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Towards better scientific communication in urban climate

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With 2 Figures

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Summary

Better communication both within the field of urban climate and between urban climate and cognate fields is necessary to both bind the subject internally and to more effectively move it into interdisciplinary interaction. A brief statement of the wide diversity of the field and its several modes of study and application leads to the view that it would be beneficial to consider adopting aids to increase dialogue. This includes standardization of symbols, terminology and indices, classification of phenomena, a protocol to generalize site description, adoption of principles of experimental design and the use of dimensional analysis and normalization to aid the transferability of results.

The focus of this paper is how to facilitate scientific interaction between participants within the field of urban climate, including both those who study its mechanisms and effects and those who apply such knowledge to the improvement of human settlements. As a by-product it may also assist communication between urban climatologists and workers in cognate fields as well as those we wish to entrain in the fields of policy development and environmental management. Section 1 explains the nature of the urban climate field and its practitioners, especially the diversity of scholarly disciplines, the range of topics studied and the motivations for doing so. Section 2 describes the sequence of investigative modes associated with achieving coherent understanding and intelligent application of urban climate. Section 3 attempts to outline some essential elements which might promote discourse between these modes such as the use of a common set of symbols and terminology and ways of expressing results so as to standardize variables and thereby assist comparison and transferability of results.

1. The urban climate field

The study of urban climates is relatively young (for a short history see Kratzer, 1937; Yoshino, 1975; Landsberg, 1981; Arnfield, 2003). The first study was undertaken less than two hundred years ago and it has been a recognized subfield for probably less than eighty years. The field is concerned with interactions between the atmosphere and human settlements. It includes the impact of the atmosphere upon the people, infrastructure and actvities in villages, towns and cities as well as the effects of those places upon the atmosphere. Here, for convenience, the term *urban climate* is used as an omnibus term to include the study of meteorological processes, atmospheric phenomena and the longer term amalgam expression of these as climates in areas that have undergone urban development. It is simply a convenient contraction of the phrase urban meteorology and climatology.

The range of disciplines that different urban climatologists call their ‘home’ is remarkably large. It includes meteorology, climatology, physics, geophysics, geography, biology, ecology, environmental science, hydrology, engineering (civil, mechanical and chemical), building and landscape architecture, building science, town planning, social science and medicine. Hence the community spans most of the natural, social and applied sciences.

Individual scientists come to urban climate with their own curiosities about the fundamental physics, chemistry or biology of urban atmospheres or the wish to apply existing knowledge to questions of building better houses, neighbourhoods and cities that are efficient, safe, healthy and frugal with resources such as water and energy. Some are professional practitioners charged with forecasting severe weather, floods, heat waves or air quality, or the management and engineering issues arising from potentially harmful winds or stormwater or the design of appropriate buildings and other structures for urban living. Yet others are teachers who seek to relate the nature of urban environments to their students for many purposes.

The field also deals with a wide range of temporal and spatial scales. Time scales extend from parts of a second as in small scale turbulent fluctuations, to centuries, as in the long-term climatic changes over a city's life history. Space scales range from millimetres in fine turbulent eddies, to thousands of kilometres in the extent of the pollutant plume from a megalopolitan region. Some example urban climate phenomena are sketched on a standard Time:Space grid in Fig. 1. The main focus of work is on micro-, local and meso scales encompassing interactions between weather and climate and buildings up to whole city regions, but larger influences such as the synoptic and macroscale are also involved. Further, every city is unique with respect to its geographical location and setting, cultural history and architectural expression. This diversity, that makes travel so interesting, makes urban climate comparison especially challenging.

As if these dimensions are not enough diversity, the field is also intimately connected with the application of urban climate knowledge in building and urban design, construction and planning, the development of policy and urban environmental management geared to the goal of creating more sustainable settlements. These aspects require a meaningful interface between the natural and engineering sciences and the social sciences, humanities and fine arts and professions such as law, medicine, forestry ... the list goes on.

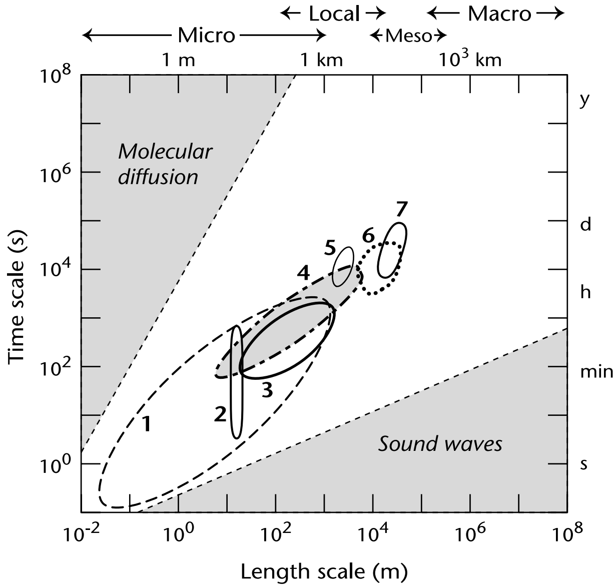


Fig. 1. Time and space scales involved in urban climate phenomena. Examples of some motion phenomena: 1 – mechanical eddies shed by obstacles; 2 – cross-canyon vortex; 3 – individual building wake; 4 – chimney stack plume; 5 – urban park breeze circulation; 6 – urban-rural breeze system; 7 – uplift in city 'plume'. Similar sets of envelopes can be constructed to describe thermal, humidity and other atmospheric phenomena. Long-term urban climate effects identifiable in historical records extend into macro time scales. It is not clear whether these 'phenomena' have lifetimes in the same sense as those included here

Another way to view the scope of the subject is to view it in terms of the modes of investigation or practice employed by those involved in urban climate:

- Conceptualization
- Theorization
- Field observation
- Modelling (statistical, scale and numerical)
- Validation of models
- Application in urban design and planning
- Impact assessment (post-implementation)
- Policy development and modification

Ones initial take on this list suggests it is organized in a linear fashion, like a chain, even a chronology of the field. In general, the first four modes are well represented in modern urban climate work (see Grimmond, 2006; Masson, 2006; Kanda, 2006 in this volume). Validation of models although of prime importance, is less well developed (see Masson, 2006). Without it models are of dubious merit and can not be used with confidence to simulate the outcome of development scenarios. Many lament the relatively slight use of urban climate knowledge and tools (like models) by the design and planning professions, i.e. application. But, just as more validation of models is needed, there is need to assess carefully the outcome of applied urban climate measures in design and planning (Mills, 2006) and forecasting (Best, 2006). It is difficult to find examples to illustrate the positive or negative impact (in climatic, economic or other terms) of designs inspired or informed by urban climate input. Ideally such assessments should form the basis of policy directives and management plans to move towards more sustainable practices in the ongoing development and operation of settlements.

2. Communication in urban climate

A fully healthy field should, however, not act as a chain but foster interaction between as many parts of the field as possible. There has to be, crosstalk between the eight investigative modes for the field to function well. For example, modelling and observing groups need to work together to facilitate validation, this is a two-way street: not only are measurements gathered and shared but also the experimental design of the field operations are geared to the information needed by the models – the two are not always compatible. By the same token the modelling and application groups need to ensure that models deal with useful scales and variables, that input requirements are not too onerous and that models can be implemented by non-specialist users. All three groups must interact effectively if impact assessment is to be successful and they in turn have to work with socio-economic teams to construct cost-benefit analyses and make policy recommendations of relevance to decision-makers.

If this multi-player system is to be effective there must be good communication across disciplinary boundaries. Indeed even within apparently relatively close fields there are impediments to exchange, 'solitudes' tend to develop – groups who share a philosophy, background training, technique, literature or jargon and don't talk much with those nearby. With the increasing tendency to specialize this means research groups and their students can find a critical mass of like devotees who 'validate' their worth largely within that small community. Examples might be measurement specialists who use an expensive instrument-based technique that makes it rare, or numerical modellers who use very complex codes requiring unusually large computer capacity or speed, or theoreticians for whom the only meaningful language is highly mathematical. Each may be making significant advances in their self-defined realm but the potential of realizing new insight or catalytic enhancement of the work of cognate colleagues and the larger subject field is lost.

Twenty years ago I wrote about the problem of lack of communication (Oke, 1984) especially in relation to the lack of applied urban climate. I argued the need for the science part of urban climate to focus on achieving predictive power. That in turn required greater methodological rigour, attention to seeking general relations rather than case studies and greater emphasis on process studies and numerical modelling. For the applied part of the subject, in the absence of predictive power at that time, I suggested the need to draw up common procedures to process data, assess sites, and make reasoned, uncomplicated solutions to the design and planning needs of communities in different climate zones. In particular I noted the ill preparedness of the field to respond to the fast-growing needs of cities in the tropical world. An assessment at the start of the twenty-first century, would attest that the science-oriented part has made significant progress in advancing predictive power, general relations are emerging, our knowledge of processes is much better and modelling has grown remarkably (e.g. Arnfield, 2003). Progress in the area of applications and advancing the tropical imperative is less impressive, but still good (Klysik et al., 2004; Jauregui, 2000). What is needed now, while the science continues, is increased attention to the last four modes of investigation listed above (validation, application, assessment and policy).

Given the diversity of urban climate itself, its community and its connections to urban environments and their management it seems a good idea to maintain as common a language as possible. This should aid the ease, and improve the accuracy, of discourse. In broad terms what

I mean is a reasonably common set of symbols, terms, concepts, and ways of designing 'experiments', and standardizing the presentation of results so that comparison and transferability between members of the community and their user groups is eased, regardless of their field or geographical locale.

3. Aids to improve communication and transferability

Until the recent advent of the International Association for Urban Climate (IAUC) the field of urban climate, with its many dimensions of diversity, has had no central organizing body or journal, and it has grown organically from many perspectives and traditions. I argue that it is now time to consider the merits of a degree of standardization. The following section outlines some of the ways this might be accomplished. It may well be difficult to achieve unanimity on some of these topics, but if the outcome is improved communication across the fields, disciplines and cultural breadth of urban climate it is worth considering. In itself the exercise of seeking agreement is likely to yield a better awareness of differences that can lead to misunderstanding or lack of appreciation. The examples are only a basis for consideration and argument. I come from one discipline and perspective and cultural viewpoint hence it is unlikely my views are universally held. Therefore these examples are not forwarded for adoption, but to stimulate discussion and better suggestions that can attract wide acceptance.

3.1 Standardization

3.1.1 Symbols, abbreviations

There is no agreed list of symbols in the atmospheric sciences. It seems likely that this will not change given the wide range of fields and variables and modes of analysis. It might, however, be considered whether it is useful for our fields to settle on a recommended set for some common variables in urban climate.

3.1.2 Scales, layers and surfaces

Recognition of scale differences in cities is a central key to the design of meaningful field, laboratory or computer studies and also to create valid conceptualizations, models or interpretations of data. Table 1 and Fig. 1 provide a basis for discussion of the scales and layers involved. It would also be helpful if there is an agreed set of definitions of the 'surface' that is being referred to in observational or modelling work (see Voogt and Oke, 1997). If an observational study makes it clear from the outset that the focus is upon say, the canopy layer, and the measurement scheme

Table 1. Layers, dimensions and scales in urban climate

Name of layer	Typical dimensions	Scaling parameters[a]	Scale
UCL			
Canopy or building layer	$\sim 10^1$ m	z_H, D, L	Micro
Roughness sublayer	$\sim 10^1$ m	z_H, D, L	Micro
UBL			
Surface (inertial)	$\sim 10^2$ m	z, L, u_*, θ_*	Local
Outer (mixed)	$\sim 10^3$ m	z_i, L, W_*, T_*	Meso
UCL units	**Built features**	**Typical horizontal length scales**	**Climate scale (Orlanski)**
1. Building	Building	10 m × 10 m	Micro γ
2. Canyon	Street, canyon	30 m × 40 m	Micro β
3. Block	Block, factory	0.5 km × 0.5 km	Micro α
4. Land-use class or UTZ or UCZ[b]	City centre, residential, or industrial zone	5 km × 5 km	Meso γ (Local)
5. City	Urban area	25 km × 25 km	Meso β
6. Urban region	City plus its environs	100 km × 100 km	Meso-α

[a] Urban Terrain Zones (Ellefsen, 1990/91) or Urban Climate Zones (Oke, 2004)
[b] L – Obukhov length; u_*, θ_* – friction velocity and friction temperature; W_*, T_* – convective velocity and temperature scales; for definition of z_H, D, z, z_i – see Section 3.2

is designed to sample microscale processes and phenomena at time and space scales that are appropriate to that objective (Table 1), the results can be understood and utilized by others. It is essential that measurements, models and interpretations drawn from any of the scales are not jumbled together with others, e.g. microscale observations taken in the UCL should not be used to validate a mesoscale model designed to simulate UBL properties.

3.1.3 Site description (metadata of setting and properties)

It is important when appraising the results of a field study in urban climate to be able to fully appreciate the setting and site character. Maps and photographs are very helpful but simple classification templates honed to the interests and needs of urban climate can be improved to convey the nature and constraints of a site. If a *common* classification is used, workers with no experience of the site can gain an appreciation of its properties and, most importantly, they have an objective basis on which to include or exclude results or data from that site in their work.

The spectrum of site characteristics is of course huge, but if a set of classes and descriptors could be agreed upon it is possible to create a good representation of any site. Aspects of the wonderful diversity of place and urban form of different towns and cities that characterize different towns and cities, and of interest in urban climate, can be distilled as a function of scale:

- at the largest scale one needs to know the fundamental geographic coordinates of the city (latitude, longitude), its location relative to land and sea and major physiographic divisions (mountains, plateau, basin, delta, etc.) and its climatic region.
- at intermediate scales one needs to know the orographic setting of the city itself and the specific site as well as its relative location within the urban area (urban fringe, urban core). Wanner and Filliger (1989) provide a nice start to such a classification (Fig. 2). With the addition of a few other categories, such as level plain and coast, and no doubt others that the international community will identify as relevant to their cases, such a system could work. It has the merits of transparency and ease of application.
- at the local and microscales Ellefsen 1990/91 provides a good approach to the built components with his Urban Terrain Zone types. He initially differentiates according to building contiguity (attached (row), detached but close-set, detached and open-set) and subdivides into seventeen sub-types by function, location in the city, and the height, construction type and age of buildings. Application of the scheme needs only aerial photography, which is generally available, and he has applied it in several cities around the world. Ellefsen's scheme is a distinct improvement over others that tend to emphasize urban function, such as land-use classes that only indirectly relate to properties of significance to climate modification. Ellefsen's scheme focuses on the description of urban structure which is relevant for roughness, airflow, radiation access and screening. It is less useful, however, when built features are scarce and there are large areas of vegetation, bare ground and water.

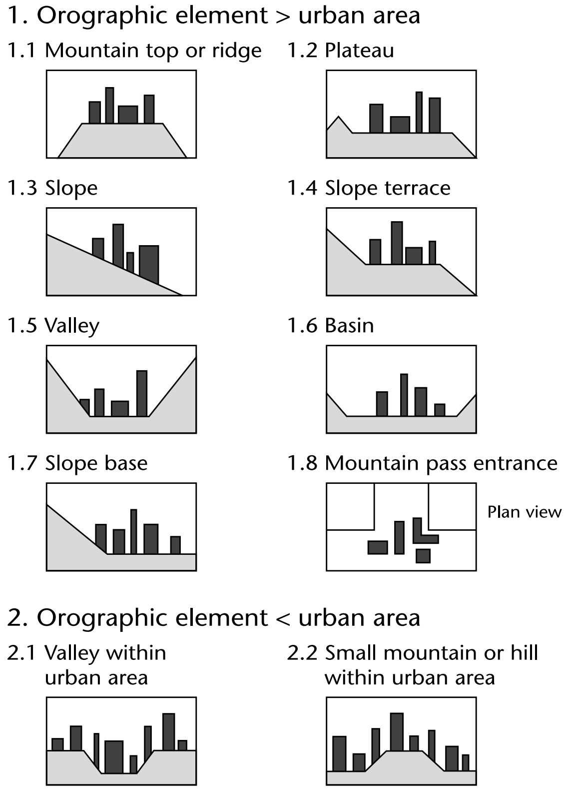


Fig. 2. An orographic classification of urban sites (Wanner and Filliger, 1989)

In a recent WMO Guide I argue (Oke, 2004) that four such controls on urban climate are significant:

- *urban structure* (dimensions of the buildings and the spaces between them, street widths and street spacing),
- *urban cover* (fractions of built-up, paved, vegetated, bare soil, water),
- *urban fabric* (construction and natural materials), and
- *urban metabolism* (heat, water and pollutants due to human activity).

It is not sensible to incorporate individual measures of these controls into a scheme to describe urban climate sites, however, we are helped by their tendency to cluster to form characteristic urban classes. For example, the central areas of many cities have relatively tall buildings that are densely packed together so the ground is largely covered with buildings or paved surfaces made of durable materials such as stone, concrete, brick and asphalt and where heat releases from furnaces, air conditioners, chimneys and vehicles are large. Near the other end of the spectrum there are districts with low density housing of one- or two-storey buildings of relatively light construction and considerable garden or vegetated areas with low heat releases but perhaps irrigation inputs.

The simple scheme of Urban Climate Zones (UCZ) in Table 2 (Oke, 2004) recognizes this clustering. It incorporates groups of Ellefsen's zones, plus a simple measure of the structure, z_H/W, (aspect ratio – average height of the roughness elements (buildings, trees) divided by the average street width) that has been shown to be closely related to flow, solar shading and the nocturnal heat island. Also included is a measure of the surface cover (% Built) that is related to the degree of surface permeability (it could have been the inverse measure, % Open and Vegetated, it is just that the numerical value increases with urban development in the % Built version). The idea is that classes are ranked approximately in order of their ability to modify the wind, thermal and moisture climate. The scheme is largely untested and undoubtedly will require modification when applied to a wide spectrum of real towns and cities, especially in the less developed world.

In the same Guide I suggest adoption of a format to report the local and microscale character of urban sites, similar to that suggested by Aguilar et al. (2003) for rural sites. The format of these site metadata is another topic for discussion by the urban climate community, including adoption of standard descriptors of the four controls mentioned above.

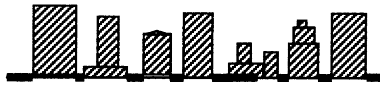
If we could agree on terms in general some of the inter-cultural difficulties of communication might be lessened. My experience is that some international colleagues have difficulty transposing some North American ways of describing city features into their own context. For example, some colleagues do not have an equivalent for the word 'suburb'. Quite simply their cities do not exhibit that kind of urban structural division, others recognize 'quarters' as appropriate urban districts. For others the concept of a city 'block' (Table 1) (the grouping of buildings defined by the street network) is of little use. The nature of the surroundings of some cities means the notion of 'rural' or 'countryside' is either of little relevance (the environs may be just *less* developed not wholly natural landscape or agricultural), or meaningless (the surroundings may be water or desert). Some of these difficulties may be alleviated by a standard set of descriptors, others are appropriately left in their cultural context. A workshop or committee report on these simple issues of site and city description could help.

3.1.4 Reference stations (siting, height of measurement)

Whilst it seems unlikely there is such a thing as a true reference station for urban climate studies, there might be a ways to identify sites and stations that are representative of a particular urban district. The UCZ in Table 2 are not claimed to describe sites with great precision, but they might classify parts of an urban area that have a roughly similar propensity to modify the local climate. The scheme was recently applied to the thermal and moisture fields in Toulouse with some success (Pigeon et al., 2004).

Even a reference site for 'rural' conditions needs careful thought. Such a concept has little meaning in an absolute sense, given the diversity of 'rural' conditions (Section 3.1.3) but it may be relevant as a relative basis for comparison

Table 2. Simplified classification of distinct urban forms arranged in approximate decreasing order of their ability to impact local wind, temperature and humidity climate (Oke, 2004)

Urban Climate Zone, UCZ[1]	Image	Roughness class[2]	Aspect ratio[3]	% Built (impermeable)[4]
1. Intensely developed urban with detached close-set high-rise buildings with cladding, e.g. downtown towers		8	>2	>90
2. Intensely developed high density urban with 2–5 storey, attached or very close-set buildings often of brick or stone, e.g. old city core		7	1.2–2.5	>85
3. Highly developed, medium density urban with row or detached but close-set houses, stores & apartments e.g. urban housing		7	0.5–1.5	70
4. Highly developed, low density urban with large low buildings & paved parking, e.g. shopping mall, warehouses		5	0.05–0.2	75–95
5. Medium development, low density suburban with 1 or 2 storey houses, e.g. suburban housing		6	0.2–0.5, up to >1 with tall trees	35–65
6. Mixed use with large buildings in open landscape, e.g. institutions such as hospital, university, airport		5	0.1–0.5, depends on trees	<40
7. Semi-rural development with scattered houses in natural or agricultural area, e.g. farms, estates		4	>0.05, depends on trees	<10

Key to image symbols: ▨ buildings; ♀ vegetation; ▬ impervious ground; ··· pervious ground

[1] A simplified set of classes that includes aspects of the scheme of Ellefsen (1990/91) plus physical measures relating to wind, thermal and moisture controls (columns at right)

[2] Effective terrain roughness according to the Davenport classification (Davenport et al., 2000)

[3] Aspect ratio $= z_H/W$ – related to flow regime types and thermal controls (solar shading and longwave screening). Tall trees increase this measure significantly

[4] Av. fraction of ground covered by built features (buildings, roads, paved and other impervious areas) the rest of the area is occupied by pervious cover. Permeability affects the ability to store moisture and hence the moisture status of the ground

for a given city. Even that requires consideration as to whether the aim of the rural site is to replicate pre-urban conditions or typical modern day conditions. Given the changes wrought on the landscape by agricultural and forest activity any notion that the pre-urban natural state can be represented by modern observations is usually doomed and in any case the natural variability of the topography, soils and vegetation around a city often renders the exercise almost impossible.

The notion of a reference height for measurements to standardize observations is, however, well established in World Meteorological Organization (WMO) practice. For example, air temperature and humidity are usually obtained at 1.5 to 2 m above ground level and wind speed and direction at 10 m and instruments should be distant from anomalous obstacles (trees, buildings). This practice needs adjustment for urban observations. For purely practical reasons, such as protection from vandalism or to avoid being struck by vehicles, it may make more sense to mount the temperature and humidity sensors at a slightly greater height than is considered 'standard' in the urban canopy. Within the canopy layer this may not create large error because vertical gradients are often slight.

Another, but quite different variance from standard practice may be needed for wind measurements. The normal reference height is sometimes too low because of interference to the flow at that height caused by tall roughness elements (buildings or trees). In addition to the difficulty of the height of the elements being too close to, or even above, the 10 m level, WMO practice states the mast must not be closer to them than 10 obstacle heights. Even with only 5 m high obstacles the required size of an open area becomes hard to find in many city districts. In low density areas it may be possible to find sites with elements less than 6 m tall where the open country WMO rules will apply, but at denser sites the guideline becomes 10 m or 1.5 times the mean height of the roughness elements, whichever is the greater (Oke, 2004). Instead of a set reference height the recommendation is to take measurements at a height where they are free of individual obstacle effects and later adjust them by using wind profile relations to a common height (say 30 or 50 m) if they are to be used in spatial comparisons. As long as the principle is applied consistently and metadata accompanies the records, other workers can have confidence in the data and adjust them for their own purposes.

3.1.5 Experimental 'control', estimation of urban effects

Lowry's framework to estimate urban effects on climate variables remains virtually the only methodological statement in urban climate (Lowry, 1977). Every study to assess the degree of climatic modification produced by urban development should consider the degree to which their experimental design meets Lowry's tests. None will be perfect, but a genuine attempt has to be made to either conform or to assess the errors associated with the lack of conformity. It is not acceptable simply to select two climate stations, one inside and one outside the urban area, and take the difference between their records of climate variables as a measure of the urban effect, without considering the implications of Lowry's framework. Similarly using time trends of data to estimate urban effects with no evidence as to whether regional or global trends co-exist, or at least devising means to nullify their effects, should not be accepted as part of urban climate discussion. The argument that such work is worthy, because no other stations are available, even if that is true, should not prevail. Acceptance of such work serves to confuse not enlighten.

The field could greatly benefit from a careful treatise on ways to establish a degree of experimental control in urban climate work. As Lowry noted, genuine experimentation is possible using validated models. For example, it is then possible to set up an experiment that simulates urban effects such as when the city is present or absent. Synoptic weather controls can also be altered at will. Such control is not possible in field studies (therefore they should not be called experiments) but advance thought about experimental design lies at the heart of all successful studies. So it would be valuable to have a manual for workers in urban climate to aid them to design observational networks that are sensitive to appropriate temporal and spatial scales, or to design and conduct mobile traverses with a minimum of error, or to construct strategies to eliminate or at least nullify the effects of confounding influences, or to stratify or filter data so as to expose the control exercised by the variable under study, or to select statistical analyses that will reveal meaningful relations. It might be the single most significant contribution to raising the standard of work in urban climate since Lowry's seminal paper.

3.1.6 Classification of phenomena

The field has yet to establish an agreed system to name some of the most common urban climate phenomena. For example, there is no agreed method to define a heat island. Even after having considered both of Lowry's cautions about using urban-rural differences as surrogates for urban effects on climate, and of avoiding the zone inside the 'urban-affected' area that is impacted by advected urban effects (Lowry, 1977), there are many ways of assessing the urban-rural difference. Mobile traverse data may be able to resolve semi-continuous spatial transects of air temperature along a line or over an area. Using such data some workers define the heat island as the difference between the lowest value in the countryside and the highest in the urban area, others use the lowest and highest values sustained over more that a single point thereby avoiding potentially short-lived anomalies at the bottom of a valley or when the vehicle with the sensor is stalled in a traffic jam, others restrict their difference to that between two fixed sites (e.g. an 'ideal' flat open rural area and the geographic centre of the city), others let the urban location be wherever the core of the warm air is located because it can be advected around, others take the difference between averages of two sets of points in the two environments, and so on. A similar range of favourite schemes exists when fixed sites are used, some arising from scientific design others because of necessity ('the only stations available'). Szymanowski (2005) points out the pitfalls if such analysis neglects the effects of thermal advection on urban-rural temperature differences during the passage of fronts.

There is no accepted classification or nomenclature of the many types of heat island (e.g. Oke, 1995). The types differ either because of where they are located (sub-surface, surface, near-surface air in the UCL or above roof-level in the UBL) or because of the limitations of the observing system (the instrumental field-of-view for a remote sensor), or whether it is a fixed or a mobile sensor. One only has to look at the use of the expression 'surface heat island' to appreciate the lack of precise definition. The surface temperature as defined through observation or modelling can be very different: it might be the temperature of the surface of the ground, or the three-dimensional air-surface interface, or at screen-level, or at zero-plane displacement level, and so on. It is obvious that comparison of such 'surface' heat islands is inappropriate. I have been inconsistent in my own use of abbreviations and symbols for these different phenomena over the years. Such lack of precision should be minimized through the adoption of a common system of definitions, types, names and symbols.

Similar fuzziness exists with respect to defining and naming phenomena such as negative heat (cool?) islands, urban-rural humidity effects (islands?), urban-rural (country?) breezes and others.

3.1.7 Bioclimatic indices

For those not part of the specialist community the array of possible bioclimatic indices available to describe or quantify human comfort can seem bewildering. It is also a little intimidating because there seem to be strong schools of opinion regarding the 'best' or most appropriate ones to use. It might be helpful if an authoritative review and intercomparison were undertaken giving recommendations regarding the applicability of these methods to both indoor and outdoor environments in cities. A positive sign is the existence of a joint study by an Expert Team of WMO and a Study Group of the International Society for Biometeorology focused on the development of a Universal Thermal Climate Index (UTCI). Such international cooperation is promising.

3.2 'Universality' through dimensional normalization

At the beginning of the 1970s Ted Munn noted the difficulty we face over the fact that the individual peculiarities of cities make it inherently difficult to generalize (Munn, 1972). At that time Munn found very few examples of “universal” relations in the field and he recommended we could learn from analyses conducted in boundary layer meteorology. It demonstrates the power of dimensional analysis and the fundamental continuity imposed on the system by the energy balance framework. He saw this as the way to escape the tyranny of trying to extract generality from never-ending case studies, regression analysis in the absence of physical explanation and unrealistic “infinite-plane thinking”. In the succeeding thirty years we have made great strides along this path, but we need to continue to encourage emphasis on achieving ‘universality’ in our work. The examples which follow show it has much to offer in terms of providing a basis for comparison and improved communication.

A simple example is given by Fortuniak et al. (2006, their Fig. 4) which shows how normalization reveals the similarity of the diurnal course of the heat island in all seasons despite the fact that the absolute magnitude of the heat island and the day length is very different between the seasons. The result is almost identical to that of Vancouver (Runnalls and Oke, 2000) who used the normalization procedure of Oke (1998) which involves no more than non-dimensionalizing the graph axes: expressing the magnitude of the heat island as a fraction of the largest value, and time relative to the times of sunset and sunrise. The infinite diversity of dimensions and geometric arrangements of surface elements present in cities can be usefully made similar by expressing their height relative to an appropriate length scale (Table 1). In the UCL this might be z_H (mean height of the elements (buildings)) or D (mean element spacing) or the canyon aspect ratio (z_H/W) that has proved invaluable in making generalizations about flow regimes, roughness parameters, solar access and the infrared cooling potential of street canyons. Other dimensionless descriptors like the plan area index (for measures of fractional cover) or the frontal area index (for aerodynamic flow resistance) also render similar otherwise apparently very different places and hence aid comparative analysis. In the UBL the appropriate lengths may be z (height above ground) or z_i (the depth of the urban boundary layer) (Table 1). Such measures have been used in engineering for many years and their widespread adoption in urban climate has considerable merit.

Comparison of energy balance fluxes from different seasons or between cities with very different energy climates is made possible by the simple device of non-dimensionalizing fluxes by expressing them as ratios of the net radiation or of other fluxes such as in Bowen’s ratio, the Priestley-Taylor aridity index or the McNaughton-Jarvis coupling factor (see Oke, 1997).

The Monin-Obukhov similarity framework is the perfect example of the power of dimensional analysis in making sense of the complexities of the atmospheric boundary layer. Its applicability over relatively uniform terrain is proven and its extension to urban atmospheres, with some caveats, looks increasingly promising. Högström (1982) showed that in the heterogeneous urban boundary layer above roof-level, turbulence properties scale with local values of the friction velocity, and Rotach (1993) shows that this extends down into the roughness sublayer. Such work opens up possibilities to parameterize turbulence properties and mean profiles down to about roof-level, or even below. A particularly good example, of the value of these approaches is the survey of the turbulence characteristics of cities by Roth (2000). By using local scaling, Monin-Obukhov similarity and height scaling using z_H and z_i, Roth was able to present, compare and draw generalizations from data measured in both the UCL and UBL of different cities over different surfaces in different stability regimes. This is surely what Munn hoped for in 1972.

Research into precipitation modification by cities faces more difficulties than for other climate elements. There are several inherent challenges related to the relatively discontinuous nature of precipitation patterns in space and time, the implications these carry for the design and operation of observational networks, and the inherently poor sampling of precipitation gauges. In addition the scale of integration of urban effects on precipitation means that large areas need to be studied. The effects of topography and orography cast their additional subtle influences on top of the unique properties of the urban system as does the different nature of precipitation physics and dynamics in continental versus maritime, or convective versus frontal, or cold versus warm clouds. Lowry (1998) noted the pressure this places upon the methods employed. It requires closer attention to aspects of experimental design, sampling, stratification, replication and randomization so that a measure of universality and transferability of results between cities is established. Experiments using validated mesoscale numerical models of the urban atmosphere that include pollutant emissions and cloud physics offer the possibility to test, with or without, the inclusion of orography or the urban area. Such experimental control may provide good insights into this controversial topic.

4. Conclusion

The field of urban climate attracts workers from a wide variety of disciplines who pursue many modes of enquiry and whose objectives are very different. To ensure discourse in the field is understandable and accurate across this spectrum of interests, and to minimize the development of overly-specialized cliques it seems time to pay attention to a degree of standardization of terminology, methods of classification and description. The utility of work, especially its transferability is enhanced if care is taken in experimental design and through the use of dimensional analysis and normalization.

References

Aguilar E, Auer I, Brunet M, Peterson TC, Wieringa J (2003) Guidelines on climate metadata and homogenization, WCDMO-No. 53, WMO-TD No. 1186, Geneva: World Meteorol Organiz

Arnfield AJ (2003) Two decades of urban climate research: A review of turbulence, exchanges of energy and water and the urban heat island. Int J Climatol 23: 1–26

Best MJ (2006) Progress towards better weather forecasts for city dwellers: from short range to climate change. Theor Appl Climatol 84: 47–55

Davenport AG, Grimmond CSB, Oke TR, Wieringa J (2000) Estimating the roughness of cities and sheltered country, Preprints Conference on Applied Climatology, Asheville, Amer Meteorol Soc, Boston, 96–99

Ellefsen R (1990/91) Mapping and measuring buildings in the urban canopy boundary layer in ten US cities. Energy and Buildings 15–16: 1025–1049

Fortuniak K, Kłysik K, Wibig J (2006) Urban-rural contrasts of meteorological parameters in Łódź. Theor Appl Climatol 84: 91–101

Grimmond CSB (2006) Progress in measuring and observing the urban atmosphere. Theor Appl Climatol 84: 3–22

Högström U, Bergström H, Alexandersson H (1982) Turbulence characteristics in a near-neutrally stratified urban atmosphere. Bound-Layer Meteor 23: 449–472

Jauregui E (2000) Tropical urban climatology at the turn of the millenium. In: deDear RJ, Kalma JD, Oke TR, Auliciems A (eds) Biometeorology and urban climatology at the turn of the millenium. Geneva: World Meteorol Organiz, pp 537–540

Kanda M (2006) Progress in the scale modeling of urban climate: Review. Theor Appl Climatol 84: 23–33

Kłysik K, Oke TR, Fortuniak K, Grimmond CSB, Wibig J (eds) (2004) Proceedings Fifth International Conference on Urban Climate, Vols. 1 & 2. Łódź: Univ Łódź, Int Assoc Urban Climate and World Meteorol Organiz

Kratzer A (1937) Das Stadtklima. Braunschweig: Friedr Vieweg

Landsberg HE (1981) The urban climate. New York: Academic Press

Lowry WP (1977) Empirical estimation of urban effects on climate: a problem analysis. J Appl Meteor 16: 129–135

Lowry WP (1998) Urban effects on precipitation amount. Progress Phys Geog 22: 477–520

Masson V (2006) Urban surface modeling and the mesoscale impact of cities. Theor Appl Climatol 84: 35–45

Mills G (2006) Progress toward sustainable settlements: a role for urban climatology. Theor Appl Climatol 84: 69–76

Munn RE (1972) Urban meteorology: some selected topics. Bull Amer Meteor Soc 54: 90–93

Oke TR (1984) Towards a prescription for the greater use of climatic principles in settlement planning. Energy and Buildings 7: 1–10

Oke TR (1995) The heat island of the urban boundary layer: characteristics, causes and effects. In: Cermak JE, Davenport AG, Plate EJ, Viegas DX (eds) Wind climate in cities. Dordrecht: Kluwer Academic Publishers, pp 81–107

Oke TR (1997) Surface climate processes. In: Bailey WG, Oke TR, Rouse WR (eds) Surface climates of Canada. Montréal: McGill-Queen's University Press, pp 21–43

Oke TR (1998) An algorithmic scheme to estimate hourly heat island magnitude, 2nd Symp Urban Environ, Albuquerque, NM, Amer Meteorol Soc, pp 80–83

Oke TR (2004) Initial guidance to obtain representative meteorological observations at urban sites. IOM Report No. 81, WMO/TD No. 1250, Geneva: World Meteorol Organiz http://www.wmo.ch/web/www/IMOP/publications/IOM-81/IOM-81-UrbanMetObs.pdf

Pigeon G, Augustin C, Legain D, Durand P, Masson V (2004) Characteristics of the urban thermodynamic island and the energy balance on Toulouse (France) during winter and spring periods of the CAPITOUL experiment. 5th Symp Urban Environ, Vancouver, BC: Amer Meteorol Soc

Rotach MW (1993) Turbulence close to a rough urban surface. Part II: variances and gradients. Bound-Layer Meteor 66: 75–92

Roth MR (2000) Review of atmospheric turbulence over cities. Quart J Roy Meteor Soc 126: 941–990

Runnalls KE, Oke TR (1998) Dynamics and controls of the near-surface heat island of Vancouver, B.C. Phys Geogr 21: 283–304
Szymanowski M (2005) Interactions between thermal advection in frontal zones and the urban heat island of Wrocław, Poland. Theor Appl Climatol (in press)
Voogt JA, Oke TR (1997) Complete urban surface temperatures. J Appl Meteor 36: 1117–1132
Wanner H, Filliger P (1989) Orographical influence on urban climate. Weather and Climate 9: 22–28
Yoshino MM (1975) Climate in a small area. Univ Tokyo Press, Tokyo

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