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Urban climatology: History, status and prospects

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ABSTRACT

This paper is a description of the historical development, current status and prospects for urban climatology, the field concerned with the study of the urban effect on the atmosphere and the application of this knowledge to the better design and planning of cities. Urban areas have a profound effect on the overlying air as a result of changes to the nature of surface cover (urban form) and emissions of heat, water vapour and materials that attend human activities (urban function). Whilst these changes have been well known and observed for over 100 years, it is only recently that urban climatology has developed a coherent structure for organising this knowledge so that urban observations can be conducted and urban models developed that are transferrable from place to place. In this paper, I give a personal perspective on the history of the field from the vantage point of its current standing. In addition, I suggest some pathways that the field may take in the near future.

1. Introduction

Urban climatology is concerned with the study of the climate effect of urban areas and the application of the knowledge acquired to the better planning and design of cities. It is defined primarily by its focus on the city and incorporates aspects of many different disciplines, including meteorology, climatology, air pollution science, architecture, building engineering, urban design, biometeorology, amongst others. Each of these disciplines has its own focus and has developed distinctive tools and methods (including vocabulary) appropriate to their interests. As a result, much of the knowledge base

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that urban climatology draws upon is fragmented and is still in the process of being assimilated into a comprehensive (and coherent) field of study.

Cities modify the overlying atmosphere significantly in nearly every respect. These modifications are the result of changes the surface cover, fabric and geometry (urban form) and the attendant anthropogenic emissions of waste heat, water vapour and materials (urban function). The fact of the modifications has been well known for nearly two centuries but the nature of the processes responsible have only been explored in detail in the last four decades. In this article, I present an overview of the history of, current status of, and prospects for urban climatology (UC) based on my perspective, which is that of a physical geographer trained in the Anglo-American education system; a concern for human–environment relationships and the detectable effect of cities on local climate explains the historic link of Geography with urban climatology. Of course, there are other relevant perspectives that may emphasise other aspects of the development of UC. Meteorology, in particular, is a closely related and professional field and has many sub-fields that have urban applications; these include the study of the Earth's boundary-layer and of air quality. However, its traditional concern on forecasting weather and weather-related events has meant that (for the most part) its measurement programmes and modelling efforts have excluded city scales. Its focus on meeting user needs (which have changed over time) has also directed its resources toward other topics. Interestingly, over the last decade changing user needs (e.g., growth in urban population and concerns about the effects of climate change) and the dramatic improvement in atmospheric modelling has brought urban-scale issues to the fore (NRC, 2012). This has occurred as meteorological theories and practices have been incorporated by climatologists into UC so that today the terms 'urban climatology' and 'urban meteorology' are largely synonymous. However, the development path that is outlined here has its origin in the geographic tradition.

The fundamental motivation for the study of urban climates was outlined by Kratzer (1956): *Only when we possess sufficient knowledge of the bright and dark sides of city climate are we in a position to use this information and to formulate a technique for city construction based on considerations of climate. Yet something is already accomplished, when we realise that we do not have to accept city climate simply as a fact but can influence it.*

2. Historic development

Although Luke Howard may not have been the first to recognise the influence of urban areas on the climate elements (e.g., Cerveny, 2009), his study of the climate in and around London represents the scientific beginnings of UC. He maintained a meteorological station outside the city of London for 26 years and, with the help of his family, recorded air temperature, pressure, precipitation, etc. on a daily basis. The product of his work was *The Climate of London* published in three volumes in 1833. It is primarily a description and analysis of climate from the vantage of London rather than an examination of the climate in cities. However, he identifies one aspect of the urban heat island effect (UHI) when he compares his air temperature records (the 'rural' temperature, T_R) against those maintained by the Royal Society (the official scientific body) in the centre of London (the 'urban' temperature, T_U),

$$\Delta T_{U-R} = T_U - T_R \tag{1}$$

The evidence from plotting these data showed the urban area had a distinct warming effect on the near-surface atmosphere (Fig. 1). Howard concluded that the *Mean Temperature of the Climate…is strictly about 48.50° Fahr.: but in the denser parts of the metropolis, the heat is raised, by the effect of the population and fires, to 50.50°; and it must be proportionately affected in the suburban parts* (Howard, 1833). He speculated on the processes responsible for this UHI and correctly identified most of the causes we now study: anthropogenic heating; multiple reflection; lack of evaporation and; the retardation of airflow (Mills, 2008).

The development of the field since this auspicious beginning is summarised in Table 1, which separates the period since 1900 into two main phases. Prior to the 1970's the majority of the research was dominated by descriptive climatology and was based on observations of the weather elements, especially air temperature and humidity, at urban scales. In the period since, physical climatology, with its

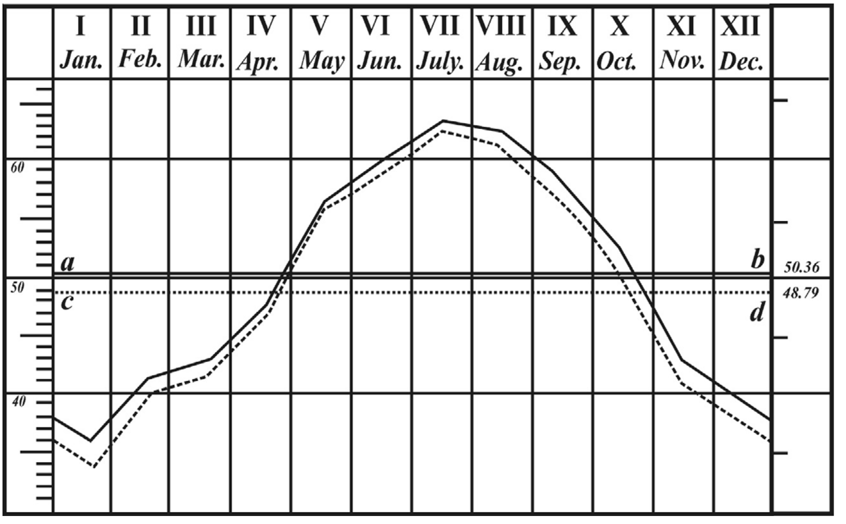

Fig. 1. A comparison between the air temperature observations by Luke Howard (solid) against those made by the Royal Society within London (broken). Source: Howard (1833).

Table 1
Approaches to the study of urban climate effects.

Time period	Approach
1900	Observation and description of urban effects using conventional meteorological equipment (thermometers, hygrometers, etc.)
1960	Move toward measurement of 'process' variables – radiation, sensible and latent heat exchanges. The use of statistical methods to summarise and generalise results
1970	Application of conventional (micro-)meteorological theory to urban climates. Use of energy budget as a framework to explain the urban effect. Observation of process variables: radiation, estimated fluxes. Use of computer modelling techniques. More rigorous definition of urban 'surface', urban scales and observing urban effects
1980	Adoption of an experimental approach: Select common urban forms (streets become canyons). Use of scaled-physical models and direct measurement of fluxes
1990	Relationships between real urban forms and climate effect. Urban field projects examined by research teams. Generalizations based on a range of settlements
2000	Development of realistic urban climate models. Employment of novel techniques for examining urban climate

emphasis on the principles of conservation of energy, mass and momentum, has come to the fore. This is not to say that the work that characterised the earlier period is not still continuing. For example, urban heat island studies probably still represents the majority of urban climate studies currently undertaken.

2.1. Descriptive climatology

During the early 20th century the number of studies on urban climates expanded. Much of our knowledge of the urban effect during this period came from research in central Europe that framed the urban effect within the context of landscape studies and micro-scale climatology. For example, Geiger's first edition of the *Climate near the Ground* appeared in the German language in 1927 and it was not until 1965 that it was published in English (Geiger, 1965). Similarly, Kratzer completed a survey of work done on the *Climates of Cities* (Stadtklima) in 1937 (the English translation, The Climate of Cities was published in 1956). By comparison, there was less work on these topics elsewhere; one of the best known studies on the local effect (including that of towns) in Britain by Balchin and Pye (1947) appears a decade later.

Many of the basic methods for examining local climates were established during this period. For example, to capture the spatial detail of the UHI a dense network of stations was needed. Moreover, the instruments would normally require visual inspection *in situ* at the appropriate time to resolve the temporal character of the phenomenon. For some variables such a wind, observing the urban effect across the city under these conditions required ingenuity. For example, Okita (1960) used the opportunity provided by a winter storm that resulted in rime formation (supercooled droplets that freeze in contact with a surface). In the presence of wind these features were shaped by the airflow and allowed the study of wind patterns in city streets. For air temperature and humidity that respond more conservatively over shorter time periods, the transect method was developed. Sundborg's (1950) study of the UHI around Lund is based on this method and exemplifies the personal investment of time and effort required to gather information at this scale. Chandler (1965) work on the *Climate of London* represents the epitome for this type of work. This treatise is the culmination of an extraordinary amount of data acquisition and analysis and describes in a systematic way the effect of the urban area on each atmospheric property.

Despite the accumulation of evidence on the urban air temperature effect, much of it was specific to particular places and used distinct methods that made generalisations difficult. Oke's (1973) study on the UHI and city size showed that abstraction from the specific to the general was possible if the available evidence was screened to remove extraneous effects, such as variations in topography and weather. The linear relationship between the maximum value of $\Delta T_{U-R(\max)}$ and city size tells us a great deal about our knowledge of cities and the possible controls on the UHI at this juncture. For the available North American data the relationship stated

$$\Delta T_{U-R(\max)} = 2.96 \ \log \ P - 6.41 \tag{2}$$

Population (P) was used as a surrogate variable for actual measures of urban form and function that were needed to offer a physically based empirical relationship. The fact that different coefficients were needed to capture the same relationship for European cities was indicative of a failure to acquire relevant information on cities (e.g., materials, surface cover and geometry). Oke's (1981) study nearly a decade later replaced population with a measure of urban geometry (the ratio of building height (H) to street width (W), or alternatively sky view factor, ψ_{sky}) that characterised the city centre and produced a universal relationship based on available data for cities in different climates,

$$\Delta T_{U-R(\max)} = 7.45 + 3.97 \ln\left(\frac{H}{W}\right) = 15.27 - 13.88\psi_{sky} \tag{3}$$

Yet, although there was a considerable body of empirical data that had been accumulated during this period that supported, complemented and extended the findings of Howard, UC had not undertaken the task of measuring and modelling the causative mechanisms.

A final point on the use of observations to assess the urban effect is worth making. There have been few expositions on the methodology that has underpinned much of the observational evidence for the urban effect. It has been common practice to compare urban observations with those acquired in a nearby 'rural' setting (which represents the pre-urban environment) and assume that the difference is the urban effect. This was the framework used by METROMEX, the first grand urban project (Lowry, 1974). However, Lowry (1977) characterised the problem of identifying this effect amongst all the other climate effects, including climate change, as fundamentally intractable; to measure the urban effect one needed a long-term set of *in situ* measurements that dated from the period prior to urban settlement. Unfortunately, such information is not usually available as stations are moved to offset the 'contamination' of records caused by urbanisation.

2.2. Physical climatology

UC experienced a significant advance in the 1970's with an increase in the numbers of investigators and a changed perspective. For physical geographers in the Anglo-American realm, this resulted in the adoption of a quantitative and systematic approach to research. For example, Sellers' (1965) *Physical Climatology* was a core textbook in the educational training of a new generation of researchers.

The most common expression of the new approach to the study of UC was the surface energy balance,

$$Q^* = Q_H + Q_E + Q_G \tag{4}$$

This described the partitioning of net radiation (Q^*) into the turbulent exchanges of sensible (Q_H) and latent (Q_E) heat with the atmosphere and the conductive exchange of sensible heat (Q_G) with the substrate. Adopting this approach shifted the research focus from describing effects (responses) to seeking their cause (processes) and linked its study to the broader topic of boundary-layer meteorology. This field had already conceptualised the nature of surface–air interactions and developed schemes to estimate surface energy exchanges, albeit for homogeneous surfaces. Terjung (1976), for example, argued that physical geography should move up the research hierarchy and *could investigate the varying responses to different inputs, throughputs, and outputs of energy, mass, momentum, and information to portions of the environmental envelope of concern to mankind. I urge that this be the beacon towards which physical geographers set their sights... Climatologists, increasingly, should adopt the research level of physical process-response systems relevant to the world of man.*

Translating this approach into research was not straight-forward however. There were no generally available measurement systems that could record the turbulent fluxes directly; the typical approach was to record the vertical gradients in wind-speed, temperature and humidity near the ground and estimate the energy exchanges from these. On the other hand, researchers could now access computer resources, which allowed theories to be translated into computer code and simulated. In his well-known paper on the UHI, Myrup (1969) stated that in *surveying the explanations* [for the formation of the urban heat island] *the complete absence of numerical estimates of the order of magnitude of the suggested mechanisms is striking*. To address this issue he converted the individual terms of the energy balance statement into a series of relationships amongst measurable atmospheric variables (e.g., wind-speed, air temperature, etc.) and solved these equations for a single unknown term, the equilibrium 'surface' temperature. The UHI was calculated as the difference in surface temperature between a grass covered surface (rural) and a concrete slab (city). It is difficult at this remove to gauge the effect of this paper, which was considerable; this simple model showed how complex ideas could be translated into solvable form to test hypotheses and put numbers to fluxes. Nevertheless, there remained theoretical obstacles too. One of the most important of these was the definition of the surface itself where exchanges were calculated; Myrup's model avoided this issue by simply treating the layer of air below roof level as isothermal, even though most of the UHI observations were made in this space.

The new approach was seen in Terjung's approach to UC which, stated that: *In contrast to the many inductive-observational studies in urban climatology, few have been based on inferences derived from theory* (Terjung and Louie, 1974). The model developed to address this weakness examined the exchanges along a surface transect that extended from the roof of one building, down its face, across the street and up the side of the opposite building. At regular intervals along this transect the surface energy balance was simulated. This technique, of representing the micro-climatic urban environment using a transect, was adopted by others in later work (e.g., Arnfield, 1982). However, there was still no definitive statement of what constituted the urban surface in common usage by researchers; Oke (1976) finally defined the urban canopy layer (UCL) as the lowest part of the urban boundary layer (UBL), occupying the space between the ground and the mean height of buildings. Observations (and simulations) made within the UCL were driven by micro-scale processes such as the radiation exchange between building surfaces. The atmosphere above the UCL responded to exchanges at an interface at the top of the UCL, which included both the rooftop surfaces and the open canopy. This simple distinction clarified much of the work to this point and allowed the adoption of simple configurations (such as the urban canyon to represent the city street) to represent the complex and heterogeneous UCL.

One of the most important pieces of work from this period is that by Nunez and Oke (1977) on observations within the UCL. In the introduction they state that although *progress has been made, there is still no comprehensive study available concerning the surface energy balance of an urban area. The present study was designed to investigate the energy input, partitioning and output of a characteristic* *urban canopy layer structure – an urban canyon*. The results of this work provided valuable data for subsequent modelling exercises and showed the significant differences in the energy balance that occurs at surfaces within the canyon, including the contribution of multiple reflections. Remarkably, the aggregated results at the canyon top interface showed that the variations within the canyon compensated for each other; the net radiation showed a smooth diurnal curve not much different from those found over rural environments and the critical urban effect was to partition this energy mainly into Q_H and Q_G, as there was little evaporation. It is worth pointing out that the urban canyon as a unit of study was already firmly established in the air pollution community as a means of evaluating pedestrian exposure to vehicular pollutants (e.g., Johnson et al., 1973).

Much of the foundations for our current understanding of the urban climate effect was established during the 1980's and 1990's as the research frontier moved away from a description of the urban climate in a given city toward quasi-experiments that could be replicated. The urban canyon (with its geometrical descriptors of height (H) and width (W)) provided a useful context for bringing together research in a number of different areas and for structuring research projects; for example the importance of the sky view factor (ψ_{sky}) as a regulator of night-time surface cooling and a key indicator of UHI potential was an important outcome of this work. Oke (1984) could draw on this research to provide guidance for good urban design practice that was based on the evidence, rather than speculation. Nevertheless, much of the work during the 1980's originated from remarkably few teams of researchers, scattered globally with few opportunities for interaction. An indication of the status of the field at the time can be found in the proceedings of the second international conference dedicated to UC held in Mexico City, and focussed on the urban climates of the Tropics (Oke, 1986). Many of the papers were descriptive in nature and there were few that employed the energy balance approach.

During the 1990's the intensity of UC research increased substantially; the number of researchers increased and there was greater attention paid to the make-up of the urban landscape and the integration of UC into the corpus of boundary-layer meteorology. Much of the observational work shifted from the UCL into the atmosphere above roof level, where the micro-scale effects of the underlying urban surface might be assumed to have been integrated, effectively producing a distinct neighbourhood, or local-scale, signal. These projects attempted to close the energy budget of a representative volume that extended from the substrate, through the UCL to a level above the buildings:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \tag{5}$$

The new terms here are the anthropogenic heat flux (Q_F) the storage of heat (ΔQ_S) and the advection of energy through the sides of the volume (ΔQ_A). Observing these terms in the complex urban setting was not a simple task; instruments needed to be located within a suitable fetch of a reasonably homogenous urban area (so that ΔQ_A could be assumed negligible) and positioned at a height where the turbulent fluxes are reasonably constant. Guidelines for dealing with the challenge of making urban observations have become a core part of UC knowledge (Oke, 2006a).

Numerical modelling of the urban environment has proceeded apace; as computer power has improved local-scale and micro-scale models of increasing sophistication and detail were developed. The simple descriptions of the urban surface (e.g., concrete slabs) used in earlier models were replaced by more realistic descriptions of land cover (e.g., vegetated and impermeable surfaces), material properties (e.g., asphalt and concrete), geometry (e.g., street dimensions and building plan area) and functions (e.g., traffic and heating) that define different types of urban neighbourhoods. These improvements at the urban-scale have been matched by advances in modelling the hierarchy of climate scales from global to regional to meso-scale which are now capable of incorporating the presence of cities to varying degrees (e.g., Best, 2006; Masson, 2000; McCarthy et al., 2010). Advances in computing power has also allowed computational fluid dynamic (CFD) models that have traditionally been used to simulate flows around individual buildings to be applied to entire neighbourhoods (e.g., Hanna et al., 2006). One of the changes that emerged during this period has been the co-operation amongst research teams that has allowed for more comprehensive research projects that incorporated different observation and modelling systems (e.g., Rotach et al., 2005).

Some of the advances in this period could be attributed to demographic change; students trained in UC during the 1980's were now themselves teachers/researchers with their own students. The transformation of UC during this period is described by Arnfield (2003).

3. Current status

Much of our understanding of the urban boundary layer is encapsulated in Fig. 2. It distinguishes between the three scales of effect (micro-, local- and meso-scales) and suggests that the processes that dominate in each differ. It shows the vertical layering of the urban atmosphere: the surface layer, which is comprised of roughness (RSL) and inertial (ISL) sub-layers (the urban canopy layer is immersed in the former); the mixed layer above is where the urban 'surface' exchanges are blended into the wider atmosphere and transported downwind. Critically, the ISL is the level at which the atmosphere has adjusted to the underlying urban landscape such that observations of energy, mass and momentum fluxes made at this height are representative of the amalgam of microclimates (created by gardens, roofs, walls, etc.) that comprise a local-scale 'neighbourhood'. On the other hand, instruments positioned within the RSL are exposed to the individual microclimatic effects so that the sources of measured fluxes are difficult to disentangle. So, if a measurement site is selected over a reasonably homogeneous urban landscape and within its fetch, then one can link observations to the character of the underlying surface (for example, the proportion of the surface that is occupied by buildings, impervious surfaces, vegetation, etc.) This understanding allows the application of traditional micro-meteorological theory to urban settings, which were hitherto regarded as too complex owing to their great spatial heterogeneity. A growing number of urban flux measurement sites are located in city environments based on this understanding are providing greater understanding of the linkages between background climates and the surface-air exchanges associated with different urban neighbourhood types (Christen et al., 2009).

Oke (2006b) described the evolution of UC using eight modes of investigation or practice: Conceptualisation; Theorisation; Field observation; Modelling; Model evaluation; Application in urban design and planning; Impact assessment (post-implementation) and; Policy development and modification. He opined that whereas the first four modes had progressed significantly in recent

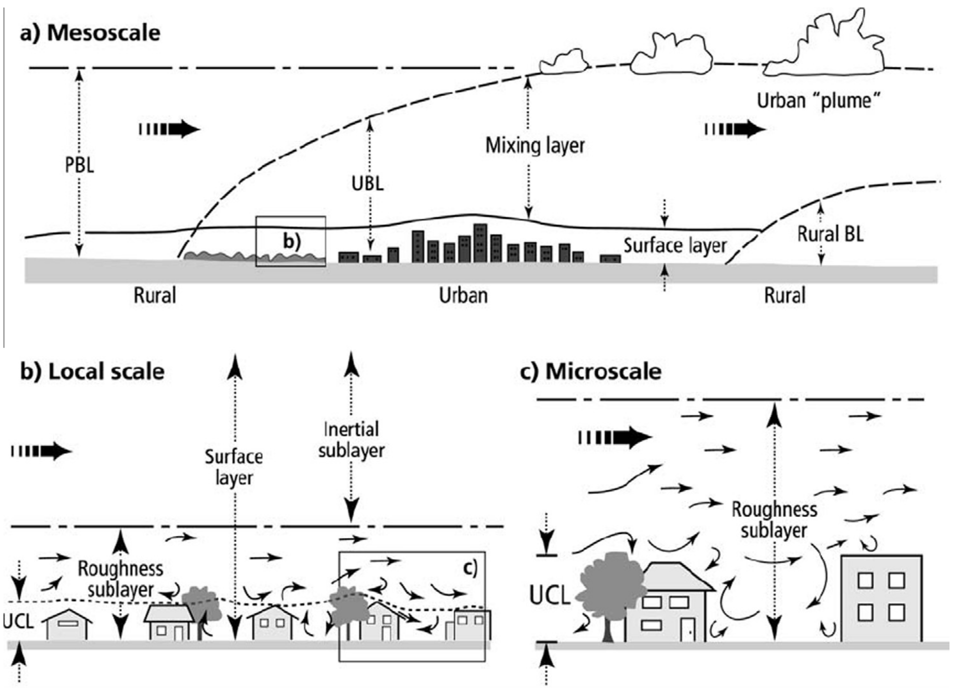

Fig. 2. The scales of the urban climate effect. Source: Oke (2006a).

decades, the evaluation of urban models and the transfer of knowledge into planning practice remained undeveloped. The process of evaluating models has just begun yet this stage is needed if they are to be used to simulate the effects of climate-based urban policies, such as albedo modification or rooftop greening.

Transferring this scientific knowledge into practice on a widespread basis remains a major challenge (Hebbert and MacKillop, 2013). Part of the problem is due simply to the perceived importance of such information in making planning decisions; when placed alongside other planning issues, concerns for the urban heat island (as an example) have been seen as of marginal interest. However, the failure of UC in general to structure its scientific knowledge in an accessible and applicable manner has also been part of the problem. This is not universally true however; the example of the urban climatologist office in Stuttgart is a case in point (Reuter, 2011). Established in the late 1930's to manage the air resource over the heavily industrialised city, the office has maintained a presence to this day that has acted as an exemplar for other places. Moreover, German scholars have maintained a perspective on the connection between settlements and their landscape context and on the biometeorological consequences of urbanisation (e.g., Mayer and Höppe, 1987). As a result, the understanding of links between land cover, topography and urbanisation has resulted in a versatile and flexible approach to climate mapping at scales of urban planning that has proved adaptable to many different climates and planning circumstances (Ren et al., 2011).

4. Future prospects

Oke et al. (2006) characterised the recent history of UC in terms of 'reducing solitudes', by which he meant the bringing together of what had been a diverse and scattered community often working in isolation. Professional associations have played a large part in this: the American Meteorological Society has a Board of the Urban Environment, which has been involved with symposia on urban-related themes (e.g., boundary layer meteorology and air pollution) since 1982; the Japanese–German Meeting on Urban Climatology has held at regular intervals since 1994. By the turn of the millennium it was apparent that there was sufficient interest and expertise to establish an organisation dedicated to UC; The International Association for Urban Climates (IAUC) was formed in 2000 and has assumed responsibility for organising a series of international conferences dedicated to the topic of urban climates. These events have provided opportunities to assess the status of UC in some key areas and identify lacunae (see for example, Mills et al., 2014 in this journal).

There remain many gaps in our scientific knowledge; for example, the urban effect on precipitation has been researched for nearly forty years but progress has been very slow and the results are still not definitive. This is especially ironic as it was the search for this effect that was the impetus for the Metromex experiment; however it may be a problem that is ideally suited to numerical modelling (Shepherd, 2005). Also, there have been very few observations made within the ML of the urban boundary layer, yet this information is needed to understand the impact of cities beyond their boundaries. However, the outstanding gap in my view is the paucity of information on the rapidly growing cities of the less prosperous regions, many of which are located in the tropics. Meeting this challenge will require a considerable international collaborative effort. Ideally, such a programme would put in place both an observational and educational infrastructure to conduct some basic research. The cost of meteorological equipment remains an impediment to acquiring information in the places that it is most needed. It may be that rapid advances in sensor technologies linked to telecommunication devices can provide some of the more basic data but acquiring flux information will need a concerted effort. On the other hand, data on the nature of the urban landscape in such places could be very valuable; for example, much of the UC knowledge on surface–air exchanges that is encoded in numerical models could be transferred to new urban settings if we had suitable data on those places. Even a simple but consistent physically-based description of urban landscapes, using the scheme of Stewart and Oke (2012) perhaps, could be of great value. This is one area where the potential of remote sensing for acquiring information on cities globally is great (Miller and Small, 2003).

Overcoming the barriers to knowledge–policy transfer will require both accessible knowledge and appropriate tools and, I would venture a supportive political context. Recent publications (e.g., Erell et al., 2011; Grimmond et al., 2010; Mills et al., 2010; NRC, 2012) have discussed the current state of UC knowledge and its value for urban planning and design. Moreover, there are modelling tools available that can run on inexpensive computers that may be used to explore urban micro-climatic variations and to test the climatic implications of different design options. As examples: SOLWEIG (Lindberg, 2007) employs databases on urban morphology to calculate access to sunshine and sky-view factors, two of the most relevant variables in assessing urban micro-climates and; ENVI-MET (Bruse and Heribert, 1998) is a remarkably versatile local scale model that can simulate three dimensional flow fields and surface–air exchanges. However, achieving Kratzer's vision of a climate-informed urban planning may require the political impetus created by some form of crisis – at an urban scale, it is likely that poor air quality in many Chinese cities will eventually be simply unacceptable and prompt action, just as it did for cities elsewhere. At a global scale, concerns about climate change may provide this impetus. In the past decade, the role of cities as sources of green-house gas emissions and their vulnerability to climate changes has generated a great deal of research on urban-scale adaptation and mitigation and on urban sustainability (e.g., Rosenzweig, 2011; Stone, 2012). Unfortunately, much of this research makes little or no reference to a large body of existing UC research. Naturally, it will be important that policies designed to achieve outcomes with respect to global scale issues are consistent with those designed to improve conditions at the urban scale, where the decisions on transport, on heating/cooling, etc. that regulate emissions are made. Currently climate research in cities and that on cities and global climate change are proceeding along parallel paths and there needs to be far greater interaction.

5. Conclusions

Advances in our understanding of the urban climate effect have come about very quickly and comparatively recently. Establishing the scientific foundation of UC only really began after the 1970's; prior to this most work based on comparing the measured atmospheric properties in urban areas with those in surrounding rural areas. For some places, such as London, the work produced outstanding comprehensive climatologies of a city but for most places the information gathered was piecemeal and did not allow for either an examination of causes for the effect or comparative analysis between cites. For example, studies of the near-surface urban heat island were prolific but made little substantial progress on Howard's work completed over a 100 years earlier. The adoption of the energy balance/budget approach and all that it implied was critical to the development of the field as it lent itself to numerical modelling and demanded a different type of observation. Moreover, applying it to the three dimensional city with its distinct urban canopy layer forced a consideration of the character of the urban surface to which instruments were exposed (or to which model results referred). The slow advance in our understanding since its adoption can be attributed partly to the fewness of those working in the field; most research was done in relative isolation at few places. Major advances in the last two decades have resulted from: increased interest in the places that most live (from many other disciplines, including meteorologists); technological advances in instrumentation and computing power and; the development of institutional frameworks, which have helped develop and foster a community with shared interests in city climates.

Scientific progress in UC seems assured but two major challenges remain: acquiring information on the climates of cities in less prosperous regions, which are growing rapidly and many of which have Tropical climates in which there have been few studies and; transferring urban climate knowledge into routine planning/design practice.

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