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# Climate Information for Improved Planning and Management of Mega Cities (Needs Perspective)

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**Abstract**

The majority of the population of the planet (6.6 billion) now live in urban areas, which have distinct impacts upon climate at scales from the local to the global. This urban effect is due to the physical form of the city (its three-dimensional geometry and material composition) and its functions (the day-to-day activity patterns that generate emissions of waste heat and materials into the overlying air). While a substantial body of knowledge on the science of urban climates has been developed over the past fifty years, there is little evidence that this knowledge is incorporated into urban planning and design practice. This paper focuses on this gap by examining the nature of urban climate expertise and the needs of those that make decisions about urban areas. In conclusion it makes recommendations to maintain and enhance urban observations and data; to improve understanding of local, regional and global climate linkages; to develop tools for practical planning; and to disseminate urban climate knowledge and its relevance to urban planning to both practicing meteorologists and urban decision makers.

*Keywords:* Urban Climate, Planning and Design, Observations and data, Meteorological applications

## 1. Introduction

The population of the planet is 6.6 billion of which half now live in urban areas. Together these places comprise less than 3 per cent of the land area [1] yet they form a network that connects most parts of the world through the exchange of materials, goods and people. The urbanization of the world's population is set to continue: by 2025 the world's population is projected to be about 8 billion, of which nearly 5 billion will live in urban areas. While most live in settlements of 500 000 or fewer people, many occupy large cities (over 1 million) and some reside in very large megacities (over 10 million). The numbers and locations of the large and very large cities reveal the scale of global urbanization [2]. In 1900 there were just 16 large cities, mostly located in Europe and North America, but by 2000 there were nearly 300. In 1950, there were just two megacities but by 2007 there were 19, of which 11 are located in Asia. By 2025 it is projected there will be 27 megacities (Table 1). While some of these places have been studied and seem familiar (Tokyo), little is known of others (for example, Jakarta).

Urbanization, defined here as the increasing share of a population living in urban areas, is reflected in two distinct processes: changes in the living patterns of humans, and the physical transformation of the natural cover into an urban landscape. The first describes urban functions, the patterns of activities that generate distinctive urban land uses, and requires a continuous flux of materials and people. The second describes the urban form, the topographical and material composition of the city that produces distinctive urban land-covers, often associated with particular land uses. Both the form and the function of the city modify the overlying atmosphere, creating a distinctive climate. At the urban scale this climate is can be significantly different from the natural climate and deleterious to human health [3]. This urban air eventually becomes entrained into regional and global climate systems so that the contributions of cities can be seen, albeit at a diluted level, in global atmospheric chemistry. In fact, the majority of the anthropogenic flux of $CO_2$ may be attributable to activities concentrated in urban areas [4]. Conversely, changes in climate are likely to have a particular impact on cities, which are most often situated along rivers, at low elevations and close to coasts – places that are vulnerable to changing rainfall regimes, sea-level rises and storm surges.

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Table 1. Population of urban agglomerations with 10 million inhabitants or more, 1950, 1975, 2007 and 2025 (in 000 000s)

| | 1950 | | | 1975 | |
|---|---|---|---|---|---|
| *Rank* | *Urban Agglomeration* | *Population* | *Rank* | *Urban agglomeration* | *Population* |
| 1 | New York-Newark USA | 12.3 | 1 | Tokyo, Japan | 26.6 |
| 2 | Tokyo, Japan | 11.3 | 2 | New York-Newark, USA | 15.9 |
| | | | 3 | Mexico City, Mexico | 10.7 |
| | 2007 | | | 2025 | |
| *Rank* | *Urban Agglomeration* | *Population* | *Rank* | *Urban agglomeration* | *Population* |
| 1 | Tokyo, Japan | 35.7 | 1 | Tokyo, Japan | 36.4 |
| 2 | New York-Newark, USA | 19.0 | 2 | Mumbai, India | 26.4 |
| 3 | Mexico City, Mexico | 19.0 | 3 | Delhi, India | 22.5 |
| 4 | Mumbai, India | 19.0 | 4 | Dhaka, Bangladesh | 22.0 |
| 5 | São Paulo, Brazil | 18.8 | 5 | São Paulo, Brazil | 21.4 |
| 6 | Delhi, India | 15.9 | 6 | Mexico City, Mexico | 21.0 |
| 7 | Shanghai, China | 15.0 | 7 | New York-Newark, USA | 20.6 |
| 8 | Kolkata, India | 14.8 | 8 | Kolkata, India | 20.6 |
| 9 | Dhaka, Bangladesh | 13.5 | 9 | Shanghai, China | 19.4 |
| 10 | Buenos Aires, Argentina | 12.8 | 10 | Karachi, Pakistan | 19.1 |

Abstracted from Table 1.6 in United Nations, 2007
In 2007 there were 19 mega-cities, of which the top ten are shown. In 2025 there is expected to be 27 mega-cities, of which the top ten are shown.

While urbanization is driven by the actions of people and their enterprises that are coordinated primarily by markets, cities are also amenable to purposeful planning and design. It is difficult to determine precisely whether a given city is sustainable, but a city may be described as more sustainable if it reduces its use of resources and its negative impacts on ecosystems without threatening the health and well-being of its citizens. This paper is focused on the needs of urban designers and planners for useful meteorological information that can help in achieving more sustainable cities.

### *1.1 Global urbanization*

Although the first cities appeared more than 5 000 years ago in the fertile valleys of the Tigris and Euphrates rivers, the transformation of the world's population from rural to urban has come about very recently [5][6]. Modern urbanization has its origin with the Industrial Revolution (circa 1750), which heralded advances in technology based on the intensive use of fossil fuels. The period since can be divided into two waves of urbanization [7]. The first wave peaked in the 1950s, by which time 50 per cent of the population of the more developed regions (chiefly Europe, Japan and North America) lived in urban areas. Over the period of this urbanization, the internal geographies of these cities followed similar paths of development as form and function jointly changed. Initially, population growth occurred as a result of rural migration into densely occupied settlements that lacked systems for the supply of clean water and the removal of wastes. With improved public health due to investments in urban infrastructure (including housing and transport), natural increase, rather than migration, resulted in further urban population growth. City footprints began to grow at faster rates than population growth as population density fell and distinctive land uses occupied physically separate parts of the city. As a consequence many cities have acquired a characteristic form that consists of low-rise residences surrounding a high-rise core.

The second wave of urbanization is now occurring in the less developed regions and is happening at an unprecedented rate. It is important to remember that at the peak of the first wave in 1950, the global population was 2.54 billion and 47 per cent lived in less developed regions. By 2007, the global population was 6.67 billion and 80 per cent (5.45 billion) lived in less developed regions. This second wave has yet to peak: currently 44 per cent of the population of the less developed regions live in urban areas yet these account for 2.38 billion, compared to just 910 million living in the cities of the more developed regions. In other words for every three urban inhabitants, two live in the cities of the less developed regions. This urban population will continue to grow both in real and proportionate terms into the future, mainly due to natural increase rather than rural migration. The urban transformation that has taken more than 250 years in the more developed regions is happening in less than half of this time, with a vastly increased population, in less developed regions. The consequences are evident in the urbanized landscapes of the less developed regions where many residents (sometimes the majority) occupy informal settlements that have no basic infrastructure and no security of tenure.

Unfortunately, there is no comparable data on the form and functions of cities at a global scale. The available data are inconsistent and incomplete and draw upon two sources [8][9]. The first are census databases on population and land use for urban areas with defined administrative boundaries. However, these places rarely coincide with a clearly identifiable contiguous urbanized landscape. In many cases, large areas of non-urban landscape are incorporated into city boundaries whereas, in other cases, the urban footprint extends far beyond the limits of the city. In some instances, cities have effectively merged to create a single continuous area of urban fabric that is fractured into different administrative regions. For these urban agglomerations, information for several places may have to be combined (as is the case in Table 1). The second source of information is based on remote sensing and can, with some field verification, provide information on the urbanized land cover. In areas where is no census, this information can be used to provide a measure of urban extent and, with some assumptions, of population density. Ideally, both sources of information can be employed to provide a spatially precise picture of the detailed geography of cities. This information could be usefully employed to assess the global impacts of cities and their vulnerability to environmental change [10].

### *1.2 Sustainable cities and climate*

The term "sustainable" is employed in many different ways and it is useful to clarify the use of the term for our purposes. The term sustainable development was adopted in the United Nations resolution establishing the World Commission on Environment and Development in 1983, in response to the fear was that conventional development strategies were so environmentally damaging that long-term development prospects were being undermined. The Commission was to help achieve sustainability by proposing environmental strategies enabling development "to meet the needs of the present without compromising the ability of future generations to meet their own needs" [11]. In the past quarter century, the concept of sustainability has expanded to encompass social, economic and various other dimensions. On the other hand, as the evidence on global climate change has grown increasingly dire, the importance of environmental sustainability has also grown.

In an environmental sense, a system is sustainable if it can be maintained indefinitely over time, without, for example, depleting the resources it depends upon. Given the increasingly global character of human interdependencies, when it comes to human-centred systems, the concept is most readily applied at the planetary scale where the Earth's resource base and its ecosystems can be assessed in relation to the total human demand [12]. Current assessments indicate that the global resources and ecological systems humans depend upon are deteriorating rapidly. Climate change is adding a new set of global threats to sustainability, as well as beginning to impose environmental burdens on the current generation. However, any analysis shows that resource consumption is concentrated in the cities of more developed regions whereas environmental health burdens are similarly concentrated in the cities of the less developed regions (for example, Satterthwaite [13]; UNFPA [7]).

The concept of sustainability has also been applied to cities, treating the urban system as though it was an organism requiring sustenance. One approach that has been applied is to examine its metabolism – the inputs, storage and outputs that allow an urban area to function [14]. Inevitably, these exchanges cross the urban–rural boundary so that the impact of cities is felt beyond their limits. In this sense, cities are not, and cannot be made, sustainable. It is possible, however, to assess the intensity of the exchanges and the geographical extent of a city's resource catchment (for example, Girardet [15]; Kennedy et al., [16]; Newman [17]; Rees and Wackernagel [18]; Rees [19]). Urban sustainability then becomes a relative concept: the more sustainable city is the one which uses fewer resources to fulfil its functions. Generally, relative sustainability is evaluated on a per capita basis, though there is a sense in which a city with a high natural population growth rate can be less sustainable as a result. Alternatively, a city that attracts more population from outside its boundaries will also increase its own resource use, but may actually decrease net resource use if the migrants would be using more resources if they had not migrated. Again, this serves to emphasize the importance of treating urban sustainability in a global context. In any case, there is an important sense in which the goal is not to have sustainable cities, but cities that contribute to global sustainability, or to sustainable development.

Among affluent cities, a compact, high-density city having its parts linked via a mass transit system is more sustainable, in terms of resource use, than a sprawling automobile-based city (for example, Lyons et al. [20]; Rogers [21]). On the other hand, if we take the use of fossil fuels and other natural resources as a measure, then all of the very affluent cities are far less sustainable than very poor cities, where most of the population cannot afford to consume fuel or fuel-intensive commodities. In this sense, more sustainable cities are not necessarily more desirable. Indeed, they are not necessarily environmentally superior. After all, the less sustainable affluent cities generally have management systems to protect air and water quality and have the resources to ensure the safety of urban residents. The poorer cities of the world are more sustainable (by this measure) but their residents often have no basic infrastructure to ensure safe, secure and healthy living environments.

The environmental changes that most affluent cities have gone through can be conceptualized as an urban environmental transition. In very simplified terms, the shift was from sanitary problems of the nineteenth century, to pollution and waste problems in the twentieth century, to sustainability problems in the twenty-first century. This shift involved a change in scale (from hazards in and around the home, to those of the city region, to the global burdens of sustainability) and timing (from immediate health effects to the long-term degradation of life support systems). While these shifts were predicated on economic growth, they were also the result of urban-centred policies and social movements, including the sanitary movement of the nineteenth century and the environmental movement of the twenty-first century. However, economic development has been extremely uneven across the globe, and the urban environmental challenges faced in different parts of the world are also very different [22].

In the cities of high-income regions, most of the infrastructure is in place and much of the physical stock is protected. For these cities the challenge is to retrofit the city to make it more sustainable (or less unsustainable). On the other hand, many of the cities in low-income regions are still growing, demographically as well as economically, and their form is still emerging. The challenge is to improve the lives of their inhabitants without following the trajectory of wealthy cities. For all types of cities, weather and climate information should form part of the corpus of knowledge that underpins design and planning philosophy and practice.

## 2. Urban climate: science, impact and response

### *2.1 Science*

The focus of the companion paper on capabilities is on urban climate science. In this section, we will focus on the framework of the current scientific understanding of urban climate that is relevant to planning and design.

Urban landscape changes typically involve the substantial replacement of natural cover by manufactured material that is generally impermeable and has distinct thermal and radiative properties. Moreover, this new surface has a unique geometry (associated with building form and relative placement) that generates turbulence and interferes with radiative exchanges. Complementing these physical changes are emissions of heat, water and materials that are the by-products of human activities. At the scale of the city, the effect of urban form and function is to produce an "urban boundary layer" (UBL), a plume of air that has acquired distinctive characteristics through its interactions with the surface below. It forms as air moves across the urban edge and experiences a rapid change in surface properties. Urban surfaces are aerodynamically rough and usually dry and the near-surface air is turbulent, warm and enriched with a host of gases and particulates. Surface–air exchanges carry these properties into the overlying atmosphere creating the UBL, which grows in depth from the upwind edge.

Cities, however, are not uniform and most can be decomposed into sub-areas (neighbourhoods) that exhibit distinctive types of urban form and/or functions that reflect the organization of the urban area. The properties of the UBL are formed by the blending of all the upwind contributions from the surfaces below. Closer to the urban surface (at approximately twice the height of the buildings), however, the unique contributions of a neighbourhood can be detected. Below this height the individual elements of the neighbourhood (buildings and trees) begin to dominate over neighbourhoods.

The lowest part of the UBL, below the rooftops of buildings (and the tops of trees) is termed the "urban canopy layer" (UCL). This layer consists of closed (and managed) indoor spaces and open (weakly managed) outdoor spaces. These spaces are connected to each other by exchanges across the building envelope and both are connected to the deeper UBL through exchanges of energy, materials and momentum at the rooftop interface. This is the zone of human occupation and its management is at the heart of climate-based planning and design. Decisions on the nature of the UCL at a neighbourhood level (including street layout, building forms, activity patterns, vegetation and recreational areas and so on) will regulate its contribution to the developing UBL. More directly, these decisions create the myriad of micro-climates found between buildings (for example, Eliasson et al.[23]; Offerle et al. [24]).

It is important to remember that the urban climate effect is moderated by the regional/local climate within which it is situated. Cities are located preferentially in river valleys, basins and along low-lying coasts. These topographies are themselves subject to climate effects such as mountain/valley and land/sea breezes that can accentuate the urban effect by limiting circulation and the dilution of urban emissions. Moreover, their regional location can further enhance/diminish the urban effect. For example, in a strong regional airflow, the urban effect will be dampened. Similarly, the high air temperatures and strong radiation environment of the subtropics are ideal for the generation of ozone, once the precursor emissions generated by a city are present (see Elliot et al. [25] and Raga et al. [26] , for example, on Mexico City).

Urban climate science is only now grappling with how climate change is likely to impact specifically on cities and their climates. Until recently estimates of carbon emissions into the atmosphere were carried out at a sectoral level with crude spatial disaggregation. However, emission inventories that have been conducted at sufficient spatial resolution illustrate the significant role of cities in the global anthropogenic emission (for example, Andres et al. [27]). Even so, this inventory-based approach needs to be verified by observation. Such research is very recent and is fraught with difficulty owing to the heterogeneous nature of urban carbon sources and sinks. Nevertheless, the emerging evidence reveals the urban atmosphere as carbon enriched with values near those predicted for the planet in fifty years' time. Much work still has to be done to link the urban landscape to the carbon emissions that arise.

Climate change models are not yet capable of generating predictions at a city scale. We do predictions for regional climate change that will perforce have implications for cities. For example, changes in weather patterns will inevitably alter the water and food resources upon which cities rely. The changing statistics of weather will require the re-examination of infrastructure design to cope with averages and extremes. However, while these prognostications pose management problems for cities, they do not elucidate the unique effect that climate change may have on cities. In this respect, we may only make informed speculation. Thus, for example, until we can grasp the effect that urban areas currently have on regional patterns of precipitation, predicting such effects in the future is of little value. This inability is reflected in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which includes settlement with industry and society in its consideration of impacts, adaptation and vulnerability [28]. There is a great need for more spatially detailed modelling focused on major population concentrations.

### *2.2. Impact*

The urban climate has a demonstrable impact on cities and their populations. In terms of consequences for humans, it is the urban canopy layer that is of greatest interest and, in this regard we can differentiate between the indoor and the outdoor environments. Indoor climates are regulated through mechanical and/or behavioural intervention and are designed to meet specific goals, most notably a healthy and safe environment. Here the focus is on the outdoor environment, which has less defined goals. It is important to bear in mind that the indoor and the outdoor environments are linked through exchanges across the building envelope. Thus, the net effect of building emissions is to alter the state of the outdoor environment. Similarly, poor outdoor air quality may enter the indoor setting. The impact of the outdoor urban effect on inhabitants may be divided into thermal, advective and air quality impacts.

#### *2.2.1 Thermal impact*

Humans have complex thermoregulatory systems that must manage energy exchanges with the environment to balance heat gains and losses. Assessing these exchanges is difficult as it requires consideration of ambient conditions (radiation, wind-speed, air temperature and humidity) and of the actions and behaviours of individuals. In addition, thermal responsiveness must account for issues such as age, health and psychology. A concept employed in this work is the notion of thermal comfort, where achieving this balance requires the least effort. The stress placed by environmental conditions and the strain experienced by the body can be used as means of assessing the degree of discomfort experienced.

There are scientific frameworks for linking measures of environment and behaviour to the thermal sensation experienced by individuals (for example, Fanger [29]; Konz et al. [30]; Fiala et al. [31]; Horikoshi et al.[32][33]; Kalkstein and Smoyer [34]). Moreover, several computer supported models and thermal comfort indices have been developed [35][36][37][38][39][40][41][42][43][44][45][46][47][48][49]. These models have become increasingly sophisticated and incorporate the ability to acclimatization [50][51]. However, applying this approach requires information that is not routinely available (for example, long-wave radiation). For urban contexts, this problem is compounded by the need to establish the microscale conditions to which individuals are exposed. This requires either detailed microclimatic observations or the use of models to "urbanize" conventional meteorological data and predict environmental conditions at the appropriate scales of space and time. As a result, this approach is most often employed to examine significant events, such as heatwaves. These events have a particular impact in urban areas where the abnormal heat gain is enhanced by the Urban Heat Island (UHI) effect and lower urban wind speed impedes heat loss. The fact that the UHI maintains higher temperatures during the night places a particular burden on the thermoregulatory system, particularly for those who are elderly and those who rely on natural ventilation to reduce body temperature.

Meteorological services most often rely on simple measures to ascertain the environmental stress during such extreme circumstances. In the absence of a standard approach, a plethora of measures and indices was developed to provide a link between environment and discomfort. Work is currently underway to provide a Universal Thermal Comfort Index and will provide guidance on this issue for national health services [38].

### 2.2.2 Airflow effects

Airflow patterns within the UCL are highly turbulent and, with the exception of simple building configurations, difficult to characterize. These flows will transfer air and its properties within the UCL and between the UCL and the overlying atmosphere. As such, the UCL regulates the natural ventilation of buildings and outdoor spaces and plays an important role in regulating air quality and comfort. In cold climates where snowfall is common (or in arid environments where duststorms are frequent) the relationship between ambient airflow and urban configuration will produce patterns of deposition that can impede access. In the case of human comfort the airflow effect is both thermal and mechanical. The former is associated with the ability of the body to retain or lose heat and is closely associated with the thermal effects discussed above. In warm and humid tropical climates, access to airflow is an important means of reducing heat stress. On the other hand, in cold climates, areas that receive sunshine and are sheltered are more pleasant. The mechanical effects of wind are due to the force it exerts against the body. There are a number of criteria in existence to evaluate the degree of discomfort under different circumstances [52][53]; the challenge, however, is to assess these criteria at a given urban location using conventional meteorological data collected at a non-urban site [54].

### 2.2.3 Air quality effects

The urban impact on air quality has been well studied by comparison to other effects. Research on the impacts of poor air quality has relied on both toxicological and epidemiological data to identify critical thresholds where health impacts are detectable. For most cities of the more developed regions, air pollution issues focus on emissions from transportation sources, and air quality management strategies exist. In the cities of less developed regions basic information on the types and magnitudes of emissions is not available and there is no monitoring and no response system in place. The limited evidence available indicates that air quality in the cities of the less developed regions is significantly worse on average that that in the cities of more developed regions [55][3].

### 2.2.4 Climate and climate change

One of the major challenges facing urban planning and design is that of global climate change, primarily as a result of greenhouse gas emissions, and its regional consequences. This change is expected to occur within the planning life cycle (50 years) and will modify temperature and precipitation regimes, alter storm frequencies and magnitudes and cause sea-level rise. These changes will affect urban areas by changing the existing climate context within which they are placed and for which they may be adapted [56]. Moreover, they will affect the resources of the surrounding landscape (water and food resources, for example) upon which the city relies for sustenance. Sea-level change is likely to have a significant impact on cities given their preponderance in low-lying coastal locations. An increase in average sea level will have implications for storm and tidal protection schemes and is likely to result in saltwater incursion into subsurface water resources. A detailed assessment of the impacts of such changes will require more precise spatial modelling of the nature of sea-level rise coupled with detailed topographic and infrastructure information on individual cities. This information is generally absent. It is in the area of global warming that most city-based climate change research has been conducted (for example, Kalkstein and Smoyer [34]; Kalkstein et al. [57]; Nakai et al. [58]; Díaz et al. [59]; Laschewski and Jendritzky [60]; Kyselý [61]; Gabriel and Endlicher [62]; Kovats and Jendritzky [63]; Stone [64]; Tan et al. [65]; van Vliet et al. [66], Ziska et al. [67].

## 2.3 Response

Each of the impacts alluded to above can be linked to a scale of climate–urban interaction at which intervention can be effective (for example, WMO [68]; Hough [69]; Cleugh et al. [70]). Here, for simplicity, the scales of urban decision-making are categorized into urban, neighbourhood and building levels (Table 2), each of which has specific objectives and tools that require different types of meteorological information. Urban air quality management provides a good model for the incorporation of climate information into planning and design. It relies upon a scientific understanding of the emissions, dilution and chemistry of pollutants, measureable standards for air quality that are based on health (public good) and a set of strategies linking actions designed to achieve specific goals. The strategies include technological, design-based and behaviour-modifying tools (for example, fuel substitution, land-use zoning or incentives to use mass transit, respectively). These strategies are often integrated into broader urban policies (such as transportation and housing) at different scales and their efficacy tested through economic and social cost-benefit analyses.

### 2.3.1 Climate-based planning and design

In this section, we present an idealized framework for including climate information into planning and design practice. While recognizing the multi-faceted and politicized nature of planning and design practice, this schema is deliberately skewed in favour of climate concerns.

Table 2. A summary of the tools (gray diagonal) employed at the building, building group and settlement scales to achieve climatic objectives at those scales

| *Objective* | *Impacts* | *Limits* | | |
|---|---|---|---|---|
| | | *Buildings* | *Building Groups* | *Settlement* |
| Indoor comfort | Buildings | Location<br><br>Materials<br><br>Design (shape, orientation, etc.) | Access to light, solar energy, wind.<br><br>Air quality | Building codes |
| Outdoor comfort<br><br>Outdoor health | Building groups | Local climate change:<br><br>Emissions<br><br>Materials/surfaces<br><br>Building dimensions – flow interference and shadow areas | Building placement.<br><br>Outdoor landscaping, materials and surfaces.<br><br>Street dimensions & orientation | Guidelines on:<br><br>Densities<br><br>Heights<br><br>Uses<br><br>Green spaces |
| Energy use<br><br>Air quality<br><br>Protection from extremes | Settlement | Energy efficiency<br><br>Air quality<br><br>Urban climate effect | Mode and intensity of traffic flows.<br><br>Energy efficiency<br><br>Air quality<br><br>Urban climate effect | Zoning<br><br>Overall extent and shape.<br><br>Transport<br><br>Policy |

From Mills, 2006 [71]
The application of tools at each scale has a climate impact at (below the diagonal), and places limits on decisions made at (above the diagonal), the other scales.

Overall management of the urban system is conducted at the urban scale where the climatic objectives include protection against extremes, ensuring urban air quality and addressing climate change (for example, limiting fossil fuel energy use). Conventional meteorological information, including substantive observational data from a nearby site and numerical forecast models, are often sufficient to establish the statistics (averages and extremes) of the current climate context. Predicting these statistics under climate change scenarios for dates in the future is a major challenge that will require more precise modelling capabilities. In the absence of such information historical records of past climates at a regional level could provide opportunities for creating such scenarios. In terms of addressing the drivers of anthropogenic climate change, obtaining information on energy use and carbon emissions associated with urban land-cover and land uses is essential. This information could be usefully employed to evaluate the impact of new urban development and the effectiveness of climate change policies [72][73].

At the building scale, the objective is to provide shelter and an indoor climate suited to its purpose, ideally with minimal resort to external energy sources. For most commercial and residential buildings the indoor objective is to moderate outdoor extremes and provide a comfortable environment. The architect's tools include building placement, material selection, the design of the building envelope and landscaping in the immediate environment. Sustainable architecture employs information on weather and climate to guide decision-making. However, the atmospheric context for the building within the city includes both the natural climate and the urban effect. The latter includes overshadowing by neighbouring structures and modified atmospheric characteristics. For architectural purposes conventional meteorological information must be urbanized to be of value at this scale.

The outdoor climate falls within the purview of urban design. This is where overall urban policies are translated into building groups (neighbourhoods). Decisions on street layout, building dimensions and placement and landscaping are made at this scale. It is at this scale that the needs of individual buildings must be matched with overall urban policy. For example, narrow streets restrict access to daylight, provide shade and limit air circulation. These attributes may be desirable for hot and windy locations but not for cold conditions. The urban designer requires meteorological information on the nature of the urban microclimate that will be created under different design scenarios.

A climate-based planning system would attempt to integrate decision-making at each level to ensure compatibility. A building that is designed to be sustainable may find itself compromised by the microclimate generated by decisions made at the urban design level. Similarly, urban-scale goals can only be achieved if decisions at the lower levels are consistent. In reality, cities are the result of historical layers of decision-making at these different levels with little coherence.

*2.3.2 Mitigation and adaptation*

Mitigation strategies are focused on eliminating the circumstances that have produced undesirable outcomes (for example, Solecki et al. [74]). Adaptation strategies focus on coping with the altered environmental circumstances (for example, Shimoda [75]). Whereas mitigation research tends to have clearly bounded research questions within specific disciplines, adaptation research is interdisciplinary and necessarily includes knowledge from the natural and social sciences, as well as policy considerations [76][77]. The policies that emerge from both approaches employ tools that can be categorized as technology-, behaviour- and design-based.

Urban policies will give rise to a variety of strategies at each scale. Much of the current climate framework for planning and design is driven by concerns for climate change at a global scale (and its regional and local implications) rather than the specifically urban climate created in cities. The accompanying strategies try to: (a) improve energy efficiency and conservation; (b) "de-carbonize" energy and electricity sources; and (c) develop natural carbon sinks. These strategies can be compatible with those designed to deal with unwanted urban effects [78].

The development of appropriate strategies for climate adaptation and mitigation necessarily involves collaboration among disciplines for research and practice. Such collaboration needs to build upon a mutual understanding of basic concepts important to collaborating practitioners from different disciplines [79][80]. It is important to distinguish between the climate risk and climate vulnerability. The former is associated with assessing the probability of an event of a given magnitude recurring in a particular place. The latter is a measure of the degree to which a community is exposed to harm as a result of the risk. Whereas risk does not distinguish between the residents in an area, vulnerability is a measure of the ability to cope. Generally for a given level of risk it is the poor that are most vulnerable. "Climate change threats illustrate the distinction between risk and vulnerability. People living in the Ganges Delta and lower Manhattan share the flood risks associated with rising sea levels. They do not share the same vulnerabilities. The reason: the Ganges Delta is marked by high levels of poverty and low levels of infrastructural protection. When tropical cyclones and floods strike Manila in the Philippines, they expose the whole city to risks. However, the vulnerabilities are concentrated in the over-crowded, makeshift homes of the slums along the banks of the Pasig River, not in Manila's wealthier areas" [81]. Interdisciplinary research at a city scale is needed to engage the planning and design professions in creating sustainable communities and in the evaluation of strategies in the built environment that serve as both carbon mitigation and as adaptive responses to climate change.

#### *2.3.2.1 Mitigation*

Where the built form is already in place, the scope for change is limited by the basic morphology (building dimensions and placement, street width and green areas) having been in place for a long period of time. Consequently, efforts have focused on changing the properties of the urban surface to modify its radiative and evaporative properties. Much construction material (asphalt, in particular) has a low albedo that results in high near-surface air temperatures that can place a heat burden on the population and, in more developed regions, can result in higher air conditioning needs. Brightening the urban surface by replacing materials or employing new surface cover has the effect of reducing the radiation heat gain and reducing the magnitude of urban heat island (for example, Rosenfeld et al. [82]; Taha [83]). Vegetation is probably the most versatile tool for managing microclimates [84][85]. It can provide shade and evaporative cooling and manage noise and air pollution, among other uses. However, employing this strategy in arid climates will have to balance the requirement for water against the benefits derived. Both of these strategies can be used to manage the urban thermal effect and can contribute to mitigation of both the urban heat island and climate change emissions.

Where the urban area is yet to be built there is an opportunity to embed good design into the urban fabric itself. For example, good design can ensure both high-density occupation and adequate access to daylight for streets and buildings [86][87]. In the United Kingdom it is estimated that densities of 200 dwellings per hectare can be achieved by allowing obstructions of up to 30° for south-facing building facades [88]. This represents a building density that is eight times the current United Kingdom average. Similarly, in hot and humid climates, good street design can ensure ventilation of the urban area by channelling airflow. In the United States many state and local governments have updated building codes to require energy efficiency and the use of renewable energy sources in the built environment, and have promoted the creation of compact urban form and the use of non-motorized transportation. For less developed regions, mitigation strategies seek to employ clean, low carbon and renewable energy sources while avoiding options that will require carbon intensive fuels.

#### *2.3.2.2 Adaptation*

There is an extensive body of research, much of it done by planning and design professionals, on hazard mitigation risk management and disaster planning. This research includes the consideration of weather-related extreme events. Moreover, many cities have, to a considerable degree, incorporated climate and its vagaries into their overall design, albeit in a fragmented and often ad hoc manner. Thus, for example, coastal cities that have experienced hurricanes and storm surges employ a combination of strategies including erecting protective barriers, protecting natural buffers and evacuating the population. Similarly, when air quality becomes deleterious, many cities initiate responses to restrict emissions (limit traffic flows) and to minimize exposure (issue alerts to stay indoors). Such strategies rely on effective planning that includes acquisition of environmental information, an assessment of its import, communication with the public and response services and an integrated and coordinated response. Developing an adaptive capacity that minimizes impacts on public health and safety and limits disruption from extreme events poses a major challenge to the planning community [89][90][91].

In the absence of information on weather and climate now and in the future, it is difficult to develop adequate responses. Even where data exist there is a need for collation and analysis to generate useful information. The heatwaves in summer 2003 in Europe (in which between 50 000 and 70 000 people died) showed clearly the vulnerability of the population and the deficiencies of current coping strategies [92][93]. This is of particular concern because climate change simulations suggest that heatwaves will increase with regard to frequency, duration and intensity (for example, Meehl and Tebaldi [94]; Patz et al. [95]; Anderson et al. [96]; Endlicher et al. [97]). Creating an adaptive capacity will require short- and long-term solutions. Modifying the urban environment to allow respite from extreme heat will take some time to implement. In the short term, establishing a Heat Health Warning System (HHWS) that generates biometeorological forecasts and prompts a locally adjusted emergency response plan is needed.

A successful adaptation strategy addresses both the natural hazard and the circumstances that place urban areas and people at risk. For example, anti-poverty policies that improve housing and the safety of neighbourhoods play a central role in reducing heat-related mortality, particularly for older citizens [98][99]. Green living and cool roofs can be used to reduce indoor temperatures in residences lacking air conditioners. This approach, which combines environmental issues with economic and social concerns, is at the heart of sustainable planning and design. Globally, adapting to climate and climate change as experienced in the city will have to address both the need for good science and the social, demographic, economic and cultural contexts that govern vulnerability.

## 3. Applying urban climate science

As much as there is a need for planning and design practitioners to be knowledgeable of climate, there is an onus on climatologists to be aware of the context within which planning and design practice occurs [71]. Modern architecture and urban planning is carried out by teams of professionals from a number of fields, and that process is generally driven by economic forces in response to market demand for housing, retail space and other uses. Urban climate considerations compete for attention with other considerations, and are likely to be addressed by specialist consultants. Generally, the input regarding climate will be sought in response to proposals made by an architect or a design team. To be effective, this input must recognize the other issues that the planners must resolve in the preparation of a town plan or an architectural design. In addition, multiple and sometimes contrasting information has to be reconciled, and most of the time a compromised, rather than an optimized, result emerges.

Plans for cities are often set within regional scales with a decision lifespan of 40–50 years. Typically these plans address socio-economic needs, and make decisions in terms of land use, density, transportation, resources and so on. These plans may be set within national objectives and take account of political aspirations for spatially balanced growth, preservation of greenbelts, urban hierarchies and international opportunities. It is rare that climate information is considered explicitly when plans are done at this strategic level, which places the city within a broader spatial, economic and demographic context. It is decisions on land use and infrastructural support at the city scale and below that will effect microscale and mesoscale urban climates and determine vulnerability to climate impacts. Urban roughness, the proportion of the urban landscape that is sealed, the floor area ratios and built density, the area given over to transportation and other matters are all established at these scales.

Climate information must be appropriate to the task at hand. At the city scale, the planner needs to grasp general patterns and isolate critical issues. This type of information is descriptive in content, is not overly complex and is often available in synthetic form on a map (for example, Masumoto [100]). This allows planners a holistic appreciation of the urban climatic characteristics of the area. The map content itself may be the result of rigorous modelling and observation but it is the communication of the results that is the key to making planning decisions (for example, Katzschner [101]; Stuttgart [102]; Yoshie et al. [103]). For example, a spatially detailed simulation of temperature and wind at ground level for Tokyo has been used as a basis for establishing a wind path into an area previously sheltered [104][105]. A more sophisticated understanding is needed if planning is to incorporate climate-based planning scenarios that employ causal relationships between a planning parameter and its bioclimatic outcome. This requires urban climate knowledge that identifies the net impact of planning interventions [106]. Traditionally, this type of research, which compares the efficacy of different planning/design options in achieving a given outcome, has not been done. Finally, simple rules of thumb that are free of jargon and easily communicable can be very useful in convincing politicians and the public of a planning/design strategy. As an example, for the subtropical summers of Hong Kong, 20–30 per cent greenery is deemed to be reasonable, desirable and practical for the thermal mitigation of the negative efforts of high density and bulky buildings in the city [107][108][109][110].

At the same time, it is important for planning and design practitioners to be aware of the consequences of urban planning and design decisions that have already been made. Such information would include climate related issues of issues of comfort, health, productivity and attractiveness. In this vein, there is an onus on planners to incorporate the views of the local residents on quality of life issues, which perforce includes environmental factors. This information needs to be complemented by observations on aspects of outdoor environmental quality. Where there has been intervention, it would be especially valuable to have before and after data to illustrate the benefit of intervention. Unfortunately, such data are rarely available.

Different climate information is needed for building-scale decision-making. It is rare that appropriate site-specific observational data exist – more commonly, data from the nearest available site are employed as a substitute. For many purposes, this information is employed in the form of a Typical Meteorological Year (TMY) that is best suited in the design heating/cooling needs for isolated and artificially managed buildings. It is less suitable, however, in the design of passively heated/cooled buildings situated in complex urban microclimates. Increasingly, architects must deal with these types of situations as developers seek to acquire environmental status in the form of meeting a zero-carbon objective or acquiring Leadership in Energy and Environmental Design (LEED) certification from the United States Green Building Council, for example. The advent of intelligent building information management systems and clever electronics means that the building may find a way to actively engage the changing climate on an hourly or instantaneous manner [111].

### *3.1 Impediments to knowledge transfer*

There are very few projects where climate experts take part in ongoing design processes over many years, beginning with environmental impact assessments at the stage of site selection for large urban developments, and continuing throughout the entire planning process. This is due in part to the number of, and the hierarchical structures of, authorities that are involved in the planning and regulatory approval of such projects. However, the integration of climate in the planning and design process may be improved if the following principles are observed [112].

(a) Purpose: Climate knowledge should be integrated into planning and design to achieve distinct goals that have measurable targets against which the plan can be judged.

(b) Timing: Climatic analyses should be carried out at the very beginning of the design process before possible avenues are blocked off by uninformed decisions. Appropriate climatic strategies can rarely be applied retroactively to rectify errors made in the initial stages of the design.

(c) Subsidiarity: In planning and design, the final design is a result of an optimizing process that involves different levels of planning. Establishing the benefits of a particular approach in general terms at the lowest level is of great benefit, but if the desired result can be achieved by several methods, then the method that can be applied as late in this process as possible should be preferred.

(d) Complexity: Architects and planners must synthesize information from many fields, of which urban climatology might be one. Any climate-based recommendation should define its goals and recognize that narrowly prescribed solutions can yield undesirable outcomes. For example, a design for pedestrian comfort is not necessarily compatible with one for building energy savings.

(e) Economic viability: Any recommendations of urban climatologists with respect to city planning are likely to have significant financial implications. Street width, for instance, is generally determined by the requirements of vehicular access, while building height reflects the desire to maximize the value of land. There is a real need for the development of a framework to assess the economic consequences of any recommended climatic strategy.

(f) Sustainability: Evaluating economic viability is a necessary but insufficient metric to assess a planning project and its climate consequences. Increasingly, climate considerations must incorporate other aspects of sustainable planning, and must account for social and environmental concerns.

(g) Clear and immediate benefits: In the absence of quantitative studies on the effect of proposed designs upon climate, decision-makers will downgrade the importance of climatic considerations. The field needs sufficiently accurate and reliable predictive tools, capable of testing different scenarios.

(h) Comprehensive approach to problem solving: Recommendations that are derived from a limited group of factors may be misleading if a critical factor is omitted. Computer modelling offers the opportunity for comprehensive analysis of the urban microclimate. However, to be useful, models must address the issues that are foremost in the decision-maker's mind.

### *3.2 Deriving useful meteorological information*

For most planning and design, it is the meteorological data that are available at a nearby station that provides the basis for climate-based decision-making. However, these data are rarely in a form that can be directly employed in a planning and design context. Clearly, information for design purposes must first address the time and space scales appropriate to the task. For some purposes, meteorological data must be processed to make a design day or a typical meteorological year that incorporates averages and extremes. These data are often required by building simulation programmes and form the basis for decisions on heating and cooling needs and the capacity of the system for dealing with extremes. For other purposes, such as the design for extreme winds or precipitation events, return periods that identify the rate of recurrence of an event of a given magnitude are employed. In addition, the spatial scale of the project (urban versus building, for example) affects the types of information needed, such as which parameters are required and whether this information, gathered at a specific site, needs to be adjusted to the site of application [113].

Buildings are designed to last for decades, towns for centuries. The compilation of useful statistics for design purposes should be based on an analysis of observations made at the same site over an extensive period of time. By comparison, it is difficult to generate these data from stations that have records of varying timespans at different locations, even when proximate. This is particularly true in rapidly changing environments, such as urban areas, where significant variation relevant to planning and design occurs over short distances. Thus, the protection of useful urban (or near urban) observation sites is essential. The challenge posed by climate change is that historical data may be of limited value in long-term planning. Tools are needed to derive useful urban climate information from available meteorological data and to predict the consequences of climate change.

While weather data are useful precisely because they are representative of a large area, other data will need to be urbanized to make them useful for particular projects. Schemes for accomplishing this range from simple empirical to complex modelling methods. The chief difficulty in the generating of site-specific urbanized climate data is the diversity of urban locations, a situation that limits the effectiveness of generalization schemes. Consequently, a range of modelling tools are required if appropriate data are to be generated in different urban climate contexts. Whereas physical, scaled models offer considerable advantages for exploring the consequences of planning decisions, they are expensive to produce and require considerable expertise if useful information is to be extracted (for example, Kubota et al. [114]). The rapid development of computer modelling suggests that such methods may evolve into engineering tools suitable for application in most planning processes.

Ideally, an integrated computer modelling framework is needed to address the needs outlined above. This is likely to take the form of coupled or interlinked models representing the hierarchy of spatial and temporal scales. At each level, appropriate design elements (buildings, trees, streets, neighbourhoods and so forth) need to be incorporated in a sufficiently realistic manner. The challenge is to attain the level of generalization in these models appropriate to the task at hand. For example, the microscale model needs to capture the detailed geometry and processes within the urban canopy layer. This model can be employed to examine issues such as comfort in outdoor spaces and to provide boundary conditions for building models. Such a model has to be integrated with neighbourhood, urban and mesoscale models. The latter can establish the interaction between urban scale decisions (such as a land-use plan) on local climates, and may include topographic or coastal effects. These models must be capable of generating urbanized output for representative periods of time. More generally, this suite of models is needed to convert the predictions of global climate change models into place-specific climate scenarios.

Currently, the only models capable of representing the full detail of an urban setting are based on computational fluid dynamics (CFD). However, these require very detailed input, which is often unavailable, and extensive computing resources [115][116]. As a result, this approach is employed on problems that are either simple in design or limited in spatial extent and for short time periods. Ideally, the CFD approach could be integrated with three-dimensional urban databases, which are available for some cities [117][118][119][120]. However, the tools that link built morphology with climate dynamics to allow one to generate surface and air temperature, for example, have not yet been developed [121]. As a compromise, it is possible to generate useful microscale data using simplified city forms, such as urban canyons (for example, Erell and Williamson, [112]). Mesoscale models designed to examine the urban effect at the urban scale have been developed (for example, Masson [122]). However, these have a spatial resolution of several hundred metres, and thus require that the features of the urban canopy layer be averaged.

Unfortunately, these problems are compounded where climate change issues are concerned. It is clear that mitigation and adaptation strategies are required at a city (and intra-urban) scale. The latter requires an evaluation of future risk at an appropriate scale and precision where planning is effective. A great deal more research work and interdisciplinary collaborations will be necessary to investigate and ascertain the implications of climate change on urban planning (for example, GLA [123]).

### 3.3 Incorporating climate knowledge

Scientific knowledge may not be taken up by practitioners because it is considered irrelevant, inapplicable or incomprehensible [113][124]. In this section we focus on the means of overcoming these difficulties.

#### 3.3.1 Education

In many regions, architects, designers and planners are professionals who have been trained and who engage in continuing education. It is imperative that climate issues are incorporated into these programmes in conjunction with other relevant environmental issues [125]. It is necessary to communicate the climatic information and the climatic consequences of design choices in a form readily discernible and, more importantly, readily usable by the design community. It is here that design aids, exemplars, checklists, manuals and tools are valuable. There are examples for this, particularly in the realms of sustainable urban design and climate change. While much is known about how land-use patterns and building and landscape design features might improve mitigation and adaptation in the building and transport sectors, best practices are rapidly developing and a shared understanding of the nature of climate change in different sectors and its place-based consequences do not yet exist in the planning and design community.

#### 3.3.2 Research

There is a continuing need for research in a number of important areas, whereas other areas have perhaps received disproportionate attention. Some of these gaps are geographic (and are considered elsewhere in this paper), others are thematic. At the urban scale and below, a great deal of attention has been paid to the urban heat island effect but there has been less attention to its effect on humidity, on precipitation and on the radiation terms. We need more comprehensive assessments of the total urban effect, rather than its parts. Considerable work has been done using simple urban forms on climatic processes, but there is a need to explore more realistic urban settings to provide case study material. Generally, there is a dearth of research on the economic and social benefits of climate-based urban design. For example, in many cities green projects (green roofs, for example) are in place but there are few assessments that would aid in decisions on the types and extent of their deployment. Finally, in the area of climate change, we have little specific information regarding the potential impact on individual cities so that definitive adaptation policies can be implemented.

#### 3.3.3 Data

Meteorological information must be accessible, appropriate and consistent to ensure its employment. In general, planning and design needs climate data to support: (a) good design practice; (b) building performance monitoring and evaluation; and (c) emergency management and disaster preparedness. Good design practice is based on long-term average historical data while performance monitoring and evaluation requires current and/or recent historical data. Current climate data and weather forecasts at different time intervals are needed for emergency management purposes although disaster preparedness may rely upon long-term historical data. A critical need of the built environment professional is reliable and detailed local (and mesoscale) climate data especially in urban areas. Unfortunately for many places, these data are either unavailable (not collected) or inaccessible (costly) at the temporal and spatial scales required. Reliable and detailed stand-alone data files usable as input files for building simulations are also needed. Moreover, for many purposes (such as planning for public health during excessive summertime heat) detailed microscale climate information is needed at a neighbourhood level to assess risk and vulnerability and to respond accordingly.

The climate science community can support the planning and design community by providing clear and updated climate projections and impact assessments at the regional scale and up-to-date sets of climate change scenarios for use by local and regional planners. Research to improve the characterization of the potential implications of future climate change for different sectors and ecosystems is needed to prompt appropriate response strategies. On the other hand, the planning and design community can integrate climate change mitigation strategies into their development plans at different scales. For example, planning for a city region can incorporate climate change mitigation into the planning scenarios by explicitly addressing the link between land use, population density and transportation networks on vehicle miles travelled, and by considering the effects of urbanized land cover on local hydrology and thermal conditions. While generating feasible planning scenarios is often routine planning practice, few planners evaluate the impact on natural ecosystem services or on carbon emissions (for example, Calthorpe [126]; Farr [127]; Wheaton and MacIver [128]).

#### 3.3.4 Tools

Planners and designers depend on their current and traditional knowledge, data and models for understanding adaptation and mitigation. Ideally meteorological/climatological information could be incorporated into the support system technologies that planning and design professionals use in day-to-day decision-making. For example, there is an opportunity to integrate some aspects of the climatic simulation tools with the computer-aided design (CAD) tools [129]. Previous successful efforts in integrating building design/drafting tools with resource management, site space utilization and planning of building construction might provide a useful conceptual model to integrate climatic information with design/drafting tools.

Similarly, in the area of land-use planning, geographic information systems (GIS) play an important role [130]. Basic information on green spaces, building dimensions and traffic could be used to generate useful outputs on urban microclimates and to test alternative plans. Geographic information systems have been used effectively to generate urban climate function maps that can provide powerful visual tools that synthesize various kinds of climatic, topographic and urban morphologic information (for example, Alcoforado [131]; Mayer [132]; Scherer et al. [133]; Schirmer [134]). In the absence of urban meteorological networks that can provide up-to-date information on intra-urban characteristics, such climate function maps are valuable for planners.

Other potentially useful tools exist but require a considerable amount of expertise to usefully employ in routine planning and design. Thus, remotely sensed data on surface temperatures can be used to assess the spatial distribution of intra-urban surface temperature variation. However, its use may be limited due to its spatial and temporal resolution, its cost and the potential need for expert knowledge to process and interpret the available data [135]. In the same vein, mesoscale meteorological models can be used to evaluate the climate and environmental effects of urban heat island mitigation scenarios; however, they are sophisticated tools that require training and are really only of value for urban-scale decision-making.

#### *3.3.5 Structures*

A sustainable planning system incorporates environmental issues into routine decision-making. In the context of climate and climate change issues a dialogue is needed between planning and design practitioners, climate experts and policymakers, so that strategy is informed by climate knowledge (and uncertainty) and the tools and standards required for transforming the built environment. Two approaches for fostering such dialogue already exist. Integrated assessment modelling (IAM) integrates expert knowledge and public participation into a planning process designed to test the impact of different assumptions (or policy options) on environmental and urban health outcomes [79]. The insights obtained are potentially useful for public decision-makers and can help identify research gaps and frame research questions [136]. However, linking research fields with their diverse methods and assumptions while at the same time ensuring community participation requires considerable investment and is challenging [80]. Community-based participatory planning (CBPR) is based on acknowledgement of the interdependence of scientific knowledge and social systems in the creation of expertise. These models aim to strengthen and legitimize research by providing means for local residents to participate fully in the framing of problems and methods of inquiry for studies. Often started at the behest of community groups facing adverse exposures and impacts, CBPR is especially important to engage the equity dimensions of climate adaptations.

### *3.4 Transferring knowledge to and from less developed regions*

There is a yawning gap that needs to be bridged between those places where research is done and those places where this information is most needed. The great bulk of urban climate research has occurred in the more developed regions characterized by mid-latitude, temperate climates. By contrast, the bulk of the urban population of the planet lives in the tropical cities of the less developed regions. This section outlines some of the key barriers to knowledge transfer between the developed and developing contexts and lists key institutional needs for effective knowledge transfer between the two.

#### *3.4.1 Absence of research*

There have been relatively few studies of the urban effect in subtropical climates so our knowledge base is weak. Moreover, where our existing knowledge is useful, applying it to other places requires local meteorological and urban information (such as land cover and construction materials) that is often not available. More research on urban climates in the warm and humid and in the hot and arid regions is needed [137]. In the absence of local research capacity, greater collaboration between well-resourced urban climate experts and those with locally based knowledge is required. Among the issues needing attention are means for promoting urban-scale ventilation, providing urban shading while allowing pollution dispersal and dealing with urban thermal discomfort in year-round warm climates. International research collaboration and resource allocation need to reflect the pressing urban design and planning priorities of the less developed regions. One way to foster more equitable resource allocation is to ensure adequate representation for the developing cities in international research, with adequate mandates for resource allocation and the setting of scientific priorities.

#### *3.4.2 Institutional issues*

There is an under-representation of issues of significance to developing world cities in international networks and forums. This is partly due to the lack of a research capacity focused on cities in developing regions. The early and rapid advances in temperate zone urban climatology occurred in a relatively few centres of knowledge via higher education opportunities. A program of planned expansion of training of urban climatologists and designers/planners from the developing world is needed to widen the global knowledge transfer efforts. Such efforts must be cognizant of the priorities relevant to developing cities. Additionally, joint efforts at refining planning/design and meteorological higher education curricula in developing contexts, and the exploration of barriers to the awarding of joint degrees need to be prioritized.

#### *3.4.3 Absence of reliable data*

In general, useful meteorological data are in short supply so that there is a lower expectation of obtaining reliable and spatially/temporally appropriate information. This absence, when combined with some equivocation on the importance of urban climate issues, impedes research and its application. These problems are further confounded by non-technical issues such as attitudes towards data and intellectual property rights.

#### *3.4.4 Communication*

Much of the published work on urban climates appears in English-language journals that are not available in many developing regions. Where research work is completed in tropical cities it is often published in non-English regional journals. As a result the fruits of research work are not known in those places that need it most, and a rich source of local urban information is not incorporated into mainstream urban climate knowledge. These problems are compounded by weak knowledge dissemination networks in the tropics/subtropics.

*3.4.5 Structural changes needed*

Even the little that is known needs to be widely disseminated for effective use by the planning and design professions. Structural and institutional changes are needed to address these issues and such changes are needed to foster appropriate research and two-way knowledge transfer.

*3.4.6 Knowledge transfer*

The importance of knowledge transfer from the developed to the developing contexts is clear; the reverse transfer of knowledge is also necessary. Much of the developing world has experiential knowledge of living in a warm world. This will become valuable to the developed world as the Earth enters a period of sustained warming. Researchers from the developed cities could learn from the experiential awareness of warm contexts, historic experience of design for hot climates (in both arid and wet forms) and adaptation/coping strategies to thrive in warm, excessively wet (or prolonged dry) climates. Such two-way knowledge transfer will benefit from an inclusion of knowledge available in regional languages.

## 4. Conclusions: assessment of gaps

The gaps in our knowledge and in our ability to apply that knowledge are of several types:

(a) Theoretical: Our understanding of urban areas and their role in modifying climates at different scales is fragmented and disjointed. Urban climate research, in the broadest sense, has been driven by different research agendas at these different scales. There has been little attempt to ensure compatibility in terms of data, methods or objectives. There is especially a great deal of work to be done that links the work on the urban climate effect with the work on climate change and climate extremes.

(b) Science: There are significant gaps in our knowledge of the urban effect, particularly as it relates to the local and regional climates within which this effect is given expression. There has been little evaluation of tropical urban climates and on the net impact of climate-based interventions, such as landscape design. For many cities, often those of the less developed regions, there is little meteorological data available or accessible and what is obtainable is incomplete and inappropriate to the task at hand. There is a need for urban planners and designers to become involved in setting the research agenda for urban climate science and for interventions to be evaluated in terms of costs and benefits, both economic and social.

(c) Communication: Too little climate knowledge is accessible. There is a need to codify our knowledge of urban climates. This would provide clear guidelines for interventions that are compatible with achieving climate goals (at whatever scale). These guidelines need to be accessible and supported by relevant case studies.

(d) Application: Too little climate knowledge is applied. It needs to become embedded in the planning and design process. This requires a two-way knowledge transfer between planning and design professionals and policymakers, the integration of climate information into the planning and design process (both in terms of routine tools and political engagement) and the accessibility of relevant information.

(e) Addressing sustainability: Climate research must address sustainability issues more explicitly. This means that it must examine the relationships between climate impact and vulnerability in terms of local, regional and global socio-economic factors.

To summarize, the authors recommend a series of high priority recommendations to address the gap between urban climate knowledge and application outlined in this paper:

*Observations and Data:*

(a) Place greater emphasis on gathering information on the tropical urban effect. In the absence of local research capacity there is a case for resources to be transferred to places where observations are needed.

(b) Maintain existing urban meteorological stations and invest in good quality stations in and near the rapidly growing cities in less developed regions.

(c) Develop research programmes that are designed to meet the requirements of urban decision-makers. These need data that shows the correspondence between the urban landscape and climate effects.

(d) Acquire and maintain standardized information on city form. These data (at various scales) would be of benefit to modelling studies and would help urbanize existing meteorological data.

*Understanding local, regional and global climate linkages:*

(a) Develop integrated hierarchal models that can provide useful predictions at urban planning scales.

(b) Integrate urban climate knowledge into the practice of sustainable urban planning. Link urban climate effects with broader environmental effects and consider the effects within broader social and economic contexts.

(c) Encourage cross-disciplinary research on urban climates and their effects and a dialogue between researchers, practitioners and decision-makers.

*Tools:*

(a) Provide guidelines for good planning and design that are based upon evidence and supported by real world examples.

(b) Integrate climate knowledge into existing planning/design tools like Computer Aided Design and Geographic Information Systems.

*Education:*

(a) Train meteorologists to understand the data needs of urban planners and designers and the potential of weather/climate data in this field.

(b) Integrate an understanding of climate and climate changes into the training curricula of urban planners and designers.

(c) Develop Web-based resources that will allow for dissemination of knowledge.

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