategic map is considered as an improved communication tool for interactions with urban planners.

44 This set of maps was shared with experts in the local Urban Agency in Tunis in December 2020. They expressed their desire to continue the development of this work, by combining the mutual expertise of their agency and our research group to develop

recommendations for thermal stress improvement in the most affected areas of the Tunis region.

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NOTES

1. "Southern cities" is used as a generic term throughout this paper.
2. A climatope corresponds to a homogeneous zone with well-defined characteristics (Baumüller et al., 1992), e.g., forest climatope, aquatic climatope, or commercial climatope (referring to the type of buildings in the area).

3. Locally, the lagoons are called *sebkha*. These water bodies vary the characteristics of the surface on an annual scale because they are generally flooded in winter and dry in summer.
4. Interviews with AUGT agents concerning the informal settlements of the greater metropolitan area of Tunis were conducted in January 2018.

ABSTRACTS

Urban microclimate studies could help manage heatwave crises and improve climate friendly urban planning. This paper presents adjustments to tools and approaches, in particular the Urban Climate Maps framework, typically produced in industrialized countries for contexts relevant to developing countries, where accurate urban data are often not available. In this study, relevant urban, architectural and land use data were collected and constructed to enable numerical simulations of a heat wave episode in the Greater Metropolitan area of Tunis. The simulation results indicate that the diurnal heat stress reached very high values corresponding to an extreme heat stress level, according to the Urban Thermal Climate Index (UTCI) scale, by 9 a.m. local time. The highest sea-breeze speeds were over the sea ($\sim$8 m s^{-1}). However, the effect of the sea breeze was low over densely urbanized areas (<3 m s^{-1}). At night, the intensity of the urban heat island reached +4.5°C. Urban climatic maps were produced via a statistical analysis of the numerical simulation outputs for the diurnal heat stress and the urban heat island intensity. The impact of the sea breeze on the heat stress level is communicated using two UTCI maps. Strategic maps were also proposed to highlight critical areas for urban actors. These strategic maps illustrate the zoning of relevant territorial issues to facilitate dialog with the Urban Planning Agency of the Greater Metropolitan area of Tunis.

Les études sur le microclimat urbain peuvent être d’utiles appuis à la gestion des crises liées aux canicules et à la planification urbaine respectueuse du climat. Cet article examine l’adaptabilité du dispositif de cartes climatiques urbaines, développées au Nord, aux contextes des villes du Sud où la pénurie de données urbaines et climatiques rend difficile toute démarche d’analyse spatiale. Il repose sur une base de données architecturales, morphologiques et d’occupation du sol du Grand Tunis, constituée par les auteurs pour pallier la pénurie des données urbaines et permettre de simuler, à l’aide d’un modèle atmosphérique, les effets d’une période caniculaire sur le Grand Tunis. Les simulations montrent que le stress thermique atteint des valeurs très élevées dès 9h (heure locale), ce qui correspond à un niveau de stress thermique extrême selon les échelles de l’indicateur de stress thermique UTCI. Les vitesses de vent les plus élevées se trouvent au-dessus de la mer ($\sim$ 8 m/s). En revanche, le vent est beaucoup plus faible dans l’aire urbanisée (< 3 m/s). La nuit, l'intensité de l'îlot de chaleur urbain atteint +4,5°C. Des cartes climatiques urbaines ont été produites via une analyse statistique des résultats de la simulation numérique pour le stress thermique diurne et l'intensité de l'îlot de chaleur urbain nocturne. L'impact de la brise de mer sur le niveau de stress thermique est communiqué à l'aide de deux cartes UTCI (avant et pendant la brise). Des cartes stratégiques ont également été proposées pour mettre en évidence les zones à enjeux pour les acteurs de l’urbanisme. Ces cartes illustrent le zonage des enjeux territoriaux pertinents afin de faciliter le dialogue avec l'Agence d'Urbanisme du Grand Tunis.

Los investigadores en climatología urbana y adaptación de las ciudades al cambio climático, buscan comprender las necesidades de los actores de urbanismo en cuanto a información y experiencia climática, con el fin de desarrollar herramientas y métodos que posibiliten considerar estos nuevos desafíos en políticas urbanas. Este artículo propone una reflexión sobre la particular adaptabilidad del dispositivo de cartas climáticas urbanas tradicionalmente desarrolladas en el Norte, para los contextos de las ciudades del Sur donde la escasez de datos urbanos y climáticos dificulta establecer enfoques de análisis espacial. Se elabora una base de datos arquitectónica, morfológica y territorial del Gran Túnez para compensar la escasez de datos urbanos y permitir así la simulación atmosférica en cuanto a los efectos de una ola de calor en el Gran Túnez. Las simulaciones expresan que el estrés térmico alcanza valores muy elevados a partir de las 9 am. (hora local), lo que corresponde a un nivel extremo según las escalas del indicador de estrés por calor UTCI. Las velocidades de viento más altas se encuentran sobre el mar (~ 8 m/s). Por otro lado, el viento es mucho más débil en la zona urbanizada (< 3 m/s). Por la noche, la intensidad de la isla de calor urbana alcanza los +4,5°C. Los mapas climáticos urbanos se confeccionan a partir de un análisis estadístico de los resultados de la simulación numérica para el estrés térmico diurno y la intensidad de la isla de calor urbana durante la noche. El impacto de la brisa del mar en el nivel de estrés térmico, se constituye con el apoyo de dos gráficos UTCI (antes y durante la brisa). Además, se proponen cartas estratégicas que evidencian áreas con desafíos para los actores de la planificación urbana, cuyo objetivo es facilitar el diálogo con la Agencia de urbanismo del Gran Túnez.

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geographyun 903, 912, 788
Palabras claves: confort climático, análisis cartográfico, políticas urbanas, visualización climática
Mots-clés: confort thermique, analyse cartographique, politiques urbaines, changement climatique, visualisation climatique
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AUTHORS

ZOHRA MHEDHBI

Laboratoire Interdisciplinaire Solidarités Societés (LISST), Interdisciplinary Center of Urban Studies (CIEU), CNRS/Jean Jaurès University, Toulouse, France
zohra.mhedhbi@univ-tlse2.fr

JULIA HIDALGO

Laboratoire Interdisciplinaire Solidarités Societés (LISST), Interdisciplinary Center of Urban Studies (CIEU), CNRS/Jean Jaurès University, Toulouse, France
julia.hidalgo@univ-tlse2.fr

CÉCILE DE MUNCK

National Center of Meteorological Research (CNRM), UMR 3589, Météo-France/CNRS, 42 avenue Gaspard Coriolis, 31057 Toulouse Cedex 1, France
cecile.demunck@meteo.fr

SINDA HAOUÈS-JOUVE

Laboratoire Interdisciplinaire Solidarités Societés (LISST), Interdisciplinary Center of Urban Studies (CIEU), CNRS/Jean Jaurès University, Toulouse, France
sinda.haoues-jouve@univ-tlse2.fr

NAJLA TOUATI

Laboratoire Interdisciplinaire Solidarités Societés (LISST), Interdisciplinary Center of Urban Studies (CIEU), CNRS/Jean Jaurès University, Toulouse, France
najla.touati@univ-tlse2.fr

VALÉRY MASSON

National Center of Meteorological Research (CNRM), UMR 3589, Météo-France/CNRS, 42 avenue Gaspard Coriolis, 31057 Toulouse Cedex 1, France
valery.masson@meteo.fr