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Urban Climates and Climate Change

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Keywords

urban climate, urban heat island, climate change in cities, climate downscaling, urban planning for climate adaptation, urban climate modeling

Abstract

Cities are particularly vulnerable to extreme weather episodes, which are expected to increase with climate change. Cities also influence their own local climate, for example, through the relative warming known as the urban heat island (UHI) effect. This review discusses urban climate features (even in complex terrain) and processes. We then present state-of-the-art methodologies on the generalization of a common urban neighborhood classification for UHI studies, as well as recent developments in observation systems and crowdsourcing approaches. We discuss new modeling paradigms pertinent to climate impact studies, with a focus on building energetics and urban vegetation. In combination with regional climate modeling, new methods benefit the variety of climate scenarios and models to provide pertinent information at urban scale. Finally, this article presents how recent research in urban climatology contributes to the global agenda on cities and climate change.

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Adaptation to climate change: actions taken at the local level to modify a system (here cities) to better withstand impacts from a changing climate

World Meteorological Organization (WMO): a specialized agency of the United Nations that coordinates international cooperation on matters related to climate, weather, and hydrometeorology

1. MOTIVATION

Cities encompass the majority of people, goods, and infrastructures. Urban populations continue to increase and cities are growing denser and/or larger, with some megacities reaching more than 20 million inhabitants. This makes cities particularly vulnerable to meteorological hazards and climate change. Furthermore, governance systems in cities are often very complicated, with separate competence domains likely to be in different city administrative departments (e.g., urban planning, water network management, energy, housing, and emergency services planning), and even sometimes at different levels of governance (e.g., city, metropolis, county). Some aspects may not even be covered by official governance systems in some cities and countries, for example, where informal urban expansion is a significant component of city growth. All this increases the vulnerabilities of cities, and renders difficult the anticipation and answers to global risks such as meteorological hazards and adaptation to climate change.

Meteorological and local climatic issues related to cities are of increasing concern at the international level. Of the four challenges identified by the World Meteorological Organization (WMO) World Weather Research Program, two are urban related: high-impact weather, including impacts in cities, and urbanization.

Urban climate is a rapidly expanding research field. More and more cities have been studied in terms of urban climate [mostly air temperature urban heat island (UHI) or surface urban heat island (SUHI) patterns]. A recent review (1) showed very few UHI studies before 1990, ~30 studies

per year between 1990 and 2000, 100 studies per year in 2010, and more than 300 per year in 2015. At first addressed by only meteorologists and environmental scientists, interest in urban climate has rapidly expanded since 2010 to other sectors as consideration for energy, engineering, and building construction issues has grown. These fields have often been most interested in technical solutions focused on reducing (mitigating) urban heat (e.g., 2). There is also renewed focus on the effects cities have on the modification of precipitation, especially how buildings' effect on wind and thermal effects of cities can modify thunderstorm evolution or direction (and hence the precipitation pattern). This article presents the emerging field of study of urban climate evolution with climate change. This increase in urban climatology studies reflects the need to consider, and adapt cities to, climate change and, for some countries, the legal obligations linked to this.

Urban heat island (UHI): difference of air temperature between the city neighborhoods and the countryside

Surface urban heat island (SUHI): difference of the temperature of the surfaces (roofs, roads, grass, etc.) between the city neighborhoods and the countryside; not to be confused with the urban heat island, which concerns air temperature differences

2. URBAN CLIMATE

2.1. Influence of Cities on Local Meteorology

Cities, even megacities, can be viewed from the meteorological point of view as small objects compared to both large-scale systems that influence the weather and climate (oceans and continents; mountain ranges; anticyclones and cyclones) and local systems (coastal areas with sea-/land-breeze systems, forests, mountain and valley features, etc.). However, their extensive modification of surface and atmospheric characteristics at local scales means that cities alter almost all atmospheric variables in their vicinity. Cities thus influence locally the weather in a significant way, especially modifying, and most of the time enhancing, high-impact weather hazards. This is urban climate (3).

Observations of the urban climate started in the nineteenth century in London (4), and there is even evidence of the UHI in Paris in the literature (5). Several distinct features characterize urban climates:

- Warmer temperatures: Air temperature in cities, especially at night and in anticyclonic conditions, can be much warmer than in the countryside, sometimes by up to 10°C for big cities. These warmer temperatures are known as the UHI. This warmth extends upward into an atmospheric layer typically 1 km deep, and is transported downwind. Surface temperatures are also typically higher relative to their nonurban surroundings, with the exception of cities in desert climates. Warmer surface temperatures create a recognizable SUHI that is distinctly different from that of the near-surface air temperatures, especially by day.
- Altered winds: In moderate or strong wind conditions, the aerodynamically rough urban surface slows the wind and turns it slightly in the direction of the pressure gradient. It can also lead to areas of convergence and divergence that result in vertical motion. In light wind conditions, the UHI induces air flow into the city from the countryside in a circulation system similar to a sea/land breeze; this can also lead to recirculation of pollutants, and the rising air motion over the city that is part of this circulation contributes to urban-modified cloud and precipitation patterns.
- Urban-modified cloud and precipitation, over and downwind of the city (reviewed in 6): Altered wind flows and urban-induced circulations (see above) give rise to areas of upward motion over cities that can increase urban cloud cover and precipitation, especially associated with summer convective precipitation events. Cities can also either split incoming thunderstorms in two around the city (when synoptic flow is strong enough) or can initiate thunderstorms above and just downstream (7, 8). Flow convergence and a (slightly) higher

urban boundary layer can also form fair weather cumulus clouds and lead to increased cloud cover during summer over large conurbations such as Paris, London, or Moscow (9, 10).

Urban climate also indirectly influences air quality (which is primarily due to pollutant emissions), given a different vertical temperature structure of the atmosphere in the first 0.1–1.0 km above the Earth's surface and modified horizontal wind circulations. These can create ventilation issues leading to warm air accumulation and poor air quality, especially in dense high-rise urban areas. For example, enhancing ventilation in Chinese megacities is now a priority for both reducing the UHI and improving air quality.

Changes to surface characteristics in cities are also important to urban climate in the context of large-scale climate change. For example, imperviousness of urban surfaces increases the impacts of rainfall, such as floods, and also leads to higher surface temperatures that increase heat loading on urban inhabitants. Thus, modifications to the surface that help create local urban climates are also important to making cities less vulnerable to the impacts of climate change.

2.2. Processes Creating the Urban Heat Island

Cities are very complex systems. This makes it difficult for the nonspecialist, even for scientists in relatively closely related fields or in urban planning or other city sciences, to identify the causes of the urban climate (specifically, why are cities warmer?). This indeed leads to many misrepresentations of the causes of urban climate and therefore renders difficult or inefficient adaptation strategies to mitigate the UHI. However, the scientific reasons behind the UHI are now well identified by the urban climate community.

The UHI is a meteorological phenomenon with a rapid variability strongly governed by the solar radiation diurnal cycle, which evolves from day to day. It results from thermoradiative and energetic processes. The UHI arises mainly because of the artificialization of the surface (3). During the day, as much as half of the heat coming from the sun is stored in the urban fabric materials (brick, stone, concrete, roads, tiles, etc.). The complex three-dimensional (3D) shape of the city also favors such storage, with more surfaces being in contact with the atmosphere, and limits the loss of energy by radiation upward (**Figure 1**). Predominantly dry, impervious surfaces in cities lead to higher surface temperatures with large variations in temperature controlled by the radiative, thermal, aerodynamic, and moisture properties of the surface. Compared to rural surfaces, by day, urban surfaces are warmer, with a distinct SUHI. Urban–rural differences in evapotranspiration and convection efficiency are the main determinants of warming of the surface temperature in cities (11).

For most cities, albedo differences between the city and countryside are small. From numerous older sources, Oke et al. (3) provide the urban–rural albedo difference as a range of −0.09 to +0.03 with a suggested overall value of −0.05. The sensitivity of urban temperatures to albedo is higher during the day (E.S. Krayenhoff, A.M. Broadbent, E. Erell, L. Zhao & M. Georgescu, manuscript submitted) but the relative urban–rural albedo is not that large. Although the albedo of individual surfaces can often reach 0.30 or higher, e.g., for light-colored walls, the reflected energy is intercepted by other urban surfaces (radiative trapping), which limits the energy reflected to the sky and hence the overall urban albedo. Therefore, there is a low difference in daytime net radiation between urban and rural sites (as reviewed in 12). As net radiation is similar, this explains the larger role in the UHI formation of the processes that modify how it is consumed: higher storage and much less evaporation.

During the daytime, the UHI intensity is in general much smaller than the SUHI, because of similar low-level (1-km deep) atmospheric structure and strong mixing of the air by turbulence. Cool islands can even be observed, typically in the morning, when the rural areas warm faster than

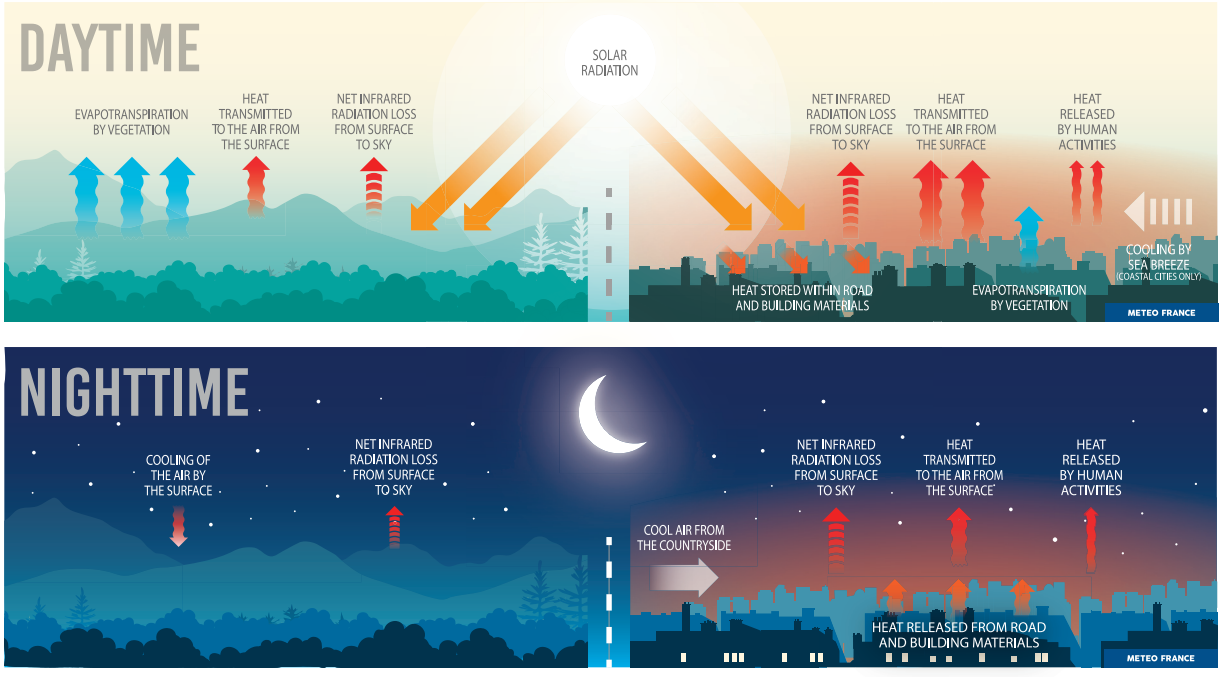


Figure 1

The main processes leading to the urban heat island. Urbanization of the surface and reduction of the vegetation cover strongly modify the energy exchanges. During the day, a large part of the radiation coming from the sun heats the urban materials; this stored heat is released at night, limiting the nighttime cooling of the air in cities and creating the urban heat island. It is also influenced and modulated by the heat released by human activities and the air flow from the countryside and, for coastal cities, from the sea or large lakes. Figure reproduced with permission from Météo-France 2020; copyright Météo-France.

the city. Building shadows in dense parts of the cities can also create localized cool islands during the day in terms of air and surface temperature, but the heat stored in the building materials will make these areas the warmest at night.

At night, the stored heat is released to the atmosphere, limiting the cooling of the air. This is why cities can be much warmer than their surrounding rural areas, especially after sunset and up to the middle of the night, even sometimes all night. The presence of pervious soils and vegetation limits this effect through evaporation of soil water and transpiration of plants, as well as shadowing effects and mitigation of incoming radiation by tree foliage during the day. For the same city population, nocturnal UHI is in general smaller in tropical areas than in temperate climates (13). Urban surface temperatures also remain warmer at night, with the SUHI similar to the UHI, although with more variability in surface temperatures, as determined by specific properties of individual surfaces.

Human activities also slightly influence the UHI by direct release of heat into the atmosphere (the main sources being domestic heating and air-conditioning, as well as heat release by traffic to a lesser extent). For the large majority of cities and meteorological conditions, this is not the main mechanism creating the UHI. For example, air-conditioning could increase urban temperatures

by a maximum of 1 to 2°C in Paris during the nights of heat waves (14) (which represents ~10 to 20% of the maximum UHI intensity); similar increases were modeled for Phoenix (15) and Hong Kong (16). Domestic heating can also lead to a large release of energy to the atmosphere. It can be as much as the incoming solar radiation over a 24-h period for a midlatitude oceanic climate (17). In cold continental climates, the domestic heating is usually large in wintertime [as in Lodz, Poland (18)], but is surprisingly weak for cities with efficient insulation and in the presence of snow on roofs, such as in Montreal, Canada (19). In some specific cases, such as in polar cities in winter, domestic heating can become the most significant process.

Even if meteorological situations favoring strong UHIs are often associated with atmospheric pollution episodes, atmospheric pollutants do not significantly modify the air temperature above cities. Only in extremely polluted megacities, such as Delhi, can the very high level of urban aerosol pollution slightly modulate the urban weather (20): In that case, the limitation of solar radiation reaching the surface (which is diffused and absorbed in the lower atmosphere instead) can contribute to create a cool island during the day.

2.3. Urban Climate in Complex Geographical Areas

Over the past five years, the urban climate scientific community has started to focus on cities influenced by complex local geography, due to topography, water bodies, etc. Under such conditions, the city-induced heat and water fluxes toward the lower atmosphere interact in a much more complicated way with the local air flows (**Figure 2**) to create city-specific urban climates. As every city has its own unique combination of climate, geography, and internal structure, it is not possible to present all the specific cases that could be encountered. Instead, we focus on only a few typical situations: coastal, mountainous, and, in the next section, cold winter climates and polar cities.

Expansion of coastal cities is expected to continue over the twenty-first century, with more than half the global population living in cities in the coastal zone by 2050 (21). Dense Asian coastal cities such as Tokyo, Hong Kong, and Singapore experience urban climates affected by both extreme high-rise urban features and complex sea-/land-breeze systems. In Tokyo and the Kanto Plain during the daytime, the extra heat released over the urbanized area (compared to the countryside) extends over tens of kilometers. On the basis of observations, Yamato et al. (22) show that the sea-breeze front (which indicates the penetration of marine air over the continent) is slowed downwind of central Tokyo. This explains warm temperature anomalies in the afternoon in this suburban region of the Tokyo agglomeration 40 km from the coastline (and densest urbanization). Matsumoto et al. (23) review past urban climate studies on the Tokyo metropolitan area. High-rise buildings on the seafront or inner city can also inhibit the cooling effect of the sea breeze on neighborhoods located downwind. This also raises ventilation issues. Kotharkar et al. (24) review 85 works on 28 South Asian cities. They show that during the daytime the sea breeze in Delhi, Mumbai, and Colombo improves thermal comfort by limiting the diurnal warming in the cities and mitigates atmospheric pollution. However, although coastal areas remained cooler than the inner city regions by day, the opposite occurred at night (25). The sea breeze in New York City reduces urban temperatures in most calm synoptic wind situations, but during heat waves, the wind typically comes from inland, and then strongly reduces this cooling effect (26). Interaction between sea breeze and UHI can even lead to cloud and thunderstorm formation. Combining observations from meteorological stations, radar, and satellite, Vemado & Pereira Filho (27) show that thunderstorms preferentially developed over the São Paulo megacity after the sea-breeze front reached the agglomeration.

Mountains, and even small hills, induce valley wind systems that strongly influence the local meteorology: typically up-valley winds during the day and a shallower wind coming down from

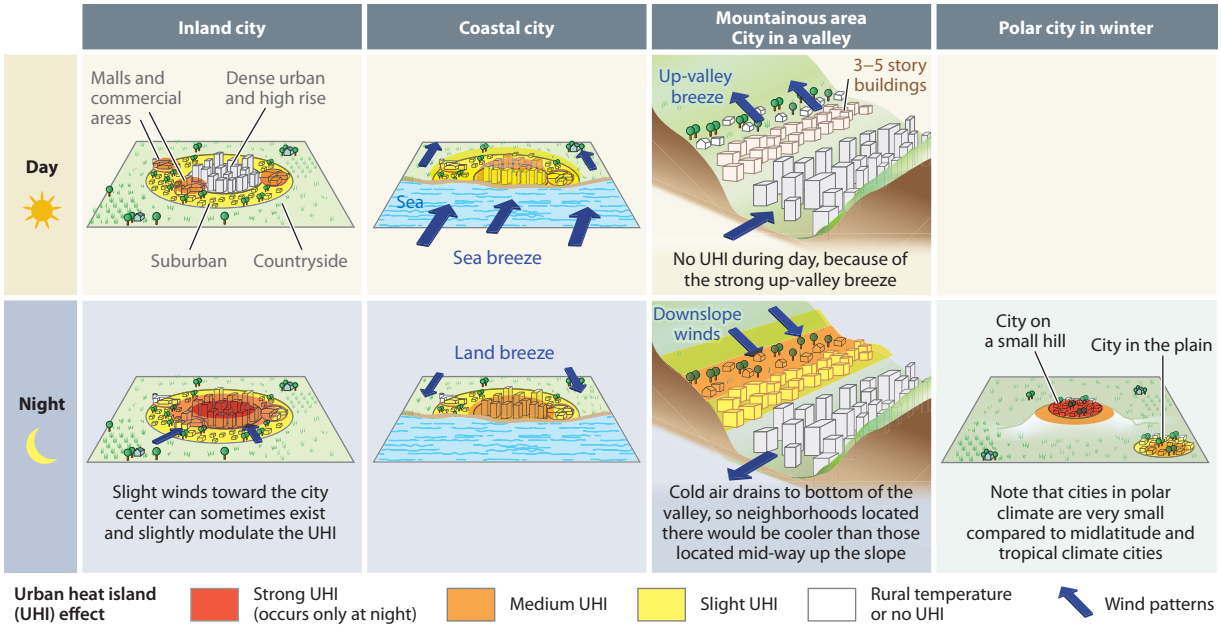


Figure 2

The urban heat island (UHI) in several geographical situations: inland city (the most studied), coastal cities, cities in mountainous areas, and polar cities in wintertime. During daytime, in inland cities, suburban areas are often slightly warmer than their countryside, especially industrial and commercial areas with large car parks. Although coastal cities are generally cooler than inland cities nearby, they can during the day be warmer than their immediate countryside, because of the blocking of the sea breeze by buildings. During nighttime, when meteorological conditions are calm, city centers are generally warmer than the countryside with strong UHI. Cities in valleys can be an exception due to orographic flows. The presence of hills can also modulate the intensity of the nocturnal UHI, especially during clear and cold nights.

the mountains during the night. Mountain cities are therefore subject to topographical effects and local flows that can influence the UHI and its variability (28) and the dispersion of atmospheric pollutants (3). To take advantage of the clean and cold air drainage flow coming from the mountains or hills at night, and considering its penetration inside the city, is a challenge for urban planners (29). Few studies are available, and this may be an emerging topic for urban climate research in the years to come. The city of Stuttgart (Germany) is one city where the effect of the hills on the nocturnal UHI has been studied. It is located in a basin surrounded by hills. This produces air stagnation over the city, leading to poor air quality as well as strong UHI. An opposite effect is observed near high mountain ranges, where nocturnal downslope katabatic or drainage flows are able to mitigate the UHI (see, e.g., 30 for Nagano, Japan). Largeron & Staquet (31) show that the flow above the city of Grenoble, France (located in a basin in the Alps region), during wintertime pollution episodes is very complex with a vertical layering resulting from the superposition of the down-valley winds flowing from the different valleys surrounding the city. Because the relative influence of city and relief on the UHI cannot be easily separated, Bokwa et al. (32), after analysis of data on the city of Krakow, Poland, proposed a new approach of relief-modified UHI.

2.4. Wintertime Urban Heat Island in Cold Climate and Polar Cities

The UHIs of cities experiencing rigorous winters and extensive periods of snow cover have also been studied, such as Montreal (33) and Helsinki (34). Using 20 meteorological stations during

the winter of 2008–2009, Malevich & Klink (35) show that the average wintertime UHI over Minneapolis under calm conditions was ∼1.0°C, with a peak near midday rather than at night. Schatz & Kucharik (36, 37) also observe a small winter daytime UHI (of the order of 0.5°C to 1°C), in Madison, Wisconsin, but the nocturnal UHI there is slightly warmer, by 0.5°C. Wintertime UHI is much smaller than in summer (4°C). The same trend is observed for the city of Iasi, Romania, for nighttime UHI (1°C in winter, 2.5°C in summer), again with a similar winter-mean daytime UHI ranging from 0.5°C to 1°C (38). This wintertime UHI, although quite small, still makes apricot trees blossom earlier (up to 4 days) in Iasi. They also indicate that the depth of the snow cover is significantly lower inside the city (up to 10 cm less for a rural snow depth of 30 cm). Malevich & Klink (35) suggest that the high albedo of rural snow cover could explain the larger daytime UHI. Bergeron & Strachan (39) show that the albedo during the winter snow cover season in Montreal was ∼50% lower (∼0.4 versus ∼0.8) at suburban and urban sites compared to that of a rural reference and that the presence or absence of snow cover on building roofs was an important determinant of temporal variability of albedo at their urban site. Millar (40) provides measurements in Syracuse, New York, on albedo changes that occur because of urban snow removal, and their impact on the UHI. The insulation properties of snow can also reduce both the heat storage and need for domestic heating, thereby reducing the UHI at night. Soil freezing and thawing of snow can also influence the surface energy balance (41). Perryman & Dixon (42) link the wintertime UHI to potential modifications in urban snowfall. Their analysis of radar data from 1992 to 2015 show that snowfall is often reduced downwind of the city but can also be enhanced instead in snow storm convective events, due to atmospheric instability and convergence of the winds over the city.

Very few studies until recently investigated cities located in polar regions, so their urban climate is poorly understood. These cities are usually small (typically of the order of 50,000 to 100,000 inhabitants, with Murmansk, Russia, having 300,000 inhabitants). Klene & Nelson (43) studied the UHI impacts in Utqiaġvik (formerly Barrow), Alaska, in summer. They used air and soil measurements from 66 meteorological stations to study air and soil (permafrost) UHI. In winter, contrary to midlatitude cities, the polar cities present stronger UHI of 1–2°C on average, but sometimes reaching 5 to 12°C depending on the city (44, 45). While in other climates, the main driver of UHI is the solar radiation stored during the previous daytime period (3), especially in summer, for these arctic cities, the main source of energy comes from the anthropogenic heat flux released due to domestic heating. The village of Utqiaġvik, Alaska (4,500 inhabitants), experiences UHI of 2°C (with a maximum of 6°C) in wintertime, due to gas consumption (46). The small city of Apatity, Russia (60,000 inhabitants), is located on a small hill. Because of the long winter night, the air is coldest near the surface but is warmer by several degrees a few tens of meters above the surface (44). Therefore, its UHI is increased compared to the tundra below (47). Suomi (48) reveals the same topographic effect for the city of Lahti, Finland. The UHI of Apatity and Lahti can reach up to 10°C in winter, which corresponds to summertime UHI of megacities of millions of inhabitants in midlatitude regions.

2.5. Scale Interactions

Urban climates exist at the crossroad of many scales. In the horizontal dimension, many scales interact, as **Figure 3** shows, with variability of air temperature at all scales. Blocken (49) describes these scales and associated modeling tools. At the local scale, buildings influence the wind flow and cast shadows, and often release heat to the atmosphere; these link with even smaller, nonatmospheric scales and processes, associated with human activities. At neighborhood scales, the urban climate is most sensitive to urban forms, land cover, land use, and the presence of vegetation. Many

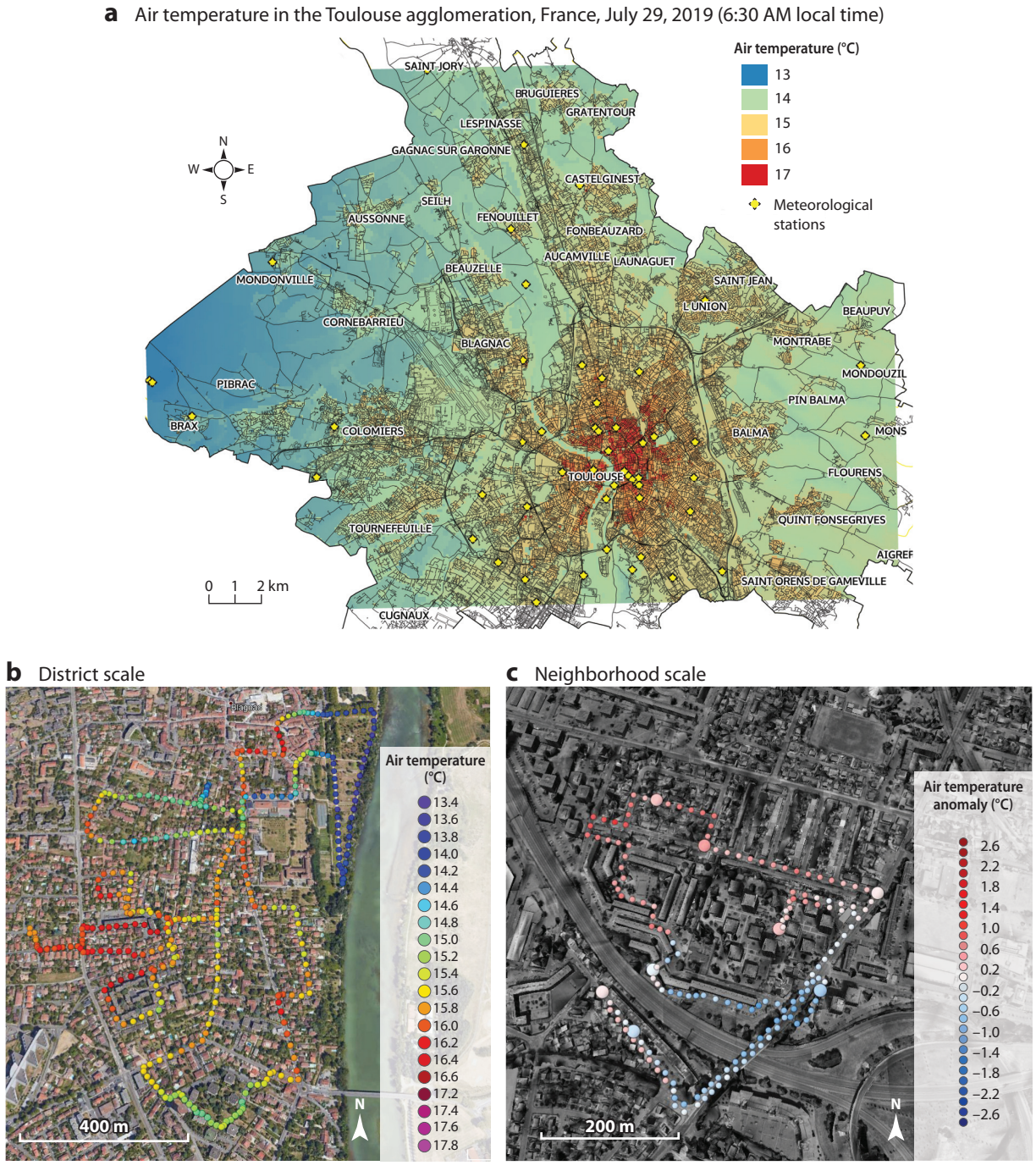


Figure 3

Nocturnal urban heat island at several spatial scales. Examples in Toulouse, France: (*a*) city scale (air temperature mapped using 50 meteorological stations of "Toulouse Metropole" territory administration), (*b*) district scale (air temperature, measurement on a bicycle, CNRM), (*c*) neighborhood scale (air temperature anomaly, pedestrian measurement). Geographical information of map *a* is from OpenStreetMap. Maps *b* and *c* plotted using Google Earth Pro using data from Centre National de Recherches Météorologiques and the EUREQUA research project, respectively.

urban planning questions refer to which urban form should be implemented to improve urban climate issues. But these local and neighborhood scales are of course linked to the urban climate and UHI evolution and pattern of the entire agglomeration. These are influenced by the local geography, as demonstrated above, but also to meteorological phenomena. The weather strongly determines the importance of urban climate. Windy or rainy conditions inhibit UHIs, for example. The succession of anticyclonic or perturbed meteorological conditions has to be addressed in urban climate studies, as well as seasonal effects. The latter are not only linked to meteorology and season (solar irradiance) but also to vegetation growth. New methodologies have recently been defined to account for the variability of the urban climate and its impacts in relation to climatic conditions (50).

Finally, climate change brings a new complex scale into the urban and city risks and resilience concerns. In the past, cities were built in accordance with a given climate. Vernacular architecture with local materials and urban planning existed from the prehistoric period and up to the beginning of the twentieth century. Urban planning and architectural practices have evolved strongly since the Industrial Revolution and accelerated after the Second World War with the generalization of modern construction methods (use of concrete, steel, and glass as materials and harmonization of building and urban forms in cities around the world). These technological changes induced an urbanism relatively less dependent on climate. Still, climate hazards were considered (e.g., in terms of extreme precipitation occurrences for infrastructure dimensioning), but in terms of a nonevolving climate. The present climate change induces a paradigm shift in urban planning, in hazards and risks evaluation, and in new emerging crisis management (such as during heat waves) so that cities can be better prepared to withstand the evolving hazards associated with climate change.

Cities, despite their globally small spatial extent, exert an important cross-scale influence on large-scale climate change. Global warming arises from greenhouse gas (GHG) emissions (including CO_2), a significant part of which is emitted by cities. These same GHG emissions do not generate local and short-term warming and do not cause the UHI effect (51) and at the same time, the local warming from the UHI is not responsible for global warming.

These complex scale interactions need development of scientific tools and methodologies to advance the creation of socially useful urban climate services. Better modeling tools that cross the various scales are necessary to provide relevant information at the adequate scale (depending on the end user). These models need more precise urban information (due to the increasing number of processes taken into account and the need for targeted service details). They also require better knowledge on the processes at play through new observations and experiments. We analyze new scientific advances on these data, observation, and modeling aspects in Section 3. We present interactions between urban climate and climate change in Section 4.

3. METHODS AND TOOLS TO STUDY THE URBAN CLIMATE

3.1. How to Describe Cities for Urban Climate Studies

To study urban climates, in addition to the knowledge of the physical, biophysical (and eventually socioeconomic) processes at play, it is necessary to have an adequate description of the city and its surroundings. As Masson et al. (52) describe, the necessary parameters can be classified as land use/land cover mapping, morphological parameters, architectural and building information, urban vegetation description data, and socioeconomic parameters (for some applications such as anthropogenic heat flux estimation). However, many issues exist when gathering such data, such the following:

- the difficulty (in terms of expertise, time, or money) to apply a methodology to produce the parameters;
- the consistency of data source, acquisition, and processing methods from one city to another; and
- the global availability of data for all cities.

Recent years have seen advances to address these issues in two major ways. The first is to use homogeneous methods and classifications of parameters for both urban climate research and applications. The second is the development of methodologies based on the exploitation of big data, social networks, and open data available on the Internet. Masson et al. (52) provide a complete review of the advances in the classical as well as new methods.

3.1.1. Homogenization of urban land use description. The exponential growth of urban climate studies has meant that it is often very difficult to intercompare their results and to reach general quantitative conclusions. For example, it is difficult to link in a comparable quantitative way the UHI intensity and its intraurban variability to urban morphology for various cities. This is because most studies are performed locally. Hence, data used are very heterogeneous from one city to another, and even the classification of land use can be very different, depending on urban data and laboratory past usages (sometimes in other fields). Stewart & Oke (53) raised this concern.

They proposed a new universal classification of urban and nonurban land use/land cover called local climate zones (LCZs) with a focus on more details on the urban surface. It includes 10 urban classes to describe these LCZs that are valid at neighborhood scale (0.1 to 1 km² typically). They mostly depend on height of buildings (high-rise, mid-rise, low-rise) and density of buildings (dense, open, sparse) and also describe specific urban fabric (informal settlement, light industry, heavy industry) (**Figure 4**). The main scientific assumption is that similar neighborhoods have a similar local effect on UHI, and with relatively homogeneous temperatures compared to nearby neighborhoods (at least those of other LCZs). This assumption has been verified by experimental campaigns, using meteorological stations (54), instrumented vehicles (55), or surface temperature satellite images. The LCZs have been widely adopted by researchers, allowing more studies to use a common classification of the urban land use and land cover, and their simplicity has also facilitated their use by urban planners and city administration officers.

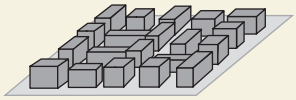
The World Urban Database and Access Portal Tools (WUDAPT) (56, 57) international initiative was launched to build such LCZ maps for any city. Bechtel et al. (58) describe a methodology to produce LCZ maps at 100-m resolution using satellite images. It requires somewhat local expertise to appropriately associate LCZs with the city's neighborhoods, but the method is easily applicable to any city in the world and has been recently completed with the addition of a quality control system (59). Demuzere et al. (60) took advantage of this to produce an LCZ map for all of Europe. The LCZ can also be computed using building inventories, where the individual shape of all buildings and roads is identified. This has been done for several cities (e.g., 61, 62). Hidalgo et al. (63) compare LCZs produced from inventories and satellite images for three French cities. Classifications based on inventories show finer spatial details within and on the edge of the agglomerations.

3.1.2. Exploitation of new sources of data. The Internet provides many sources of data of various types for use by the general public that were not originally intended for scientific use. These include, for example, data from Google Maps' Street View and OpenStreetMap (OSM). Much information can also be gathered through social media. These nonconventional data

Local climate zone (LCZ): a land cover classification scheme based on the controls of surface climates that identifies areas of uniform thermal climates

World Urban Database and Access Portal Tools (WUDAPT): an international initiative to classify cities using the local climate zone scheme and to provide tools and data needed for urban climate researchers

OpenStreetMap (OSM): an Internet-based open data resource that provides free geographic data and uses volunteered geographic information to update these data



LCZ 2: Compact mid-rise



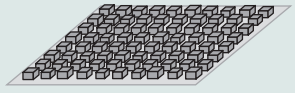
Florence, Italy Photo by J. Voogt



Quito, Ecuador J. Voogt



Amman, Jordan T. Nagel



LCZ 3: Compact low-rise



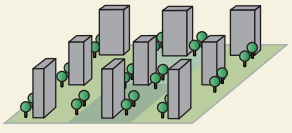
Rochefort-en-Terre, France J. Voogt



Sidi Bou Saïd, Tunisia V. Masson



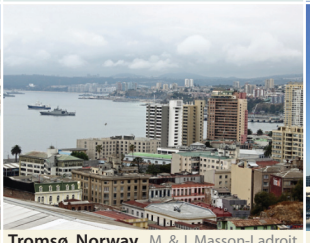
Marrakesh, Morocco J. Voogt



LCZ 4: Open high-rise



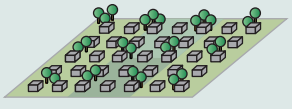
Jinan, China I. Stewart



Tromsø, Norway M. & J. Masson-Ladroit
LCZ 4 mixed with elements of LCZ 2



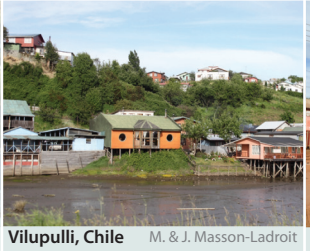
Vienna, Austria V. Masson



LCZ 6: Open low-rise



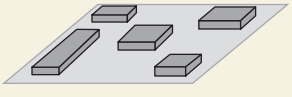
Toronto, Canada I. Stewart



Vilupulli, Chile M. & J. Masson-Ladroit



Karatu, Tanzania J. Wilson
LCZ 6 mixed with elements of LCZ 7*



LCZ 8: Large low-rise



Mississauga, Canada J. Voogt



Bogota, Colombia I. Stewart



Woodhill, Canada J. Voogt

* LCZ 7: lightweight built

Figure 4

Worldwide local climate zone (LCZ) urban description typology: examples of various neighborhoods classified as LCZ 2, 3, 4, 6, and 8 in cities around the world. Illustrations on the left adapted with permission from Stewart & Oke (53); copyright American Meteorological Society.

require specific approaches for use and processing. In the past two years, scientists have developed original methods to take advantage of this new information potential.

New technologies, mainly deep learning, are used to compute urban parameters from these data sources. The authors of Reference 64–67 perform Google Street View photograph and image analysis to automatically compute an urban parameter related to the obstruction of the sky hemisphere by buildings and trees as viewed from the street, called the sky view factor. This is an important parameter influencing both the amount of solar radiation received in a street during the day and the cooling of streets and buildings at night. Zhang et al. (X. Zhang, A. Shehata, B. Benes & D. Aliaga, manuscript submitted) also use neural network methods to reconstruct 3D shapes of buildings over large parts of cities from satellite imagery.

The urban climate community also benefits from crowdsourced initiatives such as OSM, in which volunteers and mapping agencies contribute to a global map of the world (68; see also **http://www.openstreetmap.org**). The information from volunteers enhances the information, notably on building use (presence of shops, restaurants, residential and government buildings, etc.). Olbricht (69) and Boeing (70) use OSM to improve and complete land cover maps. Kunze & Hecht (71) used OSM crowdsourced information to derive residential/nonresidential floor area. The use of building inventories is not common in the urban climate community because it requires strong expertise in geographic information systems and thus is limited in its application to specific cities [e.g., in Moscow (72)]. Bocher et al. (73) adapted such methods using inventories to be more generic and applicable with OSM data. This opens the way to global mapping of urban characteristics for urban climate applications but raises the issue of variable quality of OSM around the world.

Direct involvement of people through social networks and mobile apps is still very embryonic in the urban climate community, but it is very promising and has great potential to access specific information of primary interest for urban climate analyses, especially in cities and countries where institutional databases are lacking. In the frame of WUDAPT, See et al. (74) propose a crowdsourcing approach to gather information on building materials and function, landscape morphology, and vegetation types. This first took the form of a mobile app, intended for use by students. Mhedhbi et al. (75) adapted this questionnaire to Facebook to gather building descriptions over the agglomeration of Tunis.

3.2. Advances in Observations

Urban climates were first studied using scientific observations based on comparisons between city and countryside temperatures measured at meteorological stations. In the 1970s, in Canada and Japan especially, experimental studies started to focus on the energetic processes creating the UHI, focusing not only on description but also on understanding of the underlying processes. The objective was to quantify the radiative and heat processes, including evapotranspiration, in the urban surface energy exchanges with the atmosphere. Field studies, using often fixed towers, or using mock-ups, were carried out in select neighborhoods of a few cities. These types of experiments became more widespread after 2000. Barlow (76) and Kanda (77) present a review of such experiments for different processes.

Some urban meteorological networks have been developed to better understand the fine-scale structure of the UHI and urban climate in general (see 78 for a review). Most focus on near-surface air temperature measurements to quantify the UHI, but recent observation networks also use complete meteorological stations including measurements of humidity, wind, pressure, and even precipitation. Urbanized areas provide challenges in terms of meteorological representativity, but guidance has been provided by the WMO (79, part II, chap. 9 and 10). These networks can cover

different spatial and temporal scales depending on scientific objectives. Networks focusing on process explanation are often limited to neighborhoods or even road scale, sometimes complemented with other types of infrastructure such as energy balance flux measurement towers. Networks intended to describe the UHI variability within an entire city are in general long-term—from 1 year to permanent—systems. Recent developments examine the relationship between temperature variability and urban structure (described by LCZs). These networks use professional quality meteorological stations. Bassett et al. (80) analyzed how the wind affects the area influenced by the UHI on the inland city of Birmingham, United Kingdom. Such networks may also now be connected in real time, which opens up prospects for production and dissemination of new urban climate services. In Chicago, an open-source experimental urban measurement project, "Array of Things," which uses a network of 200 interactive, modular devices, is collecting real-time data on climate, air quality, and noise along with pedestrian and traffic counts. These data are intended to help assess the livability of the city and to be used more broadly in planning. Scientifically, these networks can also be used to validate approaches based on crowdsourcing networks (81).

Crowdsourcing and direct involvement of citizens are emerging to measure the UHI (82). Highly populated urban areas are rich in participatory data, which gives rise to the potential of using these data to study urban climates. Sensors can be installed for professional purposes, such as for building internal comfort monitoring, or installed by inhabitants. In the past few years, personal connected weather stations have attracted a lot of efforts from scientists. Netatmo stations are personal weather stations that are connected to the Internet (**https://weathermap.netatmo.com**). Weather Underground also uses a network of personal weather stations of various types. Uncertainties, biases, and errors associated with these data, mainly caused by the sensors themselves and the way they can be installed by the inhabitants, require extensive postprocessing and quality control efforts. However, the network density is such that in some cities (e.g., 10,000 in the Paris agglomeration) these data are very interesting and the most studied in the urban climate research community. The authors of References 83–85 showed for Berlin, Germany, London, United Kingdom, Paris and Toulouse, France, respectively, that these low-cost Netatmo stations can be filtered (with ~50–75% of stations passing the quality control protocols) to satisfactorily retrieve the UHI. Fenner et al. (86) analyzed the intra- and inter-LCZ temperature variability using Netatmo stations. So far, only temperature data have been used, but de Vos et al. (87) confirm that the growing number of Internet-connected private weather stations could make possible urban rainfall monitoring.

Crowdsourced urban data can also be obtained from indirect measurements. In the urban climate community, battery temperature data measured from smartphones have gained attention (88). These require substantial filtering and processing but have been shown to reasonably track urban temperatures (89). Additional corrections based on smartphone light measurements may improve the data quality. Smartphones can also be equipped with sensors to make direct measurements of air temperature and other climate variables.

Remote sensing is used to assess the SUHI. The availability of globally extensive coverage by satellite-based sensors such as MODIS, Landsat, and ASTER provides a rich dataset enabling comparison of SUHI characteristics associated with their bioclimatic setting, season, time of day, and other characteristics. The measurements obtained are restricted to clear sky conditions, although some recent work on SUHI derived from microwave remote sensing has been done, which is restricted by very coarse spatial resolution (90). They are also constrained by the time of satellite overpass, which can range from twice a day (MODIS) to once approximately every 16 days (Landsat). New, higher spatial resolution imagery from geostationary satellites or downscaling techniques may help overcome temporal resolution limitations (e.g., 91, 92) as may methods to use modeling techniques to infer time series information on surface temperatures (93, 94). These

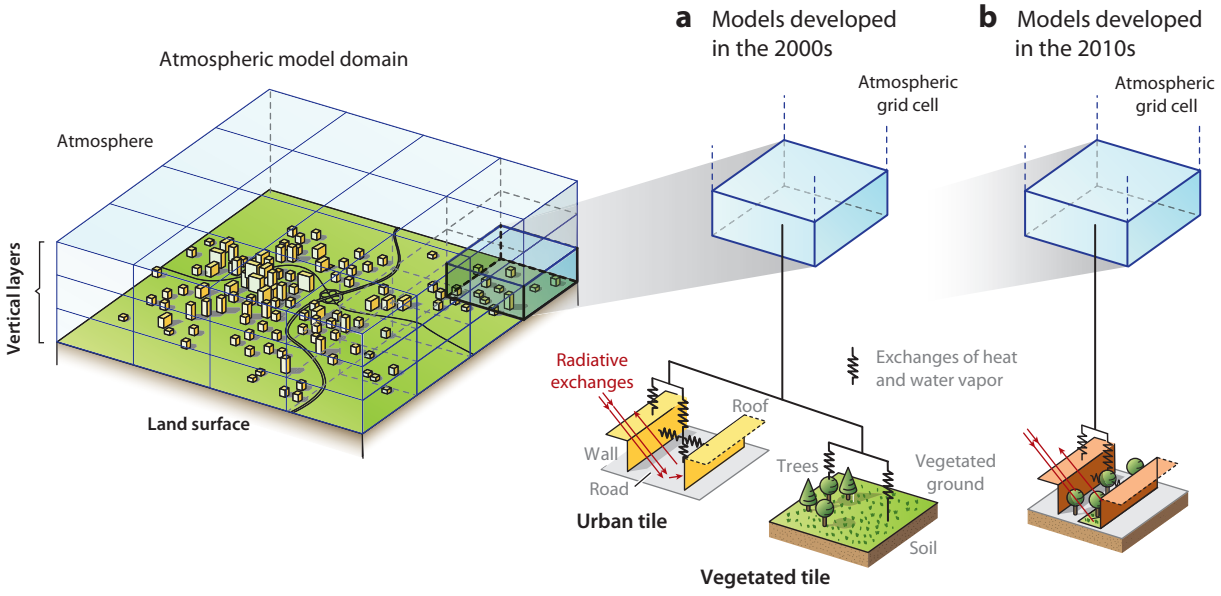


Figure 5

A conceptual atmospheric model coupled with urban canopy models that use a simplified urban geometry. Pathways for surface-atmosphere heat and water vapor transport are represented by resistance symbols; radiative exchanges are displayed as red arrows. (*a*) Early models developed in the 2000s with vegetation and impervious surfaces treated separately. (*b*) Recent models with vegetation inside the urban canyon and directly interacting radiatively (*red arrows*) and energetically (resistances) with the buildings and roads. Figure adapted from Oke et al. (3) with permission from Cambridge University Press.

allow for a higher temporal resolution assessment of the SUHI, including identifying specific classes of SUHI (95). The derived measurements are limited to surfaces that can be "seen" by the remote sensor, and are thus not a complete representation of the urban surface and can be affected by the relative viewing direction of the sensor to the 3D urban surface. Applications of these remotely sensed datasets must consider these inherent characteristics.

3.3. Advances in Modeling

Atmospheric, weather forecasting, and climate models discretize the atmosphere into grid cells, where fluid dynamics, microphysics (clouds), and radiation transfer equations are solved to simulate the evolution of wind, temperature, humidity, or clouds (**Figure 5**). At the surface-atmosphere interface, energy exchanges with the various surfaces (sea and ocean, vegetation, cities, etc.) are represented. However, these grid cells typically range between hundreds of kilometers for global climate models to 1 km for weather forecasting and 100 m for research applications at the urban scale. This means that, for the vast majority of atmospheric and all climate studies, it is still impossible to describe each building individually. Hence, physically based models of the urban surface still necessitate a geometrical approximation of the real structure of the cities. Ching (96) and Garuma (97) review developments of these numerical urban canopy models, which started two decades ago [e.g., the Town Energy Balance (TEB) model by Masson (98) and Building Effect Parameterization (BEP) by Martilli et al. (99); see an early review by Masson (100)]. They emphasize that the necessary level of complexity and detail is dependent on the intended application. Urban canopy models of moderate complexity based on a simplified 3D urban geometry (the urban canyon is a

Town Energy Balance (TEB) model: one of the models to simulate the fluxes of heat and water from cities to the atmosphere above necessary for urban climate modeling

commonly used representation) are now widely implemented in high-resolution research atmospheric models (100-m to 1-km grid mesh). These models have now reached a mature stage, with intercomparison exercises (101, 102) and extensive evaluations.

Urbanized atmospheric models, initially used for analysis of typical meteorological conditions over cities (e.g., UHI or thunderstorm studies), are now commonly used in operational weather forecasting. Such models now have a typical resolution of 1 km (103–106), and even 250 m, as was the case for the Pan American Games in Toronto (107, 108).

Computational resources now allow some applications with microscale (1–10-m) resolution; for example, computational fluid dynamics models explicitly resolve individual buildings and their details (109). However, these models are restricted to small areas (for example, to much less than 1 km^2 for urban design of an area with a few buildings) and to short periods of time (a few hours or days). The numerical method of immersed boundary conditions now allows implementation of buildings as obstacles within atmospheric models (110, 111). Lundquist et al. (110) study the dispersion in Oklahoma City's Central Business District. This coupled approach permits exploration of scale interactions between city-scale urban meteorology and neighborhood-scale detailed flows when using simultaneously coupled atmospheric models at different resolution.

Barlow et al. (112) present further future scientific challenges to advance to 100-m resolution weather prediction in urban areas. As impacts and societal domains are increasingly targeted for model assessment, it becomes critical to understand and model the feedbacks across scales and to incorporate various models for urban system components, i.e., not only atmosphere but also hydrology, energetics, other processes of importance for urban design and planning concerns, etc. Urban climate models have recently improved in two complementary ways that provide better answers to societal issues linked to cities and climate change: (*a*) the representation of urban vegetation and their interactions with the buildings, and (*b*) the evaluation of energy consumption by buildings and its interaction with the urban atmosphere.

The international urban energy balance model intercomparison conducted by the authors of References 101, 102, and 113 showed that models without vegetation perform less well for modeling urban fluxes at an urban mixed site. This motivated many efforts to improve urban canopy models by incorporating urban vegetation effects. The authors of References 114–116 implemented grass representation within the urban canyon, and the authors of References 117–122 introduced in their models street trees and high urban vegetation. This allows models to represent the processes of natural soil and vegetation and their interaction with the buildings and roads (for example, by mutual shading effects). A comparison with local-scale measurements highlights that the new tree parameterization in TEB permits better simulation of outdoor thermal comfort (123). Goret et al. (124) further included the dynamical response to the weather in terms of CO_2 emissions by urban vegetation and buildings.

Indeed, the weather also strongly influences energy consumption linked to buildings, especially cold season domestic heating and potentially warm season air-conditioning. Building energy models have been developed in the past decade to represent the processes influencing the internal building air temperature, such as solar radiation penetration through windows, air infiltration and ventilation, and heat conduction through (insulated) walls and roofs (125, 126). They allow modeling the energy demand and waste heat contribution to the outside air due to domestic heating and air-conditioning and their impact on outdoor temperatures that can contribute to UHI. Wang et al. (127) simulate the effect of alternative air-conditioning systems (direct cooling and central piped cooling towers) for the city of Hong Kong during a heat wave event. Schoetter et al. (128) improved a building energy model by representing the variability of building uses (in each model grid mesh) as well as sociologically driven energetic behaviors, thanks to a collaboration

with sociologists. This underscores the general consideration that urban climate studies, because of the complex nature of the urban system, require interdisciplinary studies.

4. INTERACTION BETWEEN URBAN CLIMATE AND CLIMATE CHANGE

In a context of global-scale changing climate, a major issue is to investigate how urban climate could evolve and to anticipate impacts for cities and residents. This evolution could result from both the mean change in climate forcings and changes in the occurrence and intensity of extreme events.

4.1. Learning from Past Trends and Events

The study of long-term observation time series informs us about past climate trends and potential influences of cities on these evolutions. For many cities around the world, warming trends in minimum and maximum daily temperatures were calculated from stations located in urban environments. For some of them, the comparison with nonurban data shows that the trends are mainly related to large-scale climate change (129, 130) without significant modification by cities. Nevertheless, Lee et al. (131) studied several Asian megacities and found that the urbanization dynamics between 1992 and 2012 led to a modification of climatic trends. Warming was enhanced due to the intensification of UHI linked to the urban expansion and the increase in anthropogenic heat fluxes. Using Japanese data, Fujibe (132) show that even low-density, sparsely populated sites may show evidence of urban effects. Varquez & Kanda (133) explicitly examine the trends of UHI over long time periods and found the strongest relation with diurnal temperature range, inferring strong control by thermal inertia on the UHI and weak effects from anthropogenic heat and population. Some work also looked at long-time series of precipitation observations. Although several climatological studies show an effect of cities on the intensification of precipitation, there is no evidence of an impact of cities on the evolution of climate trends (129, 130, 134). Nevertheless, based on an integrative indicator combining temperature and precipitation data, Salvati et al. (130) showed an increase in drought events at the city site (Rome, Italy) relative to the rural site between 1958 and 2017.

The study of past extreme events and hazards is also essential to anticipate future effects of climate change and prepare adaptation (135). The main extreme events studied in cities are heat waves and floods, which can lead to health risks, property damage, and economic losses. A large literature examines heat waves that are expected to become more frequent and intense in the future (136, 137). The meteorological conditions associated with heat waves also favor strong UHI potentially compounding impacts. On the basis of climatological analysis of past events, Fenner et al. (138) found an increase in frequency and duration of heat waves more marked in Berlin, Germany, than outside, when detection indicators take into account minimum or mean daily temperature. Similar results were found in New York City (135). In Athens, Greece, trends in nocturnal heat stress conditions during heat waves also increase more in urban than rural environments (139) but are comparable during the day. Depietri & McPhearson (135) showed that for New York City impacts on mortality and morbidity decrease despite the increase in heat waves, probably due to an adaptation of warning systems and the development of air-conditioning. They also looked at extreme precipitation events that are increasing in frequency over the period 1876–2016 and highlighted an increase in the vulnerability of transport infrastructure. However, this does not result from an accentuation of extreme events by the urban climate but rather from an increase in risk linked to changes in urban exposure.

4.2. Methods for Downscaling Climate Projections at the City Scale

General circulation model (GCM): numerical model dedicated to global climate modeling that covers the entire Earth with horizontal resolution of ~100–150 km and accounts for physical processes related to atmosphere, ocean, cryosphere, and land surface

Regional climate model (RCM): climate model applied to a limited spatial domain with a finer horizontal resolution than that of general circulation models (10–50 km), allowing a more detailed study of regional-scale climate phenomena

Studying the evolution of the urban climate under a changing climate is quite challenging based on current climate projections. General circulation models (GCMs) and regional climate models (RCMs) are generally available at spatial resolutions too coarse to capture the effects on city-scale processes, and with a time-step that is insufficient to investigate the subdaily dynamics of local phenomena. Moreover, most climate models do not integrate specific parameterization for urban covers into their surface schemes, such that they do not model potential feedback of cities on local and regional climate. Various more or less sophisticated approaches have been proposed and applied in recent years to study the impacts of climate change in cities.

4.2.1. Statistical downscaling for studying future climate of cities. To adapt the information provided by climate projections to a time and space scale more appropriate for urban studies, statistical or statistical-dynamic downscaling techniques have been implemented. They are applicable to a large set of climate projections, different GHG emission scenarios, and long time periods. Therefore, they allow accounting for the spread and uncertainty associated with models and scenarios.

Willems et al. (140) present a comprehensive summary of statistical downscaling methods for urban rainfall, some of which also apply to other climate forcings. The first method is the empirical transfer function. It links large-scale variables (predictors) to local variables (predictands) by statistical regression laws. The functions are established for a past reference period for which large-scale reanalyses and local observations are available and then applied to climate projections. The SDSM (Statistical DownScaling Model) (141) is widely applied to disaggregate rainfall at the scale of an urban catchment (142, 143). The quantile-based corrections can also be applied both on precipitation and temperature. Hatchett et al. (144) used temperature and precipitation climate data downscaled at 12-km resolution with quantile-quantile mapping (145). They applied a second fitting using monthly Tmin and Tmax calculated from long-time series collected at the Reno meteorological station (Nevada) to capture UHI influence.

The second method is based on weather typing or analog events. Local meteorological situations are associated with large-scale atmospheric circulation classes. In future climates, local time series are reconstructed day by day, according to the large-scale classes determined by the climate projections, and by assigning an analog day from the reference database of local meteorological situations. This approach has recently been adapted to correct climate data for UHI effects and more generally for local urban influences (**Figure 6**). For a selection of representative weather situations, Hoffmann et al. (146) performed 1-km spatial resolution meteorological simulations over the city area to better assess the UHI. These simulation days were recombined and weighted according to weather pattern frequencies from past and future time period climate projections to reconstruct a long-time series. Duchêne et al. (147) and Le Roy et al. (148) integrated the city's signature in atmospheric fields (temperature, humidity, wind, radiation) into long-term RCM series. In both approaches, two joint high-resolution simulations of local climate were performed, one by taking the city into account and the other by replacing the city with natural covers. The anomaly fields resulting from city influence were calculated as the difference and superimposed on climate projection data to spatially disaggregate them while correcting them from urban effects. Le Roy et al. (148) applied this correction depending on weather types and on the basis of representative days simulated at 1-km resolution with the Meso-NH model and urban canopy model TEB (149). Duchêne et al. (147) preferred an allocation by analogs based on 10-year simulations with the 4-km-resolution ALARO model coupled to TEB.

The last method is stochastic modeling or weather generators. It is more specifically dedicated to spatial and temporal disaggregation of precipitation. Using local site measurement, daily

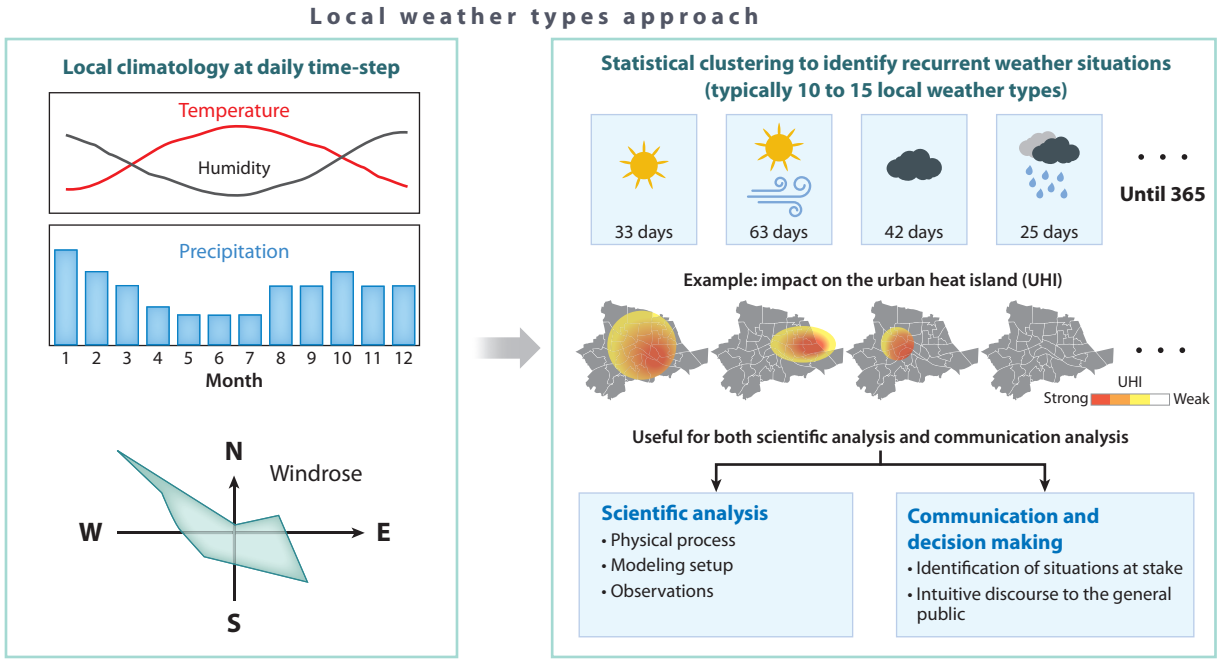


Figure 6

Local weather types method to analyze urban climate. The daily thermal amplitude and the daily means of wind information, specific humidity, and precipitation are used to identify recurrent weather situations. A systematic pre-study using this kind of climatic analysis is a good practice for performing climatic contextualization in local-scale applied studies, for both scientific analysis and communication. A windrose is a diagram that gives a synthetic view of the wind (frequency of strength and direction) at a particular location.

precipitation is decomposed at higher frequency to capture the temporal dynamics of storms and rainfall events. The parameters of the local rainfall generator follow conditional probability distributions defined from observations (150). They are perturbed by delta change factors established by comparing trends between historical and future climate simulations (151, 152). To date, such approaches applied to urban hydrology impact studies do not take into account the potential feedbacks of cities on precipitation. This correction by change factors can similarly be applied to other climatic data. For example, Arsiso et al. (129) applied a monthly delta change correction defined from GCM climatic data on 1-km-resolution gridded observations over the Addis Ababa region of Ethiopia. Lindberg et al. (153) used Rayner & Lindberg's (154) method to calculate the variation factors in daily minimum and maximum temperatures, and incident solar radiation over the twenty-first century from RCM projections. These trends were applied to observations to derive mean radiant temperature in the future and study the evolution of heat stress for Gothenburg, Sweden.

4.2.2. Integrated high-resolution climate modeling. Statistical methods have some limitations. Future projections are built from a statistical analysis of past data under a strong assumption of stationarity in time. The representation of future extreme events may also be questionable, and the interactions between urban climate and regional climate are not always taken into account. Some studies are therefore now moving toward a complete dynamic downscaling from GCM projections to a high-resolution climate modeling configuration integrating online a specific urban climate model.

Intergovernmental Panel on Climate Change (IPCC): the United Nations body for assertion of the science associated with climate change

Many studies were performed with the weather research and forecasting (WRF) model at resolutions of 1–4 km by focusing on specific periods of the year. Kusaka et al. (155) study future summer (August) urban climates of Japanese cities for three megapolises in the 2070s, and Kikumoto et al. (156) and Arima et al. (157) assess thermal environment and building cooling loads in Tokyo in the 2030s. Kim et al. (158) combine scenarios for urbanization and climate change by 2050 to study urban climate evolution of Seoul, South Korea, for the month of October. Doan & Kusaka (159) perform a similar study for Ho Chi Minh City, Vietnam, during the dry season (April for 2050–2059). For the city of Brussels, Belgium, Lauwaet et al. (160) adopt a comparable dynamical downscaling from the climate limited-area modeling community (COSMO-CLM) regional model at 25, 7, and 3 km to the Urb-Clim model running at 250-m resolution for the summer period of 2060–2069.

The issue now is directly implementing urban canopy models in RCMs for long-term continuous simulations in the Intergovernmental Panel on Climate Change (IPCC) context. Langendijk et al. (161) analyze a set of the Coordinated Regional Climate Downscaling Experiment over Europe (EURO-CORDEX) RCM projections at 12-km resolution on Berlin. By describing the city as a rocky surface, they show that the RCMs simulate an urban effect but overestimate Tmax and underestimate Tmin for the Berlin area. On the basis of 12-km spatial resolution ALADIN-Climate simulations over France, Daniel et al. (162) highlight that nocturnal UHI is better simulated by replacing the standard approach (using rocks instead of cities) with a detailed urban canopy model. In addition, they show that the cities induce a regional warming extending beyond their urban area boundaries. For higher resolution, Hamdi et al. (163) also underline the benefit of coupling by comparing long-term simulations conducted over the city of Brussels, Belgium, with the 4-km-resolution ALARO RCM with or without the urban canopy model. Hamdi et al. (164, 165) then apply these results to feed 1-km urban climate simulations in a standalone mode for past and future climates. Finally, with the emergence of new resolved-deep-convection RCMs initially implemented for the study of convective phenomena and extreme precipitation (166), a new research axis related to urban applications is developing. As an example, Lemonsu et al. (167) investigate the capability of the AROME model to simulate urban climate over the Paris region with 2.5-km resolution and its evolution with climate change.

4.3. Urban Climate Response to Climate Change

Global climate change presents significant regional variability in climatic trends and hazards. Guerreiro et al. (168) analyzed the evolution of heat waves, droughts, and floods in 571 European cities between 1951–2000 and 2051–2100, based on RCP8.5 and 50 model runs. They noted disparities in impacts. Although heat waves become more frequent for all cities, a larger increase in associated maximum temperatures is found for Central European cities, and a higher increase in number of days for Southern European cities. The latter face a combined risk of heat waves and droughts, whereas cities in Northwestern Europe are subject to an increased risk of flooding. Conducting statistical analyses by climatic analogs is another approach that characterizes the future climate of cities in relation to the contemporary climate of other existing cities (169–171). At global scale, Bastin et al. (169) showed that northern hemisphere city climates shift by hundreds of kilometers toward warmer conditions, and tropical cities toward drier conditions. In Europe, maritime cities shift slower to the south than continental and eastern ones (171).

On the evolution of UHI in a changing climate, studies show quite systematically that the phenomenon does not intensify. Nighttime UHIs remain stable or decrease slightly (164, 172, 173, 174). The first global simulations including cities (175) have shown the generalization of this trend. In winter, the UHI decrease is linked to a decrease in domestic heating resulting from global

warming. In summer, it is related to an enhanced warming of rural areas compared to urban (due to surface properties) in response to an increased longwave radiation forcing. During the day, the urban cool island phenomenon intensifies given a more pronounced drying of natural soils around the cities because of background warming (160, 172). However, these simulations do not consider urban expansion. Chen & Frauenfeld (176) and Doan & Kusaka (159) found a more marked increase in temperature in urban than surrounding rural areas (especially at night) by accounting for urban expansion for Asian cities. It results from a change in surface albedo and surface energy balance, and an increase in anthropogenic heat emissions. For US cities, Krayenhoff et al. (177) noted a warming trend but limited by a nonlinear interaction between the two drivers—climate change and urbanization—in agreement with Li et al.'s (178) findings. The latter highlighted the predominant impact of heating in winter and the crucial role of precipitation in summer that controls the water availability and evapotranspiration that promotes urban–rural temperature contrasts.

Mitigation of climate change: actions to reduce the sources, or enhance the sinks, of greenhouse gases to limit climate warming

The living conditions of urban populations can be significantly impacted by these evolutions. Studies show a worsening of heat stress conditions (155, 156, 159). In addition, the occurrence of heat waves leads to an increase in energy consumption for air-conditioning (157, 179). The work carried out for the Paris region (180–181) showed that UHI and impacts on comfort, energy demand, and water resources evolve differently according to urban expansion scenarios reflecting different urban planning policies.

Very few studies investigate the interactions between urban expansion and precipitation trends. Gu et al.'s (182) recent study based on past time series of precipitation observations over China indicates that the urban effect is significant compared to the background trend at the regional scale. However, Chen & Frauenfeld (176) did not highlight a consistent trend in future precipitation related to urbanization over the megacities Shanghai, Beijing, and Hong Kong.

5. THE ROLE OF URBAN CLIMATOLOGY IN THE CITIES AND CLIMATE CHANGE GLOBAL AGENDA

5.1. Cities and Global Climate Change Agendas

The IPCC has recognized the key role of cities in responding to climate change and has proposed that the seventh assessment cycle include a Special Report on Climate Change and Cities. First, cities are hubs of high GHG emissions that contribute to large-scale climate change. At the same time, they suffer from the consequences of climate change through a generalized rise in temperatures and sea level, the modification of precipitation regimes, and the intensification of extreme events such as heat waves, storms, and cyclones. Those impacts overlap and exacerbate the impacts of the local urban climates described above.

One of the obstacles to consider is how to best incorporate the rich local climatic knowledge that already exists into the global agendas (such as, for example, IPCC reports). One of the challenges for the communities of climatologists working at global and at local scales will therefore be to produce knowledge that takes advantage of the high spatial resolution that characterizes local climate issues but that can also contribute to political coordination at the global scale.

Bridging this gap is one of the objectives of the Urban Climate Change Research Network. It has been dedicated to the analysis of mitigation of climate change and adaptation to climate change from an urban perspective for ~15 years and has published periodic reports, the most recent in 2018 (183). To further stimulate the production and exchange of knowledge on this subject, the IPCC, supported by various international networks and associations [C40, Cities Alliance, ICLEI (Local Governments for Sustainability), Future Earth, Sustainable Development Solutions Network, UCLG (United Cities and Local Governments), UN-Habitat (United Nations Human

Heat mitigation: modifications to urban characteristics and behaviors made with the objective to reduce urban temperatures where they pose a negative impact

Settlements Programme), UN-Environment (United Nations Environment Programme), and the WCRP (World Climate Research Program)], organized the 2018 "Cities and Climate Change Science Conference—CitiesIPCC" in Edmonton, Alberta, Canada. The synthesis of contributions from that event gave rise to a document titled "Global Research and Action Agenda on Cities and Climate Change Science" (184). This Global Research and Action Agenda aims to guide future research to make it useful for "effective policy development for climate action in cities" (184, p. 8).

Recent knowledge from urban climatology can contribute to reach some goals of the Global Research and Action Agenda on Cities and Climate Change Science in several ways. Above, we focused extensively on city-level modeling and data. Here, we show as examples two other aspects: urban planning and design for future cities and knowledge sharing with local stakeholders.

5.2. Urban Planning for Climatic Adaptation Strategies

The combined effects of UHI and heat waves lead to a composite risk that clearly mixes two climate scales: urban climatology and climate change. Events in Europe in 2003 (185) and Moscow in 2010 have resulted in high mortality. Because the UHI is most intense in the densest parts of the city, more people are affected. However, poverty, poor housing conditions, lower rates of access to air-conditioning, and hypertension in seniors are also important factors that affect health outcomes (186). Akbari & Kolokotsa (187) give a panorama of three decades of UHI reduction and urban heat mitigation technologies. They identify two research foci. The first is the evaluation of summertime effects of urban heat (188) on energy use, air pollution, outdoor ambient temperature, and (to a lesser extent) citizen health. The second is the development and evaluation of so-called cool materials to counter the effects of high summer temperatures (e.g., 189).

Studies that compare the effect of several heat mitigation measures are typically less common than studies that focus on a single heat mitigation measure. This poses a problem for policy makers, who must decide on the priority and implementation of heat mitigation measures (190). Shooshtarian et al. (191) emphasize that behavioral adjustments and psychological adaptation must also be addressed. Finally, Hintz et al. (192), for America, Europe, and Australia, and Ng & Ren (193), for Asia, explore the transferability of solutions mostly based on the use of green (vegetation), blue (water), or gray (built) infrastructure. They highlight city administration as a pivotal actor for implementing solutions and emphasize the importance of inhabitants as well as local governments as essential actors for adaptation to urban heat waves.

5.3. Methods to Facilitate Sharing of Knowledge in Urban Microclimate Management

Great efforts are being made by urban climatologists to adapt or provide new methods and tools that facilitate the communication of knowledge. Those include adaptation of methods commonly used as modeling or cartographic tools to fit end users' needs, and the use of resources from other disciplines, typically human and social sciences, such as surveys or analysis of relevant policy documents such as government reports, white papers, and reports published by nongovernmental organizations (194).

Onur & Tezer (195) used surveys to define and verify the existing and future vulnerabilities in Istanbul. Živojinović & Wolfslehner (196) used interviews to better understand the role of decision-making in urban forestry in the city of Belgrade and to assess the perceptions of urban forestry stakeholders toward climate change adaptation. Finally, Mason & Fragkias (197) used organization members' mental models to investigate the potential of metropolitan planning organizations to play a formative role in climate change action and policy. The cited methods are

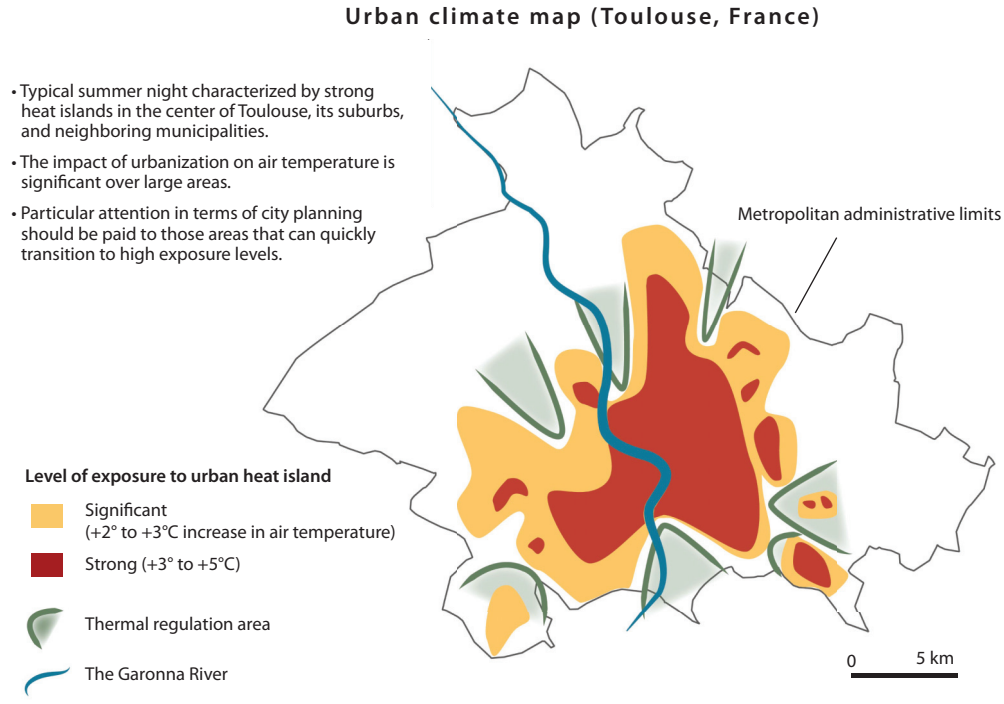


Figure 7

Climate map of the zones at stake from a nighttime thermal comfort management perspective. This example was developed in Toulouse (France) through a collaborative process between scientists, urban planners, and city administration. Abbreviations: MApUCE, Modélisation Appliquée et droit de l'Urbanisme : Climat urbain et Énergie; LISST, Laboratoire Interdisciplinaire, Solidarités, Sociétés, Territoires.

a good example of how interdisciplinarity provides clues to understand the lack of coordination and communication between stakeholders, needs of scale-relevant technical and scientific data, and needs of specific regulations and financial means.

A recent development is holistic approaches. Kraucunas et al. (198) developed the Platform for Regional Integrated Modeling and Analysis to simulate interactions among regional climate, hydrology, agriculture and land use, human systems, socioeconomics, and energy systems at scales relevant to regional decision-making. The platform can be customized to inform a variety of complex questions, such as how a policy in one sector might affect the ability to meet mitigation of climate change targets or adaptation goals in another sector.

Hatvani-Kovacs et al. (199) present recommendations for a range of integrated policy measures to increase the heat stress resilience of urban populations in Australian cities. Mahlkow et al. (200) create exploratory and anticipatory storylines for 2040–2050 using constellation analysis for heat adaptation in urban planning for the case of Berlin. Finally, cartographic tools such as urban climate maps (**Figure 7**) are being used both for climate analysis at the local scale (29) and as intermediary objects (194) that facilitate communication and climate knowledge coproduction at all stages of the urban planning adaptation process. Finally, Baklanov et al. (201) provide an overview of recent research activities of the WMO and collaborators in urban hydrometeorology,

Interdisciplinarity: way to perform research efforts that integrate knowledge and methods from different disciplines into a coordinated and coherent whole

climate, and air pollution and introduce the concept of urban integrated weather, climate, and environment-related services, highlighting research needs for their realization.

6. CONCLUSIONS

Global agendas on cities and climate change encompass a very large range of aspects, linked to mitigation of climate change and adaptation to climate change. As detailed above, recent knowledge in urban climatology can contribute to address these, especially those linked to data and models at the city scale, urban planning and design, green and blue infrastructure, knowledge coproduction, and fostering of long-term science-policy-practice collaborations.

While continuing to observe and understand the various specificities of the microclimates of cities, urban climatology has transformed from a physical science in the twentieth century into a broader, interdisciplinary science. This is due to the very nature of the complex city system. New scientific challenges also arise. These include the use of crowdsourced meteorological data and deep learning fields, the impacts of urban climate and the heat island on health, and the transfer of climatic information to city end users. New concepts based on a comprehensive description of the urban surface form and function (at neighborhood scale), by urban climatologists, geographers, and urban planners (53), facilitate such transfer.

Kilometric-scale RCMs, coupled with an urban surface scheme, are now emerging. Beyond the scientific challenges, this will allow different scientific communities focusing on, for example, climate change modeling, local urban climate, and societal impacts to work together on a common object, which is the city under climate change. Studies show that the UHI does not intensify in a changing climate and may even reduce during the daytime; however, the extra urban heat will have more impacts in the case of hotter heat waves.

Various societal needs, at different temporal scales—from storm and emergency management and recovery to urban planning—exist and should be addressed by the scientific community in an interdisciplinary way. This will permit the provision of urban weather and climate services that are of use for city administrations and stakeholders (201, 202).

SUMMARY POINTS

1. The study of urban climates has transformed into a broad interdisciplinary science that spans the social and physical sciences and recognizes the complexity of the city system.
2. The urban heat island is mostly created by the nighttime release of the heat coming from the sun that is stored during the day by impervious materials; direct heat release by human activities usually has a smaller role.
3. Research has now begun to examine the urban climate of cities in complex geographical landscapes.
4. Knowledge transfer to city end users has been facilitated by the development and adoption of the local climate zone (LCZ) classification scheme that provides a readily interpretable classification of surfaces in and around cities that is climatically relevant.
5. Models simulating urban effects in atmospheric models start to consider, in addition to urban physics, the urban vegetation, building energetics, and sociological processes. These incorporations are critical to correctly determine the impact of both climate change and mitigation efforts on human thermal comfort and building energy use in cities.

6. Urban canopy models can now be implemented online in regional climate models for long-term climate simulations with the objective of assessing city-scale climate impacts and feedback of urban processes on regional climate.
7. A variety of methods are now available to facilitate the communication of knowledge and decision-making that can be used to assist in the urban planning adaptation process. Holistic and integrated approaches to urban climate services are a current trend.
8. City administrations are a key actor for implementing solutions and urban inhabitants, and local governments are essential actors in contributing to the global agenda on cities and climate change.

FUTURE ISSUES

1. How can we make use of crowdsourced meteorological data and deep learning methods to better understand urban climates?
2. Modeling advances will require consideration of a hierarchy of models to represent scales and methods to bridge these scales.
3. There is a need to incorporate a more holistic modeling framework that incorporates feedbacks across scales from all components of the urban ecosystem. This holistic framework will also allow different scientific communities to work together on urban-scale issues.
4. Cities worldwide need to adopt urban weather and climate services to provide appropriate information to city administrators and urban stakeholders.
5. Urban climate community scientific studies need to be better linked to climate change assessments and international actions (e.g., Intergovernmental Panel on Climate Change and World Meteorological Organization).

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