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

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Abstract:

Cities modify their local climate and at the same time they suffer from the local impacts of climate change. This paper comments on progress and obstacles in three active research topics that contribute to increasing the capacity of knowledge transfer to society within the urban climate research community. The first is linked to the production of urban surface description useful for urban climate studies. The conceptualization 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 of producing information directly connected to the effects on society. This requires a strong multidisciplinary approach and nowadays, impact studies are not limited to one dimension but instead cover multiple dimensions. Finally, 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, the introduction of cartographic tools encompasses urban climate diagnosis as well as recommendations for future urbanization.

1. Introduction

A distinctive urban climate is created by the presence of a city that disrupts local and regional atmospheric features by altering the surface-air exchanges of heat, moisture, mass and momentum¹. This effect is present on all scales and impacts every meteorological variable and its magnitude. It depends on the city’s physical structure (urban form) and pattern of occupation (urban function). The most widely studied and mediated urban climate effect is the urban heat island (UHI), which describes the differences in surface, sub-surface and air temperatures in cities when compared to the surrounding ‘natural’ environment². 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 ground³.

Urban Climatology has become both an international and interdisciplinary research field. The transnational diffusion of research developments on urban climatology within the research sphere has been successful for some decades. Historically, this knowledge circulation has rested on meetings organized under the auspices of major international networks such as the World Meteorological Society (WMO), the Confédération 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, M. & F. Mackillop⁴ gave 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 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 century⁵ and later to T. R. Oke as a great contributor boosting the field from the 1970s, research production describing atmospheric conditions over

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3 55 urban areas has accelerated during the last decade, taking advantage of the development of new numerical modelling
4 technologies and attracting an increasing number of scientists from different disciplines and locations all over the world.
5 Physical geographers and experts on atmospheric physics dominated this field in its early years, orienting the scope and
6 the applied methods to studies of the outdoor environment, while architects were, generally speaking, more
7 concentrated on studying the indoor micro-climatic conditions at the building scale. These studies examined both the
8 impact of urban development upon all aspects of the atmosphere and the response of populations to the resulting
9 climate. Spatial scales covered upward from the scale of the building or the street to that of the whole city. A gradual
10 broadening has taken place in recent years including studies on fields such as urban air pollution, urban hydrology,
11 building climatology, urban vegetation and urban planning, incorporating specialists and enriching the research field.

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16 70 Urban climate science has made significant progress in linking the properties of the urban surface cover,
17 including its extreme spatial heterogeneity, to changes in the overlying atmosphere called the Urban Boundary Layer
18 (UBL). Significant gaps in the understanding of processes do remain, but it is generally acknowledged that the
19 outstanding issue for urban climate science is the need to transfer knowledge into urban decision-making. Efforts to
20 transfer knowledge to society started very early, as attested for example by Kassner's book "The Meteorological Basics
21 of City Planning"⁶ published in German in 1918, and the reader will find a comprehensive review in Hebbert and
22 MacKillop⁴, but coordinated efforts and discussions within the research community at the international scale are more
23 recent. The International Conference on Urban Climatology (ICUC8, August 2012, Dublin, Ireland) included a plenary
24 session on applied studies in urban climatology; three years later, at the ICUC9 (July 2015, Toulouse, France),
25 coinciding with the year of the 21st session of the Conference of the Parties on Climate Change Policy & Practice held
26 in December 2015 in Paris, it was clearly decided to focus "on the recent scientific activities on climate change
27 mitigation & adaptation in urban environments, as well as on the transfer to institutional stakeholders and urban
28 planners to include urban climate considerations in their practices". Concerning transfer of urban climate knowledge,
29 the session dedicated to "Transfer of urban climate knowledge to urban planners" and the session on improving "Urban
30 design with climate" drew strong attendance. Other related sessions were "Bioclimatology and public health", "Outdoor
31 microclimate and comfort", "Indoor comfort & air quality", "Human perception", "Climate resilient design" as well as
32 those dedicated to "Interdisciplinarity", attesting to the importance of applied research in this domain. The ICUC10,
33 held last summer in New York, consolidated this dynamic, proposing numerous sessions on urban planning and
34 governance, comfort and impact studies.

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38 85 The specificity of the research findings for each individual field of study makes a comparison of results and the
39 rising generic nature difficult. This should not be understood in terms of results, as knowledge transfer will emerge
40 from widely differing contexts depending on the needs and identity of decision-makers, but in terms of methods and
41 tools. The field needs to transcend local case studies and develop the search for standardization methods, the objective
42 being to develop ways to link climate knowledge and planning knowledge for cities everywhere. That the objective is
43 twofold: first, to allow comparison of research results between locations and second, to take advantage of the
44 observation protocols, modelling and cartographic tools developed in recent decades, mainly in the north. Considerable
45 efforts were made, for example, on experimental protocol guidelines for identifying and studying the impact of cities on
46 atmospheric thermodynamics and atmospheric composition in a comparable manner⁷. The research community also
47 actively developed a rich literature reviewing progress on atmospheric measurements in urban areas and modelling on a
48 variety of scales based on both numerical and experimental approaches^{8,9,10,11}.

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52 95 This paper presents three active research topics that, in our opinion, contribute to increasing the capacity of
53 knowledge transfer to society within the urban climate research community. It aims not so much to draw up an
54 exhaustive review as to give a quick overview of the state of research activity to illustrate where we stand today. These
55 interdisciplinary topics are presented and commented on here mostly through their technical angle, methods and tools,
56 rather than on the basis of their policy implications or how they relate to different categories of end-users, that, in this
57 paper, will refer mostly to urban planners. First (section 2), we present the efforts related to urban data production,
58 putting the accent on the fact that coherent and consistent urban databases suited to urban climate studies containing
59 information on both urban form (land-cover, materials and building dimensions) and function (occupation patterns) are
60 still in the early stages of development. Urban data infrastructure is important both for impact studies in urban
61 environments (section 3) -- to evaluate strategies for adaptation to climate change and urban climate mitigation -- and
62 for the integration of local climate knowledge in urban planning (section 4), where considerable efforts have been made
63 in recent years to bring to light the levers and curbs affecting this integration.

64 110 **2. Urban datasets for urban climate studies**

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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 micro-climatic studies we often focus on 3 different spatial scales¹²:

- the meso-scale, encompassing the whole city (which is the scale where the Urban Heat Island is typically defined, as for example the difference of temperature between the city center and the countryside).
- the local scale, where neighborhoods experience different micro-climates (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 the micro-scale, where variability is governed by individual urban features (cool air below a tree, ventilated street, warm and cool air on two sides of a house, etc.)

Many methods have been used to describe cities at the meso-scale and local-scale, in modelling 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'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 7 classes: dense or scattered trees, bush, low plants, bare soil, bare rock, water) or the urban one, more specifically, in ten 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, 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 micro-climate variability^{14,15,16}. 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, to represent the potential effect on the micro-climate¹⁷.

The state-of-the-art atmospheric and climate models are not able to represent the whole urban area climate on the micro-scale. They are able to represent hectometric and kilometric scales, respectively. Finest scale processes are then modelled 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 Urban Heat Islands, but also city-induced extreme precipitation events, as can occur in megacities in China or the USA¹⁸. 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 actions 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. To address that challenge, using satellite images may help. However, most land use at the global scale such as the ESA-CCI product 1.6.1 of 2016, which focuses on natural and agricultural landscape classifications, only delimits the urban area as a single class. One way to get a description of the intra and inter-city variability is to provide spatialized information on some urban parameters. For example, Dong et al (2017)¹⁹ determined a global 1-km resolution map of the 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 Europe²⁰).

The most advanced global urban database suitable for environmental and meteorological/climatic studies, to our knowledge, is the Global Human Settlement Layer, at 100m of resolution. The classification schema of the settlement 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 Ecoclimap database²³, that will then finely describe the vegetated 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

1 Database and Access Portal Tools (WUDAPT) initiative. This is an IAUC community-based project to gather a census
 2 of cities around the world²⁴. The WUDAPT methodology is based on the LCZ-mapping of cities using satellite images,
 3 such as landsat²⁴, with a common protocol, ensuring a relative homogeneity between each map's representativeness.
 4 This protocol is based on an iterative process with expert supervision. First the expert manually defines several
 5 neighborhoods for each LCZ present in the city and its surroundings. Second, a classification process is used to classify
 6 all the images, that covers the urban area under study. If necessary, the expert completes the first step again to improve
 7 the mapping. Finally, a quality control process is carried out. LCZ maps produced this way have proven to be
 8 successfully used within atmospheric models²⁶. The association of model urban parameters (e.g. building height,
 9 building cover) by means of information from LCZs alone is presented in Ching et al (2018)²⁷, as well as ways to
 10 include finer data when available. All architecture-related information on building construction (e.g., roofing and wall
 11 materials, presence of windows) also needs to be defined. Tornay et al (2017)²⁸ propose a methodology to gather this
 12 information on the regional scale. This will make it possible, for example, to describe how buildings or houses are
 13 (differently) built in several regions and countries of the world (e.g. in Western European, Chinese, South-American or
 14 Equatorial African cities). In the framework of WUDAPT, two actions have been initiated to achieve this: by
 15 crowdsourcing, with development of mobile app surveys, and by collaboration with architects at the global level. For
 16 the latter, the Passive Low Energy Architecture (PLEA) association joined the WUDAPT initiative along with IAUC,
 17 enlarging the WUDAPT scope in terms of scientific methodology as well as potential users. A mixed working group of
 18 architects and climatologists from 20 countries was formed during the PLEA 2017 conference, and dedicated sessions
 19 on WUDAPT will be continued during PLEA 2018.

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

24 **205 Multi-criteria impacts**

26 Another reason to have a finely detailed description of the city is related to the need for multi-criteria impact assessment
 27 (see section 3). For example, energy consumption due to domestic heating and air conditioning is strongly related not
 28 only to the morphology of a building, but also to its architectural fabric and use (e.g., as office, residential or
 29 commercial space). Furthermore, energy consumption is linked to how people use their heating and cooling systems and
 30 what their comfort temperature is. And to assess societal impacts, this information must be intersected with societal and
 31 demographic information. Urban vegetation, its arrangement, type and even species can also influence thermal comfort,
 32 flooding mitigation and water resources.

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 34 215 Such thematic information cannot be derived from remote-sensing approaches; there is a need for bottom-up mapping,
 35 using fine-scale source data (typically at building & road scale).

36 **(Specific) City maps from fine-scale data**

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 38 220 Many geographical studies have been performed in the past in order to provide such fine-scale and multi-parameter
 39 descriptions of cities (e.g. Lindberg (2007)²⁹). However, such urban climate-oriented fine-scale analyses on a particular
 40 city were strongly limited in reproducibility, in terms of methods, to another city, even in the same country. The reasons
 41 were twofold:

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

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 48 230 These limitations imply that few cities have fine-scale urban data available for micrometeorological studies, and when
 49 they do it is usually owing to local action. However, spatially homogeneous information is crucial for defining
 50 standardized, or at least generalized, interfaces between urban data and meteorological models.

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 52 235 Some actions have been conducted on a larger territory to provide homogeneous urban description. Note that this
 53 information is generally limited to land use or morphological parameters (such as building height and building density).
 54 Two examples are NUDAPT, where approximately 40 of the biggest cities in the USA were mapped using building
 55 elevation data³⁰, and Urban Atlas, describing 305 cities of more than 50,000 inhabitants in Europe³¹.

56
 57 240 However, the main drawback of these approaches is that they provide information only on the biggest cities,
 58 information that is limited to the cities' administrative boundaries. The description of the (sub)urban areas outside each
 59
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main city is lacking, and this limits the atmospheric modelling of the urban heat island and urban climate, given that airflows cross administrative boundaries freely.

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 scope of parameters, encompassing a building's use for example.

These approaches require a homogeneous, thematically varied, and spatially continuous source of data on a large territory. This is the case for France as a whole from its mapping agency, which has been used in the MAPUCE project. And this is also verified, even if completeness varies from one country or location to another, by Open Street Map (OSM). The openness and variety of this worldwide database promote new research to extract pertinent information for urban mapping, worldwide.

Samsonov et al (2015)³² use 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 others (such as building coverage fraction) for Moscow, Russia. The potential richness of the information provided by OSM offers prospects for mapping socio-economic information, such as the non-residential usage fraction in buildings and even population density, as was done for Dresden, Germany, by Kunze and Hecht (2015)³³. Bocher et al (2018)³⁴ produce a great deal of morphological as well as typological building information for France, based on an extensive French 2.5D building database. This is completed by demographic and sociological indicators, from national surveys on the neighborhood scale. This allows Schoetter et al (2017)³⁵ to model inhabitants' energy behaviors, and their impact on energy consumption, waste heat and the urban microclimate.

These developments in both concepts –Local Climate Zones 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 modelling. The next step in transferring this physical information into useful knowledge is to provide pertinent multi-factor indicators.

3. Analysis methods and impact indicators

As pointed out in the introduction, urban climate study covers a multitude of research topics. The historical topics are mostly related to analysis and modelling of physical processes of the urban climate, interactions between surface and atmosphere, and impact on local meteorology and the atmospheric boundary layer. They 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, professional actors in charge of living environments and urban planning are currently quite concerned by artificialization of pervious soils related to the urbanization process, and associated urban heat island issues that may lead to public health problems. Added to this are the local effects of climate change that could significantly exacerbate the 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 multi-criteria 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 cities or populations are subjected to (the subject must be defined), as well as the hazard concerned, i.e. a 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, plural-sectorial 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 disciplinary approach for impact studies is consequently limiting. Some recent research has adopted systemic and interdisciplinary approaches^{36,37} by

1 integrating different models or enriching existing models with new processes, and by feeding the models with
2 integrative scenarios for cities.
3

4 305 Urban climate models were initially designed to compute changes in meteorological variables at street level in a built-
5 up environment, i.e. air temperature, humidity, wind speed. Efforts have been made recently to simulate the complexity
6 of the urban environment more realistically. Urban vegetation in interaction with built-up elements^{38,39,40,41}, water
7 exchanges between atmosphere, surface and soil⁴², as well as building energetics^{43,44,45} are new developments that have
8 been recently implemented in urban canopy models. Such configurations now make it possible to explicitly model
9 310 interactions between all these processes, to more accurately simulate specific adaptation strategies or urban design
10 scenarios, and to enrich diagnoses. Urban scenarios describing how cities can evolve and which action levers can be
11 implemented are also an important piece of this approach. They can concern various dimensions including actions on
12 buildings and urban design and larger scale urban planning policies, as well as interventions on transportation networks,
13 315 urban expansion, architectural evolution etc. can be taken into account, based on collaborations with economists,
14 geographers, architects or urban planners. Some of these changes can be determined from numerical modelling. In
15 particular, long-term urban expansion can be calculated with economic models such as NEDUM⁴⁶, or for shorter time
16 periods with geographical models adjusted to past trends. Other developments, for instance related to implementation of
17 local policies for building renovation, urban greening, or adaptation of public transportation, can be defined based on
18 320 expert choices.

19 **Defining indicators**

20 Numerous studies evaluate urban design scenarios or strategies of adaptation to climate change only by quantifying the
21 impact on air temperature or urban heat islands. While the indicator of this impact is one relevant indicator, it can be
22 325 calculated in different ways, depending on the time of the day (daytime or nighttime), for a specific location, spatially
23 averaged, and so on, which means that results and conclusions can differ.
24

25 Studies in climate-sensitive urban design look at perceived, or “feels-like”, temperatures or people’s thermal comfort
26 for indoor and outdoor environments, through computation of indices such as Wet Bulb Globe Temperature (WBGT),
27 330 Predicted Mean Values⁴⁷ (PMV), Physiological Equivalent Temperature⁴⁸ (PET), and Universal Thermal Climate Index
28 (UTCI). These indices are related to heat stress scales, which make it possible to analyze threshold exceedance. These
29 indices are now included as diagnoses of some urban climate models for weather forecasting or impact studies. Leroyer
30 et al (2015)⁴⁹ developed an urban-scale weather forecasting system for the 2015 PanAm Games in Toronto for the
31 purpose of producing heat-stress maps using Humidex, UTCI, and the WBGT indices. Kusaka et al (2012)⁵⁰ and
32 335 Argüeso et al (2015)⁵¹ have investigated the evolution of comfort conditions in the future using the WBGT index, based
33 on regional climate simulation with the Weather Research and Forecasting (WRF) Model in Japanese cities and the
34 Sydney region, respectively. Lemonsu et al (2015)³⁷ and Daniel et al (2018)⁵² have studied the impact of urban
35 expansion scenarios on UTCI for future heat-wave conditions over the Paris region. It is, however, difficult to decide
36 340 which index to use, as well as how to analyze these indices to assess the impacts on the population in a standardized
37 manner and provide relevant urban climate services for society and users. The needs and practices can vary significantly
38 depending on the domains of application. Thus the recent urban-climate studies related to heat stress evaluation present
39 a wide range of approaches. Thermal comfort can be computed at the most critical hours of the day or combined over
40 time to evaluate potential prolonged exposure to uncomfortable conditions. For instance, Argüeso et al (2015)⁵¹
41 345 investigated seasonal averages of minimum and maximum values of thermal indices and analyzed how they changed
42 over time. Kusaka et al (2012)⁵⁰ calculated the number of hours exceeding a certain heat stress threshold. Spatial
43 analysis is also tricky. Thermal comfort can be studied as maps in order to identify sensitive areas or aggregated on the
44 neighbourhood or city scale. Lemonsu et al (2015)³⁷ showed for the Paris (France) urban area that results can be
45 substantially different if the averaging is done according to density of built covers or inhabitants.

46 350 Energy consumption for domestic heating and air-conditioning is also an important criterion in evaluating choices in
47 urban design or planning. All the more so as this falls within the context of climate change and objectives in greenhouse
48 gas reduction targeted by countries worldwide. Most urban-climate studies focus on energy consumption related to air-
49 conditioning use, which could be a major issue within a global warming context with an increase in the risk of heat
50 355 waves. But it is also important to assess the potential retroaction of some adaptation measures (or UHI mitigation
51 measures) on domestic heating consumption. For instance, De Munck et al (2018)⁵³ indicate that some forms of urban
52 greening are efficient ways to cool air temperature during summer but that this cooling may persist in winter and
53 increase demand for heating.

54 360 Water resources are also crucial for impact studies and this issue has begun to be addressed, especially in connection
55 with irrigation and greening strategies, by urban models that consider water exchanges (including irrigation) and, in
56 some cases, subsoil hydrology.

57 For a more objective and complete evaluation, indicators computed by urban climate models can be also put in
58 perspective with indicators derived from urban design or planning scenarios. Urban expansion strategies, for instance,
59 have a significant impact on CO2 emissions due to transportation. Economic cost, material life-cycle and carbon
60

365 footprint (e.g. for building renovation or green space management) are also relevant criteria for evaluation, but they are
 366 complex to estimate.

367 **Risk evaluation**

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

379 **4. The integration of local climate knowledge in urban planning and urban development**

380 International collaboration cited in the introductory section does not lead only to a rich state of the art of the
 381 urban atmosphere in physical terms; it has also led to the development of a rich bibliography presenting applied
 382 knowledge about the urban climate, to be used by planners for practical purposes of urban heat-island mitigation and
 383 wind, rain and snow management and for effective use of green space to enhance air quality and human comfort.
 384 Nevertheless the application of science-based knowledge to urban design has encountered difficulties in being
 385 disseminated and translated operationally, except for rare exceptions as in German-speaking countries where numerous
 386 publications exist, ranging from the earliest ones, Horsfall⁵⁴ in 1904 and Kratzer⁵⁵ in 1937, to the most recent ones:
 387 Stock and Baumüller⁵⁶⁻⁵⁸, to cite just a few, and, to a lesser extent, in Israel⁵⁹ and Japan^{60,61}. Retrospectively, Hebbert
 388 and Mackillop⁴ pointed to some curbs that can account for the difficulties encountered with climate knowledge
 389 integration on the urban scale. They fall into two categories, those referring to trends in urban fabric and town planning,
 390 and those related to the ways atmospheric knowledge is produced.

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

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

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

408 The laborious and expensive nature of local climate studies is nevertheless rapidly changing thanks to the
 409 development of lightweight sensors, three-dimensional urban databases that allow high resolution mapping, and GIS
 410 platforms capable of being linked to multi-scalar statistical models. Collaborative data is also strongly penetrating urban
 411 climate research⁶². But the widespread application of urban climatology in urban design and urban environmental
 412 planning was especially facilitated in the last decade by the rise of awareness of anthropogenic climate change that
 413 gained in importance in both public and political opinion⁶³. The two reports entitled *Cities and Climate Change*
 414 published in 2011 by the United Nations and the Urban Climate Change Research Network^{64,65}, putting forward the role
 415 that cities should play in greenhouse mitigation and adaptation, played a major role in placing climate issues on the
 416 agenda at the city level. It is time for the emergence of networks of cities committed to tackling climate change at
 417 international and national levels -- networks such as C40, which was given impetus by the mayor of New York City in
 418 2010, ICLEI - Local Governments for Sustainability, and the Global Cool Cities Alliance. The changing global climate
 419 has become, in a way, the window of opportunity for the transfer of climate knowledge on a local scale.

420 But what strategies and tools are available for operational application of urban climate science knowledge?
 421 Historically, the German-speaking research community has led the application of science-based climatic design with a

1 systematization of local climate studies since the first half of the twentieth century. Their cartographic techniques for
 2 mapping thermal distributions, cold air lakes and flows, wind patterns, pollution concentration, etc. combining
 3 meteorological and climate information, land-use data, and terrain information have the advantage of fitting the needs
 4 of both urban planning practices and urban planning tools. Fine-grained spatial mapping started in Germany in the
 5 425 1970s with The Climate Booklet for Urban Developments (1977) in Stuttgart and continued with the KlimaAtlas
 6 published on 1992. The Stuttgart Klima Atlas methodology has been used in Europe, Asia, and South America, mostly
 7 adapted from the earlier German model and following the German Guidelines VDI3787 Part1 Environmental
 8 Meteorology – Climate and Air Pollution Maps for Cities and Regions, first published in 1993 and updated in 2015. In
 9 430 recent years, Urban Climate Maps have become a reference tool for translating scientific climatic knowledge into
 10 guidelines and planning recommendations⁶⁶.

11 Different names are used for these cartographic tools depending on the country and scale of action, but the
 12 denomination Urban Climatic Maps (UC-Map) has been widely used in recent years. Technical choices on how to
 13 produce these cartographic tools depend on local climatological features, the available data on urban morphology and
 14 435 climate, and the scientific and cultural background of the actors (researchers and stakeholders) involved in the project.
 15 Climatological data can be produced through observations (permanent meteorological network or field campaigns) or
 16 modelling (often on the neighborhood scale). As atmospheric information is needed for the whole city, spatialization
 17 techniques are often used to statistically quantify the relations between the physical surface of the city and the
 18 meteorological variables, assuming that, for some specific weather situations such as anticyclonic situations with low
 19 440 wind speed, local climate conditions within the urban canopy are mainly driven by urban surface features. Numerical
 20 simulations coupling an atmospheric model with a Soil-Vegetation-Atmosphere transfer (SVAT) model can also be
 21 used to take into account the impact of the physical surface (e.g., land use, topography, urban morphology) on the
 22 atmospheric fields and the atmospheric dynamics for the whole city scale. This approach is particularly useful for
 23 integrating the plurality of weather situations representative of a place in the cartographic reflection⁶⁷.

24 In Ng and Ren⁶⁶ and Figure 2, experiences with recent UC-Maps are presented for large, medium-sized and
 25 small cities around the world; yet it appears that only in very few cases is the translation of recommendations for urban
 26 planning derived from the climate diagnosis really taken into account at the operational level in land use zoning, design
 27 codes or green-space and water area management. Since the scientific basis and technical tools for local climatic
 28 450 diagnosis exist, what are the specific reasons behind the fact that climate information is successfully transferred in some
 29 places, matching both policy and regulatory engagement, and not in others?

30 Planning advice is sometimes commissioned by practitioners and planners but often the study is promoted and
 31 funded by the producers of climatic data, who are almost always researchers; but what is observed^{67,69} is that all the
 32 successful examples of urban climate management entailed two key ingredients: the presence of a community research
 33 455 team, pushed to the extreme by the city of Stuttgart with the presence of in-house urban climatologists, and a long
 34 process of collaboration and acculturation between researchers and practitioners. It seems that research developments in
 35 urban climatology are effectively boosted by international collaborations and networks, but effective transfer and
 36 implementation are done from the bottom up. This doesn't mean that top-down setting of targets by national government
 37 for local governments is not an effective way to boost the development of environmental and climate codes at the local
 38 460 level^{70, 71, 72}, but, as also pointed out by Webb⁶⁹, the co-production process that allows site-specific policy and
 39 regulatory application, stabilization and institutionalization over time is usually a bottom-up phenomenon.

40 We are at a time when climate knowledge and experiences in co-construction at the local scale are also able to
 41 provide input when giving thought to climate problems on a global scale. The Intergovernmental Panel on Climate
 42 Change (IPCC), supported by C40, Cities Alliance, ICLEI, Future Earth, SDSN, UCLG, UN-Habitat, UN Environment
 43 465 and WCRP, organized a conference¹ in March 2018 to inspire global and regional research on Cities and Climate
 44 Change in view of the preparation of a future IPCC Special Report that will focus on Cities and Climate Change. This
 45 event aimed “to be a pivotal milestone in developing the global understanding of how climate change will impact cities
 46 and the role of cities in tackling climate change”. It brought “together representatives from academia, scientific
 47 470 institutions, IPCC experts, national, regional and local government representatives, urban and climate change
 48 practitioners and related networks. Its outcomes will help member states, mayors and citizens deliver on the ambition of
 49 the Paris Agreement, the New Urban Agenda and the Sustainable Development Goals”. Several sessions in this
 50 conference were organized by IAUC members on urban climate modelling⁷³ (Hamdi, Tapper et al., 2018), urban climate
 51 knowledge transfer⁷⁴ (Hidalgo et al. 2018) and climate services⁷⁵ (Baklanov et al. 2018) aiming to contribute “to
 52 establish a new contract between society and climate science in the world's cities”.

53 475 5. Conclusion/Discussions

54 Urban Climate research is now an interdisciplinary field whose international association has about 1500
 55 members. Even if the process of transnational diffusion of knowledge within the research sphere always takes time,
 56 there has been a certain degree of cohesion and maturity in the field for some decades. The accent is put here on the

57
 58 1 https://www.ipcc.ch/news_and_events/PR_citiesconference_host.shtml

difficulties encountered in disseminating and translating applied knowledge on urban climate operationally in 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 items at the forefront of urban climate studies: the urban data production issue, the development of analysis methods and impact indicators and the transfer to urban planning and urban development practices.

The conceptual approach of urban climatology through LCZ definition has been shown to be an efficient tool for dialogue between urban climate scientists and city practitioners. Such a homogeneous approach will surely help to build common methodologies of 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 under 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, such as in WUDAPT, or from building and street databases, such as in MAPUCE project. While the latter method was often applied locally, city per city, this methodology has begun to be extended through the use of homogeneous data sources over countries or even the world. Expertise, especially when no database or other traditional source of information exists, is also a valid method. This is the case for architectural information, which is in general available only for some buildings individually, but not available or even conceptualized for larger scale, 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 infers that the governance and the urban-climate related questions in one city may not be the same as in another city, rendering the building of common practice difficult. A step to overcome this is to define multi-criteria indicators, that can then be evaluated by different means, through observations or modelling. These can be linked to urban climate, energy consumption, population well-being, water resources, etc. Then vulnerability and risks, in both the present and future climate, can 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 co-production 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 the 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 today climate knowledge and experience in co-construction on the local scale can also contribute to the reflection on climate problems on the global scale.

These interdisciplinary topics were discussed mostly through their technical angle 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.

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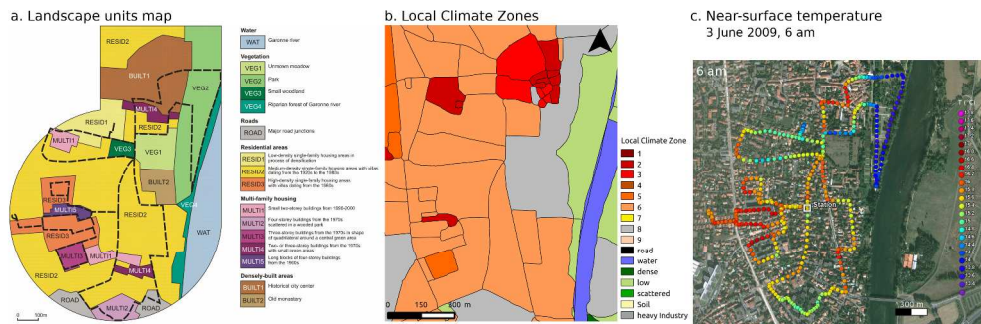
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12 **Figure legends:**

13 Figure 1: Relation between Landscape units-maps (a), Local climate Zones (b) and near-surface air temperature (c)
14 from bicycle measurements for a residential area close to Toulouse (Blagnac, France).

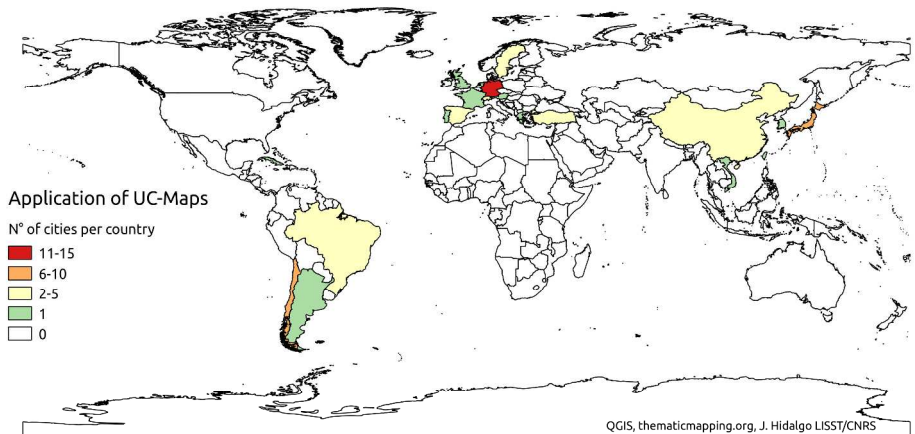
15 695 Figure 2: Urban Climate maps application around the world in 2018. Colors indicate the number of cities per country
16 that initiated studies on UC-Maps and recommendations for urban planning application. Table corresponds to the date
17 of the first published study for each city.



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