Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Climate Sciences*
PERSPECTIVE

Between progress and obstacles in urban climate interdisciplinary studies and knowledge transfer to society

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Cities modify their local climate, and at the same time they suffer from the local impacts of climate change. Our paper discusses the progress and obstacles in three active research topics that contribute to increasing the capability within the urban climate research community for transferring local climate knowledge to society. The first is linked to the production of urban surface descriptions useful for urban climate studies. The concept of *local climate zones* is now widely used to represent urban climate variability at the neighborhood scale. Land-use, morphological, architectural, and social data are also needed, and those are being gathered using different approaches. The second is linked to the necessity for producing information directly connected to their effects on society. This requires a strong multidisciplinary approach, and nowadays impact studies are not limited to one dimension but instead cover multiple dimensions. The third is to transfer all this information to city practitioners, so that urban climate features are considered, among many other aspects, in city management. For urban planning, cartographic tools have been introduced to include urban climate diagnosis as well as recommendations for future urbanization.

Keywords: urban climatology; urban data; climate impacts; urban planning; urban climate maps

Introduction

A distinctive urban climate is created by a city, which disrupts local and regional atmospheric features by altering the surface–air exchanges of heat, moisture, mass, and momentum.[1] This effect is present at all scales and influences the magnitude of every meteorological variable. It depends on the city's physical structure (urban form) and pattern of occupation (urban function). The most widely studied and known by the public/mediated urban climate effect is the urban heat island (UHI), which describes the differences in surface, subsurface, and air temperatures in cities when compared with the surrounding natural environment.[2] Other impacts include changes in turbulence and general flow dynamics as the overlying air adjusts to the complex urban surface, which influences the dispersion of air pollutants and heat emitted near the ground.[3]

Urban climatology has become both an international and interdisciplinary research field. The transnational diffusion of research developments in urban climatology within the research community has been successful for some decades. Historically, this circulation of knowledge has occurred through meetings organized under the auspices of major international networks, such as the World Meteorological Society (WMO), the Conféderation Internationale du Batiment (CIB), the International Federation for Housing and Planning (IFHP), the International Society of Biometeorology (ISB), the World Health Organization (WHO), and, more recently, the International Association of Urban Climate (IAUC). Hebbert and Mackillop[4] give a very accurate account of the dissemination of this knowledge, starting in the late 1950s in Davos with an international working group on urban climatology involving IFHP, ISB, and CIB, until the present day, when IAUC took over the cycle of conferences and the structuring of research networks on the international scale. This successful international

doi: 10.1111/nyas.13986

research collaboration and its consequent knowledge exchange and network development can be explained by the fact that key figures in urban climate research participated in these international structures in various capacities. This continues to be the case today, as some IAUC members are deeply involved in WMO or ISB, for example.

While it is common to refer to L. Howard's pioneering work at the beginning of the 19th century,[5] and later to T. R. Oke as a great contributor boosting the field from the 1970s, research describing atmospheric conditions over urban areas has accelerated during the last decade, taking advantage of the development of new numerical modeling technologies and attracting an increasing number of scientists from different disciplines and locations all over the world. Physical geographers and experts on atmospheric physics dominated this field in its early years, directing the scope and the methods applied for studies of the outdoor environment, while architects were, generally speaking, more focused on studying the indoor microclimatic conditions at the building scale. These studies examined both the impact of urban development upon all aspects of the atmosphere and the response of populations to the resulting climate. The spatial scales studied ranged from that of the building or the street to that of the entire city. A gradual broadening has taken place in recent years, including studies in fields such as urban hydrology, building climatology, urban vegetation, and urban planning, that incorporates specialists and enriches the research field.

Urban climate science has made significant progress in linking the properties of the urban surface cover, including its extreme spatial heterogeneity, to changes in the overlying atmosphere, which is called the urban boundary layer. Significant gaps in the understanding of processes do remain, but it is generally acknowledged that the outstanding issue for urban climate science is the need to transfer its knowledge to urban decision making. Efforts to transfer urban climate knowledge to society started very early, as attested, for example, by Kassner's book "The Meteorological Basics of City Planning,"[6] published in German in 1918, and the reader will find a comprehensive review in Hebbert and MacKillop,[4] but coordinated efforts and discussions within the research community at the international scale are more recent. The International Conference on Urban Climatology (ICUC8, August 2012, Dublin, Ireland) included a plenary session on applied studies in urban climatology; 3 years later, at the ICUC9 (July 2015, Toulouse, France), coinciding with the year of the 21st session of the Conference of the Parties on Climate Change Policy & Practice held in December 2015 in Paris, it was clearly decided to focus "on the recent scientific activities on climate change mitigation & adaptation in urban environments, as well as on the transfer to institutional stakeholders and urban planners to include urban climate considerations in their practices." Concerning transfer of urban climate knowledge, the session dedicated to "Transfer of urban climate knowledge to urban planners" and the session on improving "Urban design with climate" drew strong attendance. Other related sessions were "Bioclimatology and public health," "Outdoor microclimate and comfort," "Indoor comfort & air quality," "Human perception," "Climate resilient design" as well as those dedicated to "Interdisciplinarity," attesting to the importance of applied research in this domain. The ICUC10, held last summer in New York, consolidated this dynamic, holding numerous sessions on urban planning and governance, and comfort and impact studies.

The specificity of the research findings for each individual terrain makes it difficult to compare results and to increase generality. This should not be understood in terms of results, as urban climate knowledge transfer will emerge from widely differing contexts depending on the needs and identity of decision makers, but in terms of methods and tools. The field needs to transcend local case studies and develop standardized methods, the objective being to develop ways to link climate knowledge and planning knowledge for cities everywhere. That objective is twofold: first, to allow the comparison of research results between locations; and second, to take advantage of the observation protocols and modeling and cartographic tools developed in recent decades, mainly in the North. Considerable effort has been made, for example, on experimental protocol guidelines for identifying and studying the impact of cities on atmospheric thermodynamics and atmospheric composition in a comparable manner.[7] The research community has also actively developed a rich literature reviewing the progress in atmospheric measurements in urban areas and modeling on a variety of scales based on both numerical and experimental approaches.[8–11]

This paper presents three active research topics that, in our opinion, contribute to increasing the capability within the urban climate research community for transferring its knowledge to society. It aims not so much to draw up an exhaustive review as to give a quick overview of the state of research activity to illustrate where we stand today. These interdisciplinary topics are presented and commented on here mostly through their technical aspects, methods, and tools, rather than on the basis of their policy implications or how they relate to different categories of end-users, which in this paper will refer mostly to urban planners. First, we present the efforts related to urban data production, putting the emphasis on the fact that coherent and consistent urban databases suited to urban climate studies containing information on both urban form (land-cover, materials, and building dimensions) and function (occupation patterns) are still in the early stages of development. Urban data infrastructure is important both for impact studies in urban environments—to evaluate strategies for adaptation to climate change and urban climate mitigation—and for the integration of local climate knowledge in urban planning, where considerable efforts have been made in recent years to bring to light the catalysts and obstacles for this integration.

Urban datasets for urban climate studies

An adequate description of the cities is necessary at all different steps of the process of implementing cities' strategies for adaptation to climate change and mitigation of UHIs. This description encompasses issues regarding the scale as well as the nature of the data.

Scale issues

Cities are complex systems in which physical, economic, biological, social, and other processes interact. Therefore, the description of a city also encompasses a number of spatial scales, ranging from the individual, housing, and buildings, to the neighborhood, the city, and the wider conurbation. In urban microclimatic studies, we often focus on three different spatial scales:[12] mesoscale, encompassing the whole city (which is the scale where the UHI is typically defined, as, for example, the difference of temperature between the city center and the countryside); local scale, where neighborhoods experience different microclimates (e.g., a suburban residential area with gardens and small houses and a commercial area with a lot of car parks next to it); and microscale, where variability is governed by individual urban features (e.g., cool air below a tree; a ventilated street; warm and cool air on two sides of a house; etc.)

Many methods have been used to describe cities at the mesoscale and local scale, in modeling or analyses in direct link with decision makers. However, this is in general a city-case or model-based approach that is not sufficiently generic for application in another context. This is why urban climate heterogeneity at the neighborhood scale has been conceptualized by *local climate zones* (LCZs),[13] which are now widely used by the urban climate community and represent urban areas that are relatively homogeneous in type or urbanization. LCZs represent either the rural landscape (in seven classes: dense or scattered trees, bush, low plants, bare soil, bare rock, and water) or the urban one (in 10 classes: compact or open high-rise buildings, compact or open mid-rise buildings, compact, open or sparse low-rise buildings, large low-rise buildings, heavy industry, and lightweight low-rise buildings).

Because of their relative homogeneity, LCZs are supposed to homogeneously influence the atmosphere on the local scale, producing locally homogeneous air temperatures. Experimental mobile near-ground atmospheric measurements (with cars or bicycles, for example) have been performed to assess this, by documenting the inter- and infra-LCZ microclimate variability.[14–16] In Figure 1, it is possible to relate the near-surface air temperature with the ground use and building morphology represented by the LCZ.

LCZs represent the urban tissue on the local scale from the urban climate point of view. Furthermore, because they refer to urban structure shapes, they are easily understandable by urban planners, and thus are an efficient way to foster knowledge exchange between meteorologists and urban practitioners. An example of this is shown by the initiative of the Greater Paris urban planning agency to produce LCZ maps of its territory, in order to represent the potential effect on the microclimate.[17]

State-of-the-art atmospheric and climate models are not able to represent the whole urban area climate on the microscale. They are able to represent hectometric and kilometric scales,

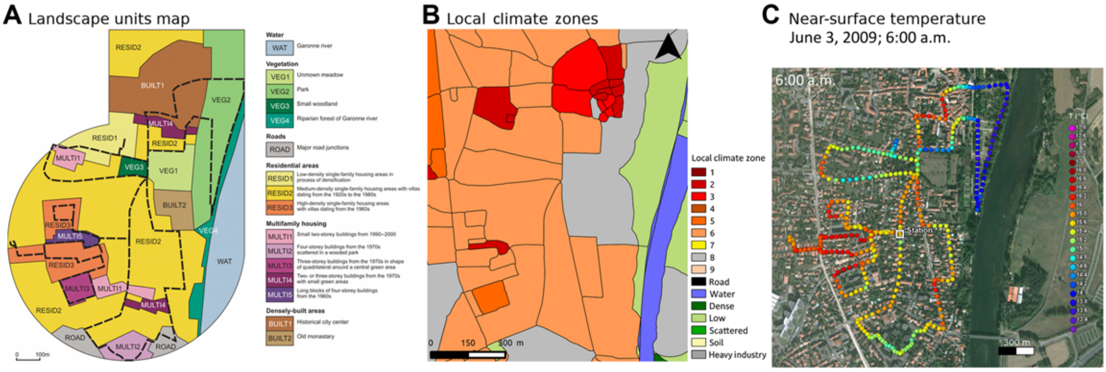


Figure 1. Relationships between landscape unit maps (A), local climate zones (B), and near-surface air temperatures (C) from bicycle measurements for a residential area close to Toulouse (Blagnac, France).

respectively. The finest-scale processes are then modeled in a simplified manner. For example, all urban canopy models in the atmospheric models represent the complexity of 3D buildings as street canyons or aligned cubes. However, these state-of-the-art models are now able to model both meso- and local scales, even for climatic studies over several years. This scale is, for example, adequate for simulating not only UHIs, but also city-induced extreme precipitation events, as can occur in megacities in China or the United States.[18] As the local-scale meteorological model meets the LCZ spatial-scale model, the LCZ approach is a very pertinent description of the city for current urban climate models.

Several initiatives have been launched in order to provide LCZ-based descriptions of cities for such meteorological urban climate models. To have such information on the whole world, for any urban area in any country, is a challenge. Using satellite images may help to address that challenge. However, most land use maps at the global scale, such as the ESA-CCI product 1.6.1 of 2016, which focuses on natural and agricultural landscape classifications, only delimit the urban area as a single class. One way to obtain a description of the intra and intercity variability is to provide spatialized information on some urban parameters. For example, Dong *et al.*[19] determined a global 1-km resolution map of anthropogenic heat flux using nighttime light satellite images. Another way is to produce maps with finer urban classifications. Refined urban classifications do exist, but they are generally limited to a region (such as CORINE Land Cover over Europe[20]).

The most advanced global urban database suitable for environmental and meteorological/climatic studies, to our knowledge, is the Global Human Settlement Layer, at a resolution of 100 m. Its classification schema for settlements distinguishes built-up areas based on vegetation content (from satellite NDVI vegetation index) and volume of buildings, the latter estimated from integration of satellite terrain and elevation data from SRTM and ASTER-GDEM.[21,22] Nine urban classes are defined, with an approach very similar to the LCZ, since it is based on the amount of impervious land use and the height of buildings. An ongoing task is the inclusion of this urban database along with LCZs in the second generation of the Ecoclimap database,[23] which will then finely describe the vegetative covers (based on ESA-CCI and ancillary data) and urban covers.

LCZ maps of cities, maps that are, in principle, more precise and expert based, are awaited from the World Urban Database and Access Portal Tools (WUDAPT) initiative. This is an IAUC community-based project to gather a census of cities around the world.[25] The WUDAPT methodology is based on the LCZ-mapping of cities using satellite images, such as landsat,[24] with a common protocol, ensuring relative consistency between each map's representativeness. This protocol is based on an iterative process with expert supervision. First, the expert manually defines several neighborhoods for each LCZ present in the city and its surroundings. Second, a classification process is used to classify all the images that cover the urban area under study. If necessary, the expert repeats the first step to improve the mapping. Finally, a quality control process is carried out. LCZ maps produced this way have been successfully used in atmospheric models.[26] The association of urban parameters (e.g., building height and building cover) in those models by means of information from LCZs alone is presented in Ching *et al.*,[27] as well as ways to include finer data when available. All architecture-related information on building construction (e.g., roofing and wall materials, and presence of windows) also needs to be defined. Tornay *et al.*[28] propose a methodology to gather this information on the regional scale. This will make it possible, for example, to describe how buildings or houses are (differently) built in several regions and countries of the world (e.g., in Western European, Chinese, South American, or equatorial African cities). In the framework of WUDAPT, two actions have been initiated to achieve this: by crowdsourcing using mobile app surveys and by collaboration with architects at the global level. For the latter, the Passive Low Energy Architecture (PLEA) association joined the WUDAPT initiative along with IAUC, enlarging the WUDAPT scope in terms of scientific methodology as well as potential users. A mixed working group of architects and climatologists from 20 countries was formed during the PLEA 2017 conference, and dedicated sessions on WUDAPT will be continued during PLEA 2018.

The main drawback of WUDAPT is that, as it is based on a subjective classification, it is done city by city (or sometimes for a larger region), and thus is not expected to cover all cities in the world, at least not for many years. A promising way to take advantage of this improved mapping of some cities is to include them in the above-mentioned global maps, which are based on the same LCZ typology.

Multicriteria impacts

Another reason to have a finely detailed description of the city is related to the need for multicriteria impact assessment (see below). For example, energy consumption due to domestic heating and air conditioning is strongly related not only to the morphology of a building, but also to its architectural fabric and use (e.g., as office, residential, or commercial space). Furthermore, energy consumption is linked to how people use their heating and cooling systems and what their comfort temperature is. And to assess societal impacts, this information must be correlated with societal and demographic information. Urban vegetation, depending on its arrangement, type, and even species, can also influence thermal comfort, flooding mitigation, and water resources.

Such information cannot be derived from remote-sensing approaches; there is a need for bottom-up mapping, using fine-scale source data (typically at building and road scale).

(Specific) City maps from fine-scale data

Many geographical studies have been performed in the past in order to provide such fine-scale and multiparameter descriptions of cities (e.g., Ref. 29). However, such urban climate-oriented fine-scale analyses on a particular city were strongly limited in their applicability, with reference to methods, to another city, even in the same country. The reasons were twofold:

- Such analyses require strong competencies and are generally performed specifically for a given area by a specific urban actor or researcher;
- And, even more crucial, the variety, accessibility, and homogeneity of the input source data are extremely diverse and limited to the area: fine-scale building model data can apply to a given city and not to one nearby, or the data may be (and most often are) in a different form and content.

These limitations imply that few cities have fine-scale urban data available for micrometeorological studies, and when they do it is usually owing to local action. However, spatially homogeneous information is crucial for defining standardized, or at least generalized, interfaces between urban data and meteorological models.

Some initiatives have been conducted on a larger area to provide a homogeneous urban description. Note that this information is generally limited to land use or morphological parameters (such as building height and building density). Two examples are NUDAPT, where approximately 40 of the biggest cities in the United States were mapped using building elevation data,[30] and Urban Atlas, describing 305 cities of more than 50,000 inhabitants in Europe.[31]

However, the main drawback of these approaches is that they provide information only on the biggest cities, information that is limited to the cities' administrative boundaries. The description of the (sub)urban areas outside each main city is lacking, and this limits the atmospheric modeling of the UHI and urban climate, given that airflows freely cross administrative boundaries.

New approaches for urban descriptions for (micro-) climate studies

New approaches are currently being developed to produce an urban description of a complete area (not limited by the city's administrative boundaries), covering a larger number of parameters, for example, including a building's use.

These approaches require a homogeneous and spatially continuous source of data on a large area. This is the case for data on France as a whole that was generated by its national geographic institute, and that has been used in the MAPUCE project. And this is also verified by the OpenStreetMap (OSM) project, even if its completeness varies from one country or location to another. The openness and variety of this worldwide database promotes new research to extract pertinent information for urban mapping worldwide.

Samsonov *et al.*[32] used OSM with an urban canyon object-oriented approach to define maps of some urban parameters, such as the canyon height-to-width aspect ratio or building coverage fraction, for Moscow, Russia. The potential richness of the information provided by OSM offers the prospect for mapping socioeconomic information, such as the nonresidential usage fraction in buildings and even population density, as was done for Dresden, Germany by Kunze and Hecht.[33] Bocher *et al.*[34] produced a great deal of morphological as well as typological building information for France based on an extensive French 2.5D building database. This was complemented by demographic and sociological indicators from national surveys on the neighborhood scale. This allowed Schoetter *et al.*[35] to model inhabitants' energy behaviors and their impact on energy consumption, waste heat, and the urban microclimate.

These developments in both concepts—LCZs as well as the gathering of fine-scale data—make it possible to produce urban climate analyses either from urban meteorological observation networks or numerical modeling. The next step in transferring this physical information into useful knowledge is to provide pertinent multifactor indicators.

Analysis methods and impact indicators

As pointed out in the introduction, urban climate study covers a multitude of research topics. The topics are historically mostly related to analysis and modeling of physical processes of the urban climate, interactions between surface and atmosphere, and the impact on local meteorology and the atmospheric boundary layer. These are of course still being investigated by the scientific community today. Nonetheless, a new field of research has been growing continuously for several years, related to expectations of civil society and public and political stakeholders. This momentum is driven by the fact that cities are a concentration of populations, infrastructures, and economic activities, which can be affected by nuisances of various kinds and are vulnerable to a host of environmental impacts. More especially, the professionals in charge of living environments and urban planning are currently quite concerned by artificialization of pervious soils related to the urbanization process, and associated UHI issues that may lead to public health problems. Added to this are the local effects of climate change that could significantly exacerbate still existing issues.

In order to provide information that is relevant and of real added value for decision makers, three main objectives must be addressed:

1. Impact studies should not be limited to one dimension but ideally cover multiple dimensions that are likely to interact, in order to produce multicriteria indicators;
2. The physically based data derived from numerical models or other types of sources have to be translated or transformed into information that is more directly connected to the effects on society (which can be effects on people or on the economy, for instance);
3. From a risk management point of view, the first step required in risk assessment is to evaluate the degree of vulnerability or exposure that cities or populations are subjected to (the subject must be defined), as well as the hazard concerned, that is, the type of event and the probability of its occurrence.

Systemic approach

The city is a complex ecosystem where diverse and heterogeneous elements interact: built-up infrastructures, natural areas, people, multisectoral activities and services, etc. Present-day meteorological conditions (the weather) and the way they evolve in a changing climate may influence the urban ecosystem and its functioning. Impacts may concern different sectors related to the elements composing the system. And the evolution or modification of one of these elements may also impact other elements or the system as a whole. A purely single disciplinary approach for impact studies is consequently limiting. Some recent research has adopted systematic and interdisciplinary approaches[36,37] by integrating different models or enhancing existing models with new processes, and by feeding the models with integrative scenarios for cities.

Urban climate models were initially designed to compute changes in meteorological variables at the street level in a built-up environment, for example, air temperature, humidity, and wind speed. Efforts have been made recently to simulate the complexity of the urban environment more realistically. Urban vegetation interacting with built-up elements,[38–41] water exchanges between atmosphere, surface and soil,[42] as well as building energetics,[43–45] are new developments that have been recently implemented in urban canopy models. Such configurations now make it possible to explicitly model interactions between all these processes, to more accurately simulate specific adaptation strategies or urban design scenarios, and to enhance diagnoses. Urban scenarios describing how cities can evolve and which measures can be implemented are also an important part of this approach. They can concern various dimensions, including measures on buildings and urban design and larger scale urban planning policies, as well as interventions in transportation networks, or policies that encourage inhabitants to modify their habits (transport modes and energy behaviors). Demographic trends, urban expansion, and architectural evolution, for example, can be taken into account, based on collaborations with economists, geographers, architects, or urban planners. Some of these changes can be determined from numerical modeling. In particular, long-term urban expansion can be calculated using economic models, such as NEDUM,[46] or for shorter time periods using geographical models adjusted to past trends. Other developments, for instance related to implementation of local policies for building renovation, urban greening, or adaptation of public transportation, can be defined based on expert choices.

Defining indicators

Numerous studies evaluate urban design scenarios or strategies of adaptation to climate change only by quantifying the impact on air temperature or UHIs. While the indicator of this impact is one relevant indicator, it can be calculated in different ways, depending on the time of the day (daytime or nighttime), for a specific location, spatially averaged, etc., which means that results and conclusions can differ.

Studies in climate-sensitive urban design look at perceived (or "feels like") temperatures or people's thermal comfort for indoor and outdoor environments through the computation of indices such as the wet bulb globe temperature (WBGT), predicted mean values,[47] physiological equivalent temperature,[48] and universal thermal climate index (UTCI). These indices are related to heat stress scales, which make it possible to analyze threshold exceedance. These indices are now included as diagnoses of some urban climate models for weather forecasting or impact studies. Leroyer *et al.*[49] developed an urban-scale weather forecasting system for the 2015 PanAm Games in Toronto for the purpose of producing heat-stress maps using the Humidex, UTCI, and WBGT indices. Kusaka *et al.*[50] and Argüeso *et al.*[51] have investigated the evolution of comfort conditions in the future using the WBGT index, based on regional climate simulation with the weather research and forecasting model in Japanese cities and the Sydney region, respectively. Lemonsu *et al.*[37] and Daniel *et al.*[52] have studied the impact of urban expansion scenarios on UTCI for future heat-wave conditions over the Paris region. It is, however, difficult to decide which index to use, as well as how to analyze these indices to assess the impacts on the population in a standardized manner and provide relevant urban climate services for society and users. The needs and practices can vary significantly depending on the domains of application. Thus, the recent urban climate studies related to heat stress evaluation present a wide range of approaches. Thermal comfort can be computed at the most critical hours of the day or combined over time to evaluate potential prolonged exposure to uncomfortable conditions. For instance, Argüeso *et al.*[51] investigated seasonal averages of minimum and maximum values of thermal indices and analyzed how they changed over time, whereas Kusaka *et al.*[50] calculated the number of hours exceeding a certain heat stress threshold. Spatial analysis is also tricky. Thermal comfort can be studied as maps in order to identify sensitive areas or aggregated on the neighborhood or city scale. Lemonsu *et al.*[37] showed for the Paris urban area that the results can be substantially different if the averaging is done according to density of built covers or inhabitants.

Energy consumption for domestic heating and air-conditioning is also an important criterion in evaluating choices in urban design or planning, all the more so as this falls within the context of climate change and the objectives in greenhouse gas reduction targeted by countries worldwide. Most urban climate studies focus on energy consumption related to air-conditioning use, which could be a major issue within a global warming context given an increase in the risk of heat waves. But it is also important to assess the potential unintended consequences of some adaptation measures (or UHI mitigation measures) on domestic heating consumption. For instance, De Munck *et al.*[53] indicate that some forms of urban greening are efficient ways to cool air temperature during summer but that this cooling may persist in winter and increase demand for heating.

Water resources are also crucial for impact studies and this issue has begun to be addressed, especially in connection with irrigation and greening strategies, by urban models that consider water exchanges (including irrigation) and, in some cases, subsoil hydrology.

For a more objective and complete evaluation, indicators computed by urban climate models can also be put in perspective with indicators derived from urban design or planning scenarios. Urban expansion strategies, for instance, have a significant impact on CO_2 emissions owing to transportation. Economic cost, material life cycle, and carbon footprint (e.g., for building renovation or green space management) are also relevant criteria for evaluation, but they are complex to estimate.

Risk evaluation

Numerous impact studies for cities are being conducted under hot summertime conditions in order to evaluate the efficiency of some adaptation measures in cooling the urban environment. Past heat wave events like the one that occurred in August 2003 have often been taken as case studies. Nonetheless, this approach has two limitations. First, it focuses only on extreme heat conditions without considering multiyear or seasonal-scale effects. This can be crucial for some adaptation choices. Notably, in the case of greening strategies, vegetative and hydrological cycles require longer time periods of analysis. Second, the representativeness of a specific meteorological event can be questioned. In a changing climate, the frequencies of heat waves, as well as the characteristics thereof (intensity, duration, and severity), will evolve. Consequently, in order to evaluate urban vulnerability rigorously, it becomes necessary to take this statistical development into account.

The integration of local climate knowledge in urban planning and urban development

The international collaboration cited in the introductory section leads not only to a rich state of the art in research about the urban atmosphere in physical terms, but it has also led to the development of a rich literature presenting applied knowledge about the urban climate, to be used by planners for the practical purposes of urban heat–island mitigation and wind, rain, and snow management and for the effective use of green space to enhance air quality and human comfort. Nevertheless, the application of scientifically based knowledge to urban design has encountered difficulties in being disseminated and translated operationally, except for rare exceptions, as in German-speaking countries where numerous publications exist, ranging from the earliest ones, by Horsfall[54] in 1904 and Kratzer[55] in 1937, to the most recent ones, for example, by Stock and Baumüller,[56–58] to cite just a few, and, to a lesser extent, in Israel[59] and Japan.[60,61] Retrospectively, Hebbert and Mackillop[4] pointed to some obstacles that can account for the difficulties encountered with climate knowledge integration on the urban scale. They fall into two categories, those related to trends in urban fabric and town planning, and those related to the ways atmospheric knowledge is produced.

Concerning the urban fabric, two key aspects are put forward by the authors:

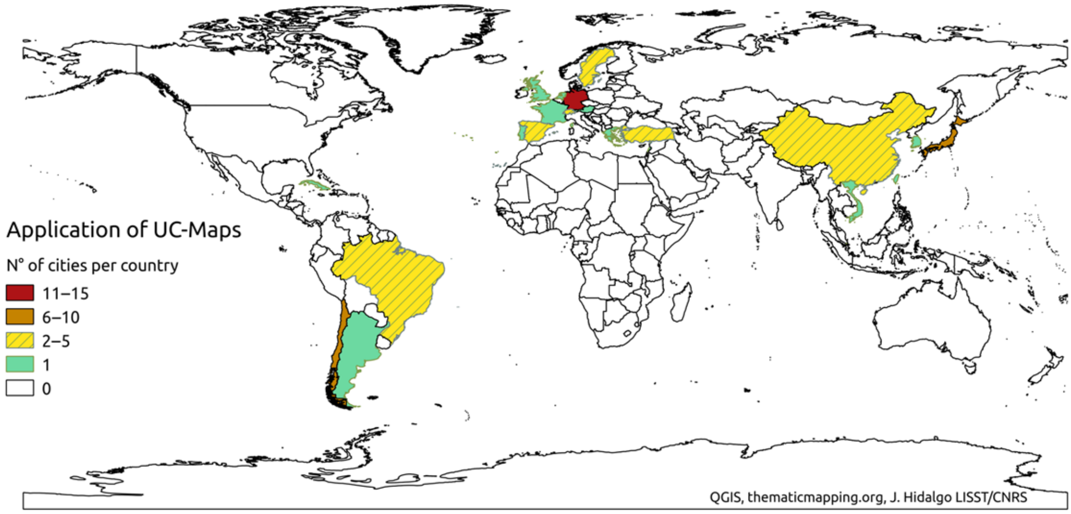
- The fact that modernism became the dominant global movement in the 20th century for urban production. This group of styles in architecture and urban design focused more on buildings rather than outdoor spaces, which were often considered solely from a landscaping point of view, neglecting climatic analysis.
- The fact that between the 1950s and 1970s environmental determinism gave way to environmental constructivism, resulting in waning interest in the impact of design decisions on the physical environment.

Regarding the basis of atmospheric knowledge production, the predominant disconnection between the national meteorological services that produce atmospheric data and analysis and the territorial planning professions is often pointed out. In urban areas, the complexity of the urban atmosphere requires location-specific and high-density observations, but the high cost of implementation and maintenance of standardized atmospheric measurements has made the general observational networks dependent on national meteorological services. However, given the nonurban orientation of main national weather services, which are dedicated chiefly to aviation, agriculture, weather forecasting, and national defense, meteorological data were historically collected for the most part outside of urbanized areas. The shift from physical measurements to numerical models in recent decades further reinforces the centralized character of the atmospheric knowledge production in the national and international meteorological services. A current initiative coordinated by WMO aims to correct this issue through the development of a "Guide for Integrated Urban Weather Environment Climate Services" that was opened for community review in March 2018.

The laborious and expensive nature of local climate studies is nevertheless rapidly improving thanks to the development of lightweight sensors, 3D urban databases that allow high-resolution mapping, and GIS platforms capable of being linked to multiscalar statistical models. Collaborative data approaches are also greatly penetrating urban climate research.[62] But the widespread application of urban climatology in urban design and urban environmental planning was especially facilitated in the last decade by the rising awareness of anthropogenic climate change, which gained in importance in both public and political opinion.[63] The two reports entitled *Cities and Climate Change*, published in 2011 by the United Nations and the Urban Climate Change Research Network,[64,65] put forward the role that cities should play in greenhouse mitigation and adaptation, and played a major role in placing climate issues on the agenda at the city level. It is time for the emergence of networks of cities committed to tackling climate change at international and national levels—networks such as C40, which was given impetus by the mayor of New York City in 2010, ICLEI–Local Governments for Sustainability, and the Global Cool Cities Alliance. The changing global climate has become, in a way, the window of opportunity for the transfer of climate knowledge on a local scale.

But what strategies and tools are available for operational application of urban climate science knowledge? Historically, the German-speaking research community has led the application of science-based climatic design with a systematization of local climate studies since the first half of the 20th century. Their cartographic techniques for mapping thermal distributions, cold air lakes and flows, wind patterns, pollution concentration, etc., combining meteorological and climate information, land-use data, and terrain information, have the advantage of fitting the needs of both urban planning practices and urban planning tools. Fine-grained spatial mapping started in Germany in the 1970s with The Climate Booklet for Urban Developments (1977) in Stuttgart and continued with the Klimaatlas published on 1992. The Stuttgart Klimaatlas methodology has been used in Europe, Asia, and South America, mostly adapted from the earlier German model and following the German Guidelines VDI3787 Part1 Environmental Meteorology – Climate and Air Pollution Maps for Cities and Regions, first published in 1993 and updated in 2015. In recent years, urban climate maps have become a reference tool for translating scientific climatic knowledge into guidelines and planning recommendations.[66]

Different names are used for these cartographic tools depending on the country and scale of action, but the name urban climate map (UCMap) has been widely used in recent years. Technical choices on how to produce these cartographic tools depend on local climatological features, the available data on



Germany
1978 Stuttgart
1978 Hanover
1979 Berlin
1985 Essen
1988 Dortmund
1988 Munich
1992 Münster
1993 Kassel
2002 Heildelberg-Mannheim
2003 Freiburg
2009 Frankfurt
2015 Hesse
2016 Darmstadt
2016 Fulda

Chile
2015 Santiago
2015 Antofagasta
2015 Calama
2015 Valparaiso
2015 Concepcion
2015 Chillan

Japan
1991 Kagoshima city
1998 Osaka
1998 Fukuoka
1998 Kobe
1998 Okayama
2000 Tokyo
2008 Sakai
2009 Yokohama
2015 Sendai

Brazil
2006 Belo-Horizonte
2006 Salvador
2015 Campinas

China
2007 Hong-Kong
2015 Wuhan
2017 Xiamen

Spain
1990 Gran Canaria
1990 Valencia
2013 Bilabo

Sweden
1989 Stockholm
1989 Gothenburg

Switzerland
1995 Basel
2001 Grenchen
2001 Umgebung

Turkey
2015 Erzurum
2015 Kayseri

Austria
1999 Graz

Argentina
2015 Tandil

Corea
2015 Seoul

Cuba
2009 Havana

France
2018 Toulouse

Greece
1996 Athens

Lebanon
2015 Beirut

Netherlands
2009 Arnhem

Portugal
2009 Lisbon

Singapore
2015 Singapore

Taiwan
2013 Kaohsiung

UK
2015 Manchester

Vietnam
2015 Ho Chi Minh

Figure 2. Application of urban climate maps (UCMaps) around the world in 2018. Colors indicate the number of cities per country that initiated studies on UCMaps and recommendations for urban planning applications. The table indicates the date of the first published study for each city.

urban morphology and climate, and the scientific and cultural background of the actors (researchers and stakeholders) involved in the project. Climatological data can be produced through observations (permanent meteorological network or field campaigns) or modeling (often on the neighborhood scale). As atmospheric information is needed for the whole city, spatialization techniques are often used to statistically quantify the relations between the physical surface of the city and the meteorological variables, assuming that, for some specific weather situations, such as anticyclonic situations with low wind speed, local climate conditions within the urban canopy are mainly driven by urban surface features. Numerical simulations coupling an atmospheric model with a soil-vegetation-atmosphere transfer model can also be used to take into account the impact of the physical surface (e.g., land use, topography, and urban morphology) on the atmospheric fields and the atmospheric dynamics for the whole city scale. This approach is particularly useful for integrating the multitude of weather situations representative of a place in the cartographic representation.[67]

In Ng and Ren[66] and Figure 2, experiences developing UCMaps are presented for large, medium-sized and small cities around the world. It appears, though, that only in very few cases is the translation of recommendations for urban planning derived from the climate diagnosis really taken into account at the operational level in land-use zoning, design codes, or green-space and water area management. Since the scientific basis and technical tools for local climate diagnosis exist, what are the specific reasons behind the fact that climate information is successfully transferred in some places, matching both policy and regulatory engagement, and not in others?

Planning advice is sometimes commissioned by practitioners and planners but often the study is promoted and funded by the producers of climate data, who are almost always researchers. However, what is observed[66,68] is that all the successful examples of urban climate management entailed two key ingredients: the presence of a community research team—implemented to the maximum by the city of Stuttgart with the presence of in-house urban climatologists—and a long process of collaboration and acculturation between researchers and practitioners. It seems that research developments in urban climatology are effectively boosted by international collaborations and networks, but effective transfer and implementation are done from the bottom up. This does not mean that top-down setting of targets by the national government for local governments is not an effective way to boost the development of environmental and climate codes at the local level,[70–72] but, as also pointed out by Webb,[69] the coproduction process that allows site-specific policy and regulatory application, stabilization, and institutionalization over time is usually a bottom-up phenomenon.

We are at a time when climate knowledge and experiences in coconstruction at the local scale are also able to provide input when considering climate problems on a global scale. The Intergovernmental Panel on Climate Change (IPCC), supported by C40, Cities Alliance, ICLEI, Future Earth, SDSN, UCLG, UN-Habitat, UN Environment, and WCRP, organized a conference[a] in March 2018 to inspire global and regional research on cities and climate change in view of the preparation of a future IPCC Special Report focusing on that topic. This event aimed "to be a pivotal milestone in developing the global understanding of how climate change will impact cities and the role of cities in tackling climate change." It brought "together representatives from academia, scientific institutions, IPCC experts, national, regional and local government representatives, urban and climate change practitioners and related networks. Its outcomes will help member states, mayors and citizens deliver on the ambition of the Paris Agreement, the New Urban Agenda and the Sustainable Development Goals." Several sessions in this conference were organized by IAUC members on urban climate modeling,[73] urban climate knowledge transfer,[74] and climate services,[75] aiming to contribute "to establish a new contract between society and climate science in the world's cities."

Conclusion/discussion

Urban climate research is now an interdisciplinary field whose international association has about 1500 members. Even if the process of transnational diffusion of knowledge within the research community always takes time, there has been a certain degree of cohesion and maturity in the field for some decades. The emphasis is placed here on the difficulties encountered in disseminating and translating applied knowledge on urban climate operationally to urban planning and urban design. An overview of the recent principal efforts for knowledge transfer to society was presented in this paper through three research topics at the forefront of urban climate studies: the urban data production issue, the development of analysis methods and impact indicators, and the transfer of urban climate knowledge to urban planning and urban development practices.

The conceptual approach in urban climatology of defining the LCZ has been shown to be an effective tool for dialog between urban climate scientists and city practitioners. Such a consistent approach will surely help to build common methodologies in urban climate studies and transfer tools in the coming years. The IAUC community drives the international WUDAPT initiative, which aims to produce maps of most of the cities in the world classified using this standard. Several ways to gather the needed urban information (land use, morphological, architectural, and social aspects) were presented. These can either be obtained from satellite data, such as in WUDAPT, or from building and street databases, such as in the MAPUCE project. While the latter method has often been applied locally, city by city, this methodology has begun to be extended through the use of homogeneous data sources over countries or even the world. Expertise is also a valid method, especially when no database or other traditional source of information exists. This is the case for architectural information, which is available in general only for some buildings individually, but not available or even conceptualized for the larger scale

[a]https://www.ipcc.ch/news_and_events/PR_citiesconference_host.shtml

of cities, regions, or countries. Finally, crowdsourcing methods are also a promising way, for urban databases such as Open Street Map or to gain architectural information.

Analysis methods and impact indicators to evaluate strategies for adaptation to climate change and urban climate mitigation constitute a field that apparently is in need of standardization or, at least, common methodologies of study. The difficulty stems from the complex systemic nature of the city, and hence of the various aspects that must be taken into account simultaneously to provide information pertinent for urban planning. This requires strong interdisciplinary and transversal analyses. This also implies that the governance and the urban climate–related questions for one city may not be the same for another city, rendering the development of common practices difficult. A step to overcome this is to define multicriteria indicators, which can then be evaluated by different means, such as through observations or modeling. These can be linked to urban climate, energy consumption, population well-being, water resources, etc. Vulnerability and risks, in both the present and future climate, can then be evaluated and actions undertaken.

Finally, tools and methods to link local climate knowledge and urban planning or urban development operations have been presented, in particular, cartographic tools that have been widely used in recent years. It was pointed out that effective transfer and implementation is boosted by a bottom-up coproduction process that allows site-specific policy and regulatory application and city empowerment over time. This fact must be taken into account by national and international meteorological services that are currently designing future climate services on the urban scale. Anthropogenic climate change appears to be a window of opportunity to put climate issues on the urban agenda, but climate knowledge and experience in coconstruction on the local scale can also contribute today to the consideration of climate problems on the global scale.

These interdisciplinary topics were discussed mostly through their technical aspects concerning methods and tools, so the ideal of standardization is not axiomatic here. Knowledge transfer emerges from widely differing contexts depending on the needs and identity of both researchers and decision makers.

Acknowledgments

The authors want to thank three anonymous reviewers for their insightful comments on this paper.

Competing interests

The authors declare no competing interests.

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