



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

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**Session Title Climate and Sustainable Cities:**

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

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**High-Priority Recommendations**

1. Observations & Data
  - 1.1 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.
  - 1.2 Maintain existing urban meteorological stations and invest in good quality stations in and near the rapidly growing cities in LD regions.
  - 1.3 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.
  - 1.4 Acquire and maintain standardized information on city form. These data (at various scales) would be of benefit to modeling studies and would help 'urbanise' existing meteorological data.
2. Understanding local, regional and global climate linkages
  - 2.1. Develop integrated hierarchical models that can provide useful predictions at urban planning scales.
  - 2.2. Integrate urban climate knowledge into the practice of sustainable urban planning. Link urban climate effects with broader environmental and set within broader social and economic contexts.
  - 2.3. Encourage cross-disciplinary research on urban climates and their effects and a dialogue between researchers, practitioners and decision-makers.
3. Tools
  - 3.1 Provide guidelines for good planning and design that are based upon evidence and supported by real world examples.
  - 3.2 Integrate climate knowledge into existing planning/design tools like Computer Aided Design and Geographic Information Systems.
4. Education
  - 4.1. Train meteorologists to understand the data needs of urban planners and designers and the potential of weather/climate data in this field.
  - 4.2. Integrate an understanding of climate and climate changes into the training curricula of urban planners and designers.
  - 4.3. Develop web-based resources that will allow for dissemination of knowledge.

Also see:

Mills G, Cleugh H, Emmanuel R, Endlicher W, Erell E, McGranahan G, Ng E, Nickson A, **Rosenthal J** and Steemer K. (2010). Climate information for improved planning and management of mega cities." *Procedia Environmental Sciences* 1:228–246.

## 1. Introduction

The population of the planet's population is 6.6 billions (b), of which half now live in urban areas. Together these places comprise less than 3% of the land area yet they form a network that connects most parts of the world through the exchange of materials, goods and people. The 'urbanisation' of the world's population is set to continue: by 2025 the world's population is projected to be 8.01b, of which nearly 5b will live in urban areas. While most live in settlements of 500,000 or less, many occupy large cities (over 1 million) and some reside in very large 'megacities' (over 10 millions). The numbers and locations of the large and very large cities reveal the scale of global urbanisation. 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 (e.g. Tokyo and New York), little is known of others (e.g. Jakarta and Dhaka)<sup>2</sup>.

Urbanisation, 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 to the 'natural' climate and deleterious to human health. 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<sub>2</sub> may be attributable to activities concentrated in urban areas. 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.<sup>3</sup>

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 (P&D). 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 urbanisation: Although the first 'cities' appeared more than 5000 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. Modern urbanisation 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'. The first wave peaked in the 1950's, by which time 50% of the population of the more developed (MD) regions (chiefly Europe, Japan and North America) lived in urban areas. Over the period of this urbanisation, 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 urbanisation is now occurring in the less developed (LD) 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 2.54b and 47% lived in LD regions. By 2007, the global population was 6.67b and 80% (5.45b) lived in LD regions. This second wave has yet to peak: currently 44% of the population of the LD regions live in urban areas yet these account for 2.38b, compared to just 0.91b living in the cities of the MD regions. In other words for every three urban inhabitants, two live in the cities of the LD 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 MD regions is happening in less than half of this time, with a vastly increased population, in LD regions. The consequences are evident in the urbanised landscapes of the LD regions where many residents (sometimes the majority) occupy 'informal' settlements that have no basic infrastructure and no security of tenure<sup>4</sup>.

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. 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 urbanised 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 urbanised 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.<sup>5</sup>

1.2 Sustainable cities & 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". 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.<sup>6</sup>

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. 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 MD regions whereas environmental health burdens are similarly concentrated in the cities of the LD regions.<sup>7</sup>

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. 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 its resource catchment. Urban sustainability then becomes a relative concept: the more sustainable city is the one which uses less resource to fulfill its functions. Generally, relative sustainability is evaluated on a per capita basis, though there is a sense in which a city whose natural population growth rate is high 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 emphasise 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.<sup>8</sup>

Among affluent cities, a compact, high-density city whose parts are linked via a mass transit system is more sustainable, in terms of resource use, than a sprawling automobile-based city. 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.<sup>9</sup>

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 19th century, to pollution and waste problems in the 20th century, to sustainability problems in the 21st 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 19th century and the environmental movement of the 21st 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<sup>10</sup>.

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 & 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.

The city however is not uniform and most can be decomposed into sub-areas (neighbourhoods) that exhibit distinctive types of urban form and/or functions that reflect the organisation of the urban area. The properties of the UBL are formed by the blending of all the upwind contributions from the surfaces below however, closer to the urban surface (at approximately twice the height of the buildings), the unique contributions of a neighbourhood can be detected. Below this height the individual elements of the neighbourhood (buildings, trees etc.) begin to dominate over neighbourhoods.<sup>11</sup>

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.<sup>12</sup>

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.<sup>13</sup>

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. Even still, 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 that links the urban landscape to the carbon emissions that arise.<sup>14</sup>

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 have on regional patterns of precipitation currently, predicting such effects in the future is of little value. This inability is reflected in the 4<sup>th</sup> assessment report of the IPCC report, which includes settlement with industry and society in its consideration of Impacts, Adaptation and Vulnerability. There is a great need for more spatially detailed modeling focused on major population concentrations.<sup>15</sup>

**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.

*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.

Fanger established a scientific framework for linking measures of environment and behaviour to the thermal sensation experienced by individuals. 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 micro-scale conditions to which individuals are exposed. This either requires detailed micro-climatic observations or the use of models to ‘urbanise’ conventional meteorological data and predict environmental conditions at the appropriate space and time scales. As a result, this approach is most often employed to examine significant events, such as heat waves. These events have a particular impact in urban areas where the abnormal heat gain is enhanced by the UHI effect and lower urban wind-speed impedes heat loss. The fact that the UHI maintains higher temperatures during the night plays a particular burden on the thermoregulatory system,

particularly for those that are elderly and those that rely on natural ventilation to reduce body temperature.<sup>16</sup>

Most often meteorological services 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 were 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<sup>17</sup>.

*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, it 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 dust-storms 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 however the challenge is to assess these criteria at a given urban location using conventional meteorological data collected at a non-urban site.<sup>18</sup>

*Air quality effects:* The urban impact on air quality has been well studied by comparison with 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 MD regions air pollution issues are chiefly concerned with emissions from transportation sources and air quality management strategies exist. In the cities of LD 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 LD regions is significantly worse on average than that in the cities of MD regions.<sup>19</sup>

*Climate and climate change:* One of the major challenges facing urban P&D 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 are adapted. Moreover, they will affect the resources of the surrounding landscape (e.g. water and food resources) upon which the city relies for sustenance. Sea-level change is likely to have a significant impact on cities given their preference for low-lying coastal locations. An increase in average sea-level will have implication for storm and tidal protection schemes and is likely to result in salt-water incursion to 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. In addition to the thermal impact, additional health problems may arise due to the immigration of highly allergenic neophytes into city habitats and the enhanced formation of ozone.<sup>20</sup>

**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. Here, for simplicity, the scales of urban decision-making are categorised into urban, neighbourhood and building levels (Table 2), each of which has specific objectives and tools, which require different types of meteorological information. Urban air quality management provides a good model for the incorporation of climate information into P&D. 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 (e.g. fuel substitution) or design-based (e.g. land-use zoning) or behaviour-modifying (e.g. incentives to use mass transit) tools. These strategies are often integrated into broader urban policies (e.g. transport and housing) at different scales and their efficacy tested through economic and social cost-benefit analyses.

**2.3.1 Climate-based P&D:** In this section, we present an idealized framework for including climate information into P&D practice. While recognizing the multi-faceted and politicized nature of P&D practice, this schema is deliberately skewed in favour of climate concerns.

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 (e.g. 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 modeling 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 developments and the effectiveness of climate change policies.<sup>21</sup>

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 'urbanised' 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 micro-climate 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 & Adaptation:** Mitigation strategies are focused on eliminating the circumstances that have produced undesirable outcomes. Adaptation strategies focus on coping with the altered environmental circumstances. 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. 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 P&D 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: improve energy efficiency and conservation; ‘de-carbonize’ energy and electricity sources and; develop natural carbon sinks. These strategies can be compatible those designed to deal with unwanted urban effects.<sup>22</sup>

The development of appropriate strategies for climate adaptation and mitigation necessarily involves collaboration between disciplines for research and practice. Such collaboration needs to build upon a mutual understanding of basic concepts important to collaborating practitioners from different disciplines. 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. Vulnerability 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’.* 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 the purposes of both carbon mitigation and as adaptive responses to climate change.<sup>23</sup>

*Mitigation:* Where the built form is already in place, the scope for change is limited as the basic morphology (building dimensions and placement, street width and green areas) will be 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 MD regions, results 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 urban heat island. Vegetation is probably the most versatile tool for managing microclimates. It can be used to provide shade, evaporative cooling, manage noise and air pollution, etc. 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.<sup>24</sup>

Where the urban area has 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. In the in the U.K. 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. This represents a building density that is eight-times the current U.K. average. Similarly, in hot and humid climates, good street design can ensure ventilation of the urban area by channeling airflow. In the US many state and local governments have updated building codes to require energy efficiency and use of renewable energy sources in the built environment, 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.<sup>25</sup>

*Adaptation:* There is an extensive body of research work, much of it done by P&D professionals, on ‘hazard mitigation’ risk management and disaster planning that has included 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, where coastal cities have experience of hurricanes and storm surges a combination of strategies including erecting protective barriers, protecting natural buffers, and population evacuation are employed. Similarly, when air quality becomes deleterious, many cities will enact responses to restrict emissions (limit traffic flows) and 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 co-ordinate 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.<sup>26</sup>

In the absence of information on weather and climate now and in the future it is difficult to develop adequate responses. Even where data exists there is a need for its collation and analysis to generate useful information. The heat waves in summer 2003 in Europe (in which between 50,000 and 70,000 died) showed clearly the vulnerability of the population and the deficiencies of current coping strategies. This is of particular concern because climate change simulations suggest that heat waves will increase regarding frequency, duration and intensity. Creating an adaptive capacity in this regard 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 generate biometeorological forecasts and prompt a locally adjusted emergency response plan are needed.<sup>27</sup>

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. 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 P&D. 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.<sup>28</sup>

### 3. Applying Urban Climate Science

As much as there is a need for P&D practitioners to be knowledgeable of climate, there is an onus on climatologists to be aware of the context within which P&D practice occurs. Modern architecture and urban planning is carried out by teams of professionals from a number of fields and that the process is generally driven by economic forces, in response to market demand for housing, retail space, etc. Urban climate considerations are just one of many that must compete for attention and are likely to be addressed by specialist consultants. Generally, this input will be sought in response to proposals made by an architect or a design team. To be effective, this input must recognize the issues that the planners must resolve in the preparation of a town plan or an architectural design. In addition, multiple and sometimes contrasting information have to be reconciled, and for most of the time a compromised, rather than an optimized, result emerges<sup>29</sup>.

Plans for cities are often set within regional scale plans 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 green-belts, 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 at the city scale and below that decisions are made on land-use parcels and their infrastructural support, which will effect micro- and meso-scale 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, etc. are established at these scales.<sup>30</sup>

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 often available in synthetic form on a map. This allows planners a holistic appreciation of the urban climatic characteristics of the area. The map content itself may be the result of rigorous modeling and observation but it is the communication of the results that is the key to making planning decisions. 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. 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 bio-climatic outcome. This requires urban climate knowledge that identifies the net impact of planning interventions – 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 subtropical summers of Hong Kong, to thermally mitigate the negative effects of high density and bulky buildings in the city, 20-30% greenery is deemed to be reasonable, desirable and practical.<sup>31</sup>

At the same time, it is important for P&D practitioners to be aware of the consequences of urban P&D 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 resident 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.<sup>32</sup>

Different climate information is needed for building-scale decision making. It is rare that appropriate site-specific observational data exists – more commonly, data from the nearest available site is 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 micro-climates. 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 LEED certification, for example. The advent of intelligent building information management system and clever electronics means that the building may find a way to actively engage the changing climate on an hourly or instantaneous manner.<sup>33</sup>

**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 hierarchical structure 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.<sup>34</sup>

- *Purpose:* Climate knowledge should be integrated into P&D to achieve distinct goals that have measurable targets against which the plan can be judged.
- *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.
- *Subsidiarity:* In P&D, 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, that which can be applied as late in this process is preferable.
- *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.
- *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.
- *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 which account for social and environmental concerns.
- *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.

- *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 modeling offers the opportunity for comprehensive analysis of the urban microclimate. However, to be useful, these must address the issues that are foremost in the decision-maker's mind.

**3.2 Deriving useful meteorological information:** For most P&D, it is the meteorological data that is 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 P&D context. Clearly, information for design purposes must first address the time and space scale appropriate to the task. For some purposes, meteorological data must be processed to make a 'design day' or a 'typical meteorological year' that incorporate 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 (e.g. urban vs. building) affect the types of information needed such as, which parameters are required and whether this information, gathered at a specific site, need to be adjusted to the site of application.<sup>35</sup>

Buildings are designed to last for decades, towns for centuries. The compilation of useful statistics for design purposes should be based on 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 time span at different locations, even when proximate. This is particularly true in rapidly changing environments, such as urban areas, where significant variation relevant to P&D 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 much weather data is useful precisely because it is representative of a large area, other data will need to be 'urbanised' to make it useful for a particular projects. Schemes for accomplishing this range from simple empirical to complex modeling methods. The chief difficulty in generating of site-specific urbanized climate data is the diversity of urban locations, which 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. The rapid development of computer modelling suggests that such methods may evolve into engineering tools suitable for application in most planning processes.<sup>36</sup>

Ideally, an integrated computer modelling framework is needed to address the needs outlined above. This is likely to take the form of coupled or inter-linked models representing the hierarchy of spatial and temporal scales. At each level, appropriate design elements (buildings, trees, streets, neighbourhoods, etc.) 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 micro-scale 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 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 that 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. 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. 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. As a compromise, it is possible to generate useful micro-scale data using simplified city forms, such as urban canyons. Meso-scale models designed to examine the urban effect at the urban scale have been developed. However, these have a spatial resolution of several hundred metres, which requires that the features of the urban canopy layer are averaged.<sup>37</sup>

Unfortunately, these problems are compounded when 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 inter-disciplinary collaborations will be required to investigate and ascertain the implications of climate change on urban planning.<sup>38</sup>

**3.3 Incorporating climate knowledge:** Page suggested that scientific knowledge may not be taken up by practitioners because it was considered irrelevant, inapplicable or incomprehensible. In this section we focus on the means of overcoming these difficulties<sup>39</sup>.

*Education:* In many regions, architects, designers and planners are professionals that have been trained and engage in continuing education. It is imperative that climate issues are incorporated into these programmes in conjunction with other relevant environmental issues. 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, 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 does not yet exist in the P&D community.<sup>40</sup>

*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 however 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 (e.g. green roofs) 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 of the potential impact on individual cities so that definitive adaptation policies can be implemented.

*Data:* Meteorological information must be accessible, appropriate and consistent to ensure its employment. In general, the P&D needs climate data to support: good design practice, building performance monitoring and evaluation, and emergency management and disaster preparedness. Good design practice is based on long-term average historic data while performance monitoring and evaluation requires current and/or recent historic 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 historic data. A critical need of the built environment professional is reliable and detailed local (and meso-scale) climate data especially in urban areas. Unfortunately for many places data for these this information is 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 simulation are also needed. Moreover, for many purposes (such as planning for public health during excessive summertime heat) detailed micro-scale climate information is needed at a neighbourhood level to assess risk and vulnerability and respond accordingly.

The climate science community can support the P&D 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 P&D 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 their scenarios by explicitly addressing the link between land-use, population density and transportation networks on vehicle miles traveled or of urbanized land-cover on local hydrology and thermal effects. While generating feasible planning scenarios is often routine planning practice few evaluate their impact on natural ecosystem services or on carbon emissions<sup>41</sup>.

*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 in to the support system technologies that P&D 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. 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.<sup>42</sup>

Similarly, in the area of land-use planning geographic information systems (GIS) play an important role. Basic information on green-spaces, building dimensions and traffic could be used to generate useful outputs on urban micro-climates and test alternative plans. This tool has been used effectively to generate urban climate function maps that can provide. For many purposes climatic maps provide a powerful visual tool that synthesizes various kind of climatic, topographic and urban morphologic information. 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.<sup>43</sup>

Other potentially useful tools exist but require a considerable amount of expertise to usefully employ in routine P&D. 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 available data. In the same vein, meso-scale 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.<sup>44</sup>

*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 P&D practitioners, climate experts and policy makers, 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 modeling (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. The insights obtained are potentially useful for public decision-makers and can help identify research gaps and frame research questions. However, linking research fields with their diverse methods and assumptions while, at the same time, ensuring community participation requires considerable investment and is challenging. 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.<sup>45</sup>

**3.3 Transferring knowledge to/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 out key institutional needs for effective knowledge transfer between the two.

*Absence of research:* There have been relatively few studies of the urban effect in (sub)tropical climates so our knowledge base is weak. Moreover, where our existing knowledge is useful, applying it to other places requires local meteorological and urban (e.g. land-cover, construction materials, etc.) that is often not available. More research on urban climates in the warm, humid and hot, arid regions is needed. 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 mandate for resource allocation and the setting of scientific priorities.

*Institutional issues:* There is an under-representation of issues of significance to developing world cities in international networks and fora. This is partly due to lack of a research capacity in developing regions focused on cities. The early and rapid advances in temperate zone urban climatology occurred in a relatively few centers of knowledge via higher educational 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 issue priorities relevant to developing

cities. Additionally, joint efforts at refining planning/design and meteorological higher educational curricula in developing contexts and exploration of barriers to the award of joint degrees need to be prioritized.

*Absence of reliable data:* In general, useful meteorological data is 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 to data, intellectual property rights, etc.

*Communication:* Much of 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. Similarly, a rich source of local urban information is not incorporated into mainstream urban climate knowledge. These are further confounded by weak knowledge dissemination networks in the tropics/sub-tropics.

*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.

*Knowledge transfer:* While acknowledging the importance of knowledge transfer from the developed to the developing contexts it is also necessary to foster reverse transfer of knowledge. Much of the developing world has experiential knowledge of living in a warm world. This will become valuable to the developed world even 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 (both in its arid and wet forms) and adaptation/coping strategies to thrive in warm, excessively wet (or prolong dry) and humid 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:

*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 work on the urban climate effect with that on climate change and climate extremes.

*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 LD 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.

Communication: Too little climate knowledge is accessible. There is a need to ‘codify’ our knowledge on 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.

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 with P&D professionals and policy-makers; the integration of climate information into the P&D process (both in terms of routine tools and political engagement) and; that relevant information is accessible.

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.

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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	Dehli, 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	Dehli, India	15.9	6	Mexico City, Mexico	21.0
7	Shanghai, China	15.0	7	New York-Newark, USA	20.6
8	Kolkata, Indai	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

Table 1. Population of urban agglomerations with 10 million inhabitants or more, 1950, 1975, 2007 and 2025. Abstracted from Table 1.6 in UN, 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.

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

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. 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. From Mills, 2006.

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<sup>1</sup> <sup>1</sup>CSIRO, Australia; <sup>2</sup>Glasgow Caledonian University, Scotland; <sup>3</sup>Humboldt University Berlin, Germany; <sup>4</sup>Blaustein Institute for Desert Research, Israel; <sup>5</sup>International Association for Environment and Development; <sup>6</sup>UCD Dublin, Ireland; <sup>7</sup>Chinese University of Hong Kong; <sup>8</sup>London Climate Change; <sup>9</sup>Columbia University, New York US; <sup>10</sup>Cambridge University, England.

<sup>2</sup> Information on the global urban population, including the populations of large and very large cities, is available from UN (2008). The concentration of this population is based upon satellite estimates (Small and Cohen, 2004).

<sup>3</sup> The term ‘urbanization’ is used in many different ways in the literature. It is important at the outset to distinguish between form and function as the definition of urbanization for each will not necessarily incorporate the same geographical area. Information on the source of the anthropogenic carbon flux is largely based on the concentration of human activities in urban areas. Emission inventories do show a remarkable concentration in the wealthy cities of the world (Mills, 2007). The concentration of populations in particular places is discussed in Small and Cohen (2004) and in McGranahan et al (2007). The nature of air quality in the mega-cities of the world is discussed in Molina and Molina (2007).

<sup>4</sup> There are few sources on the history of urban populations. In the absence of records, most historical estimates are based on archaeological findings and assumed densities (Chandler and Fox, 1974; Modelski, 2003). The division on the modern period of urbanization into two waves is from UNFPA (2008).

<sup>5</sup> Information on cities is inconsistent and incomplete. Potere and Schneider (2007) have compared the various assessments of urban land-cover at a global scale. There is no comparable assessment of the physical geographies of cities, including both their local topography and their 3-D urban form. Steemers et al (1997) have demonstrated the potential for such datasets in examining urban micro-climates.

<sup>6</sup> Our Common Future was the landmark document produced by the WCED (1987). It outlined the case for sustainable development, which recognizes that development is underpinned by the environment and that sustaining the former depends on the health of the latter. While the report highlighted a series of environmental challenges, concerns for global climate change has dominated public discourse (IPCC, 2007).

<sup>7</sup> Rees et al.(1996) provide a means of evaluating sustainability in an ecological sense by converting all resources into common units of energy that are then converted into productive area (or footprint) of the Earth. The unequal share of resources and of environmental burdens, which lies at the heart of global sustainability, has been widely reported (e.g. Satterthwaite (1997), UNDP (2007) and UNFPA (2008)).

<sup>8</sup> Wolman (1965) was the first to formally consider the metabolism of a city by examining inputs of water, fuel and food and wastes deposited into land, water and air. Others have taken up this approach by taking the city as the scale of analysis (e.g. Girardet (1999), Kennedy et al. (2007), Newman (1999), Rees and Wackernagle (1996) and Rees (1997)).

<sup>9</sup> There is a considerable literature on compact cities (see Rogers, 1997). See Lyons et al (2003) for a discussion on the relationship between the size of urban areas and the associated transportation costs.

<sup>10</sup> See McGranahan et al., 2005 Box 27.3.

<sup>11</sup> Oke has proposed an Urban Climate Zone (UCZ) classification scheme that captures the main features of these urban neighbourhoods and addresses their atmospheric effect at different scales. As most work on cities has been based in MD regions, whose cities have a characteristic form that may not be repeated in the fast-growing cities of the LD regions.

<sup>12</sup> See, for example, Eliasson et al (2007) and Offerle et al (2008) on aspects of the wind and temperature field in a city street.

<sup>13</sup> The example of Mexico City’s air quality shows the complex relationship between emissions and local and regional meteorology. See, for example, Elliot et al (2000) and Raga et al. (2001).

<sup>14</sup> See for example, Figure 1 in Mills (2007) based on an inventory (Andres et al., 1997). As an example of observations see Velasco et al. (2005) study on Mexico City.

<sup>15</sup> See Chapter 7 in IPCC (2007).

<sup>16</sup> The work of Fanger (1970) has been extended by others (e.g. Konz et al. 1977; Wissler 1985; Fiala et al. 1999; Horikoshi et al. 1995, 1997; Kalkstein & Smoyer 1993). Moreover, several computer supported models and thermal comfort indices have been developed (Stolwijk 1971; Jendritzky et al. 1979, 1990, 2002; Staiger 1997; Steadman 1984, 1994; Gagge et al. 1986; Driscoll 1992; Blazejczyk 1994; Höppe 1999; Pickup and deDear 2000; deDear and Pickup 2000; Huizenga et al. 2001; Tanabe et

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al. 2002). These models have become increasingly sophisticated and incorporate the ability to acclimatization (Fiala et al. 2001; Kusch et al. 2004).

<sup>17</sup> Although the WHO report is not complete, progress in the area can be found in Jendritzky et al. (2002) and on the website associated with the project <http://www.utci.org>.

<sup>18</sup> There are many schemes in place that assess the effects of wind in an outdoor setting. See for example, ASCE (2003) and Soligo et al. (1998). Bottema M (1999) provides simple means for estimating site-specific wind statistics from a nearby site.

<sup>19</sup> See Fenger (1999) for a comprehensive assessment of the state of the field at the turn of the Millennium and Molina and Molina (2004).

<sup>20</sup> It is important to remember that many cities are vulnerable to current climate hazards. deSherbinin et al (2007) examine the vulnerability of three very large coastal cities – Mumbai, Rio De Janeiro and Shanghai – to climate hazards. The impact of global warming on cities has been examined in a number of studies (e.g. Kalkstein and Smoyer, 1993; Kalkstein et al. 1997; Nakai et al. 1999; Díaz et al. 2002; Laschewski & Jendritzky 2002; Kyselý 2004; Gabriel & Endlicher 2006; Kovats and Jendritzky 2006; Tan et al. 2007). Ziska et al. (2003) and van Vliet et al. (2006) have examined the effects of global warming on pollen production while Stone (2005) considered impacts on the formation of ozone (Stone 2005). The UNDP in its 2007/08 Development Report suggests that warming could increase the population exposed to dengue fever, which is currently confined largely to urban areas. Warming could increase its latitudinal extent and the numbers at risk (UNDP, 2007). More broadly, deSherbinin et al (2007) examine the vulnerability of three very large coastal cities – Mumbai, Rio De Janeiro and Shanghai – to climate hazards.

<sup>21</sup> See Gornitz et al. (2002) and Jacob et al (2007)

<sup>22</sup> See Ebi and Semenza (2008) and Pacala and Socolow (2004). Hamin and Gurrán (2008) examine the roles for mitigation and adaptation and the potential for complementary and contradictory outcomes.

<sup>23</sup> See Rosenthal et al. (2007) and Aron and Patz (2001). The more general case is illustrated by a quote taken from UNDP (2007). Huq and Reid (2007) discuss community based adaptation. The World Bank (2008) has developed a primer on climate-resilient cities in eastern Asia. Lankao et al (2007) focus on the role of cities in the carbon cycle of Latin America.

<sup>24</sup> For example, in old cities the streets were not designed for motorized vehicles (Abdul-Wahab and Al-Araimi, 2004). Rosenfield et al. (1995, 1998) and Taha (1996, 1997) have examined the potential for different UHI mitigation strategies. More generally, Nowak and Crane (2002) and Nowak (2007) have outlined the potential benefits of urban forests. Lankao et al (2004) discuss the role of cities and urban development in Latin America's carbon cycle.

<sup>25</sup> The relatively simple geometry associated with urban form and access to direct solar energy and daylight more generally has provided a sound basis for urban environmental design. See, for example, Knowles (2002), Littlefair (1998, 2001) and Steemers (2003).

<sup>26</sup> Douglas (1984) and Hough (2000) provide overviews of the urban environment. On the issue of climate risks and adaptation see Smit et al., 1999, McMichael et al. (2003) and Climatelab (2009). More specifically, The World Bank (2008) has created a primer for developing climate resilient cities in East Asia.

<sup>27</sup> See Beniston (2004) and Schär et al. (2004) on the 2003 European heatwave. Others have considered the implications of climate change on heatwave frequency (e.g. Meehl and Tebaldi (2004), Patz et al. (2005), Epstein et al. (2006) and Endlicher et al. 2006) (Rosenfeld et al. 1998; Shashua-Bar & Hoffman 2000; Shimo da 2003; Solecki et al. 2005; Stone 2005; UNEP 2007; Rosenthal et al. 2007; Kress 2007; Endlicher & Kress 2008; [www.amica-climate.net](http://www.amica-climate.net), Rosenthal et al, 2008; Smoyer et al., 2001. (Kovats et al. 2004; Robine et al. 2007; Jendritzky & Koppe 2008)

<sup>28</sup> (Klinenberg, 2002), (Blasnick, 2004) (Menne & Ebi 2006)

<sup>29</sup> On the other hand, the WHO's Healthy Cities project advocates a 'new planning process' that places the creation of healthy environments at its centre, alongside more traditional concerns for the economy and society (WHO, 1999).

<sup>30</sup> There are many reasons why climate is rarely considered at this scale. Firstly, climate has been considered a "constant" entity. The advent of the issue of climate change (IPCC, 2007) and a better understanding of urban heat island and other urban climatic issues are slowly changing this perception. Secondly, climate was not seen as an important issue alongside more pressing socio-economical needs. A change of public attitude is occurring due to an increased recognition of environmental issues. Linking both is the quest for energy efficiency and sustainability more broadly, which has forced planners to address climate issues and explain their plans to the general public. This change is evident

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in planning/design research (e.g. Evans and de Schiller (1996), Emmanuel (2005), Szokolay (2004) and Kwok and Grondzik (2007)).

<sup>31</sup> As an example, rather than present all the statistics on air temperature, Masumoto (2009) has extracted statistics on just hot days and hot nights and presented this information in map-form for planning purposes. Similarly, broad guidelines on the density of buildings and the balance between paved and vegetated proportions can be more useful for planning purposes than more complex analyses (Stone et. al. (2001), BD (2009), Katzschner, 1998). Ichinose et. al. (2005) and Ashie (2005) take detailed simulations, which are the result of complex CFD models and present the information in simple-to-understand map form that allows for non-experts to participate in the decision-making process (AIJ, 2008). A similar approach has been taken in densely built-up Hong Kong (Yoshie et. al. (2008), Ng (2003, 2007a and Ng 2008) where a set of urban climatic guidelines is incorporated into the Planning Standards and Guidelines (HKPSG, 2008). Similarly, the City of Stuttgart has published Städtebauliche Klimafibel (Stuttgart, 2008).

<sup>32</sup> For planners and architects, the before and after urban climatic scenarios of an intervention is valuable. Ideally, observations would be available prior to the development process. In Tokyo for example, it is a recommendation for large urban re-development to monitor the site wind, air temperature and RH information at the pedestrian level for a year before and also after the building construction. However, this is not generally available. There may be scope for observation programmes to obtain information on the urban effect for limited period (for example, a recent study in Tokyo included mounting 190 observation points in an area of about ten square kilometers (AIJ, 2008)) however, such programmes are expensive. More generally, planners and designers rely on work completed elsewhere for guidelines (e.g. Ren and Ng (2007), Erell and Williamson (2007), Lazar and Podesser (1999) and Wong et. al. (2007)). It is important that the results of such studies are accessible to the P&D community.

<sup>33</sup> The Leadership in Energy and Environmental Design (LEED) is a rating system for sustainable buildings. See Wong et al. (2000), for example, on simulating building energy performance. Ng et al (2007) have shown how daylight availability and solar irradiation can be estimated from weather forecasts and how an intelligent building system can use this to automate its light switching pattern and cooling load needs.

<sup>34</sup> See Erell (2008) for a fuller discussion on the application of urban climate knowledge to the design of cities.

<sup>35</sup> Page outlined the effects of microclimate climate on a very broad range of issues encompassed in the field of urban planning and design. These include land-use patterns for different activities, suitable microclimates for outdoor places (e.g. parks), adverse microclimatic factors likely to affect the detailed design of urban systems (e.g. high local winds), optimisation of building form in relation to external climatic inputs (e.g. solar radiation and wind), control of water runoff; assessment of building running costs in advance of construction and so on (Page, 1967).

<sup>36</sup> Bottema (1999) provides simple methods for assessing site-specific details on wind from observations gathered elsewhere. Elsewhere, the Standards Association of Australia, for example, provides guidelines for wind loads on structures (SAA, 1989). Wind tunnels have been practiced to investigate the urban ventilation, pollution dispersion, as well as temperature fields of the urban environment (Kubota et. al., 2008)

<sup>37</sup> Erell and Williamson (2006) illustrated that such a simple canyon model can predict air temperature in a street under a variety of weather conditions for extended periods, but it is still limited to regular canyon geometries, and does not simulate other meteorological parameters. Guidelines for properly doing CFD is now available (Tominaga et. al. (2008); Franke et. al. (2004)). Bruse and Fleer (1998) have shown the potential for CFD tools in outdoor design situations on readily available computer platforms. The potential for urban topographic databases employed within commonly available remote sensing and GIS software has been shown by Steemers et al (1997, 1998), Ratti and Richens (1999) and Ratti et al (2002). Increasingly, urban features are incorporated into meso-scale models (e.g. Masson, 2000). There is a potential for modeling urban climates across the meso-micro-scale spectrum by using nested models, whereby the outputs of one are used to drive models at smaller scales (e.g. Oguro et. al. (2008), Mochida et. al. (2008a, 2008b) and Kikuchi et. al. (2007).

<sup>38</sup> London (2002, 2007) is one of the few cities that has addressed the need to adapt to the consequences of climate change. One of the interesting developments in this area is the creation of the C40 Cities, a grouping of cities formed on the basis that: *The battle to prevent catastrophic climate change will be won or lost in our cities* (C40). The World Bank (2008) has developed a primer on climate-resilient cities in eastern Asia. Revi (2008) considers the adaptation and mitigation strategies needed for Indian

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cities. As an example of incorporating climate change into planning, the KLIMES project aims to “develop a set of guidelines and to test its implementation in planning concepts with respect to the goal to achieve an improved climate protection of human beings under changed climate conditions and extreme weather events” (KLIMES, 2006).

<sup>39</sup> This assessment comes from Page (1968). However, the work of Eliasson (2000) suggests that many of these obstacles are still in place. In a case study of urban planning in three Swedish cities, Eliasson identified four main reasons why knowledge of urban climate was generally limited in its incorporation into actual planning and design decisions in the case studies. The problems included a “lack of consensus on the role and importance of climate knowledge for the planning process; communication problems between climate experts and urban planners; lack of incentives among investors” for incorporating climate knowledge into developments; and “lack of methods and techniques for collecting and analyzing climate data (p.35).” Given the uncertainty of planners regarding their climate knowledge, their lack of substantive arguments and easily accessible data and techniques in a context of limited budgets and political constraints, it is easy to see how climate can become disregarded in planning. To resolve these problems, Eliasson suggests improved institutional capacity in the social context of planning; the development of tools and courses suitable for training the P&D community; improved awareness of urban climate through increased research and public forums; and improved communication and argumentation skills in the community.

<sup>40</sup> For planners and architects, it is now important to be trained more thoroughly in sustainability and environmental design (de Schiller and Evans, 1996). The Royal Institute of British Architects has mandated that all architectural students be conversant in sustainability when they graduate. The task is for urban climatologists to engage in this enthusiasm by providing course materials and easy to understand concepts and data to facilitate the learning.

<sup>41</sup> See Leggett (2009) for a general discussion and RPA (2009) for a specific example. Generating feasible planning scenarios is often routine planning practice (Calthorpe, 1993; Farr, 2008) however few evaluate their impact on natural ecosystem services or on carbon emissions (Wheaton and MacIver, 1999).

<sup>42</sup> Chau et al. (2005) might provide a useful conceptual model to integrate climatic information with design/drafting tools. (e.g. the thermal properties of building materials could be added as additional “layers” within CAD platforms). Similarly, in the area of land-use planning geographic information systems (GIS) play an important role (Berke et al., 2006, p.91)

<sup>43</sup> The making of the map relies on a careful collection and collation of available meteorological data from the observatory. Long term temperatures, precipitation, wind, cloud and solar radiation data are input into the map and evaluated. For example, the Berlin Digital Environmental Atlas contains eleven layers of information on climate ranging from ‘long term mean air temperature’ to ‘bioclimate day and night’. It is possible to supplement observed data with simulation and experimental data (Schirmer, 1984). Climate function maps can be employed to present such information in a readily interpretable form. As examples, the prognostic model FITNAH was used for the Berlin Atlas, the Urban Canopy Simulation System (UCSS) model was used for the Tokyo Environmental Map; and the use of MM5/CALMET model for Hong Kong. In addition, the results of field surveys (e.g. tracer gas experiments, wind tunnel tests, mobile traverse temperature measurements, etc.) can be incorporated. This approach, which originated in Germany (VDI- 3787-Part 1, 1997; Mayer, 1988; Scherer et al., 1999) but is now used elsewhere (Alcoforado, 2006).

<sup>44</sup> Miller and Small (2003) give an idea of the potential of urban remote sensing at a global scale.

<sup>45</sup> Aron & Patz (2001) discuss IAM in more detail. As an example, the New York Climate & Health Project uses models that can generate alternative scenarios to bring research in the realms of physical and social scientists into the planning realm (Kinney et al., 2006). However, participatory processes for integrated assessments require a commitment to invest additional time for early, persistent, and sustained efforts at discussion of ideas, disciplinary methods and goals, beyond what many researchers may be accustomed to or can support financially (Rosenthal et al., 2007). CBPE is discussed by Corburn (2005). 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 (Rosenthal et al., 2008)

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