PAPER No: 250 Urban climatology and its relevance to urban design

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Abstract

In 1976 Chandler published a World Meteorological Organization (WMO) Technical Note (No. 149) on 'Urban Climatology and Urban Design' that sought to provide guidelines for meteorologists working in a new arena. In this paper I will present an update of this work, which is also due to be published by the WMO. When Chandler's work was completed, the field of urban climatology was still in its scientific infancy. His work focuses mainly on the characteristic features of the urban atmosphere (which were still being discovered) and emphasizes changes in temperature, humidity, etc. that are caused by urban development. For example, there is little in the observational section on the energy budget of urban environments, something that has changed significantly in the last 30 years. Since its publication our understanding of urban climates has improved considerably and this provides an opportunity to re-evaluate the relevance of urban climatology to urban design. In addition, there is now a substantial body of case-study materials and a growing area of guidelines for climate-based planning, which did not exist when Chandler produced his survey. The new publication will: focus on human health and comfort; emphasize the populated areas of the world; provide links between urban planning & design and building-scale decision making; demonstrate useful tools; provide guidelines where available and; provide case-studies of climate-based planning & design. In this paper I will present an overview of urban climatology and its relevance to urban design using case-studies drawn from the published literature to illustrate points

Keywords: urban climate, urban design.

1. Introduction

Most of humanity occupies urban environments that have dramatically altered the pre-urban, 'natural' climate in nearly every respect. This urban effect is most obvious in the urbanised area itself however it extends far downwind to have regional and even global impact [1,2]. Many aspects of the 'urban' climate are undesirable at best and unhealthy at worst. At the same time, the character of urban areas can be purposefully altered through design and planning to ameliorate unwanted outcomes.

The urban effect was first detected by Luke Howard, whose work on the climate of London in 1820 established many of the basic features of what is known as the urban heat island [3]. As a substantive area of research, the urban effect on climate was not revisited until the middle of the twentieth century. Thereafter, the research has followed parallel paths. On the one hand, designers have focussed on urban building layout with a focus on solar geometry, in particular, as a 'form giver' [4]. On the other hand, climatologists have concentrated on the outdoor climate and the causes of the urban effect. The observations of the latter are of direct relevance to the former however, with few exceptions, there has little exchange. The gap has grown particularly large in the last two decades during which the scientific sophistication and intensity of urban climate research has grown considerably. The results of this research are published in the scientific literature which is not accessible to the majority of planning practitioners. Moreover, the design implications of the results are rarely extracted in a usable form.

In this article I examine the relevance of urban climatology research to urban design and planning. This work is drawn from a report being prepared for the World Meteorological Organization (WMO) as part of its mission to ensure that meteorological observations are employed for maximum benefit. This work will build upon an earlier report on this topic completed in the 1970's at the beginnings of modern urban climate research [5]. Since this time, the global urban population has increased enormously, especially in the less developed world. Urban areas are now recognised as the foci of human activities and consequently, the drivers of planetary changes. The study of urban climates has changed apace. Designing sustainable settlements must perforce consider local climate as a resource to be managed.

Here I will draw together some of the research strands that have characterised urban climate research. I will select a few examples to illustrate key developments in the field and draw on some case-studies to illustrate the relationship between urban design and climate. Finally, I will identify some key areas where research gaps remain.

2. Urban climate science

The field of urban climate research is still relatively young and much of the research in the field up to the 1980's could be characterised a descriptive in nature. For the most part researchers would engage in measurement programmes whereby traditional instruments were employed to provide some spatial detail on the urban effect on rainfall, temperature, humidity, etc. Most often, these measurements were compared with those obtained from a nearby meteorological station that provided a (non-urbanised) standard against which to establish the urban effect. The best example of this work is the well known urban heat island (Fig. 1).

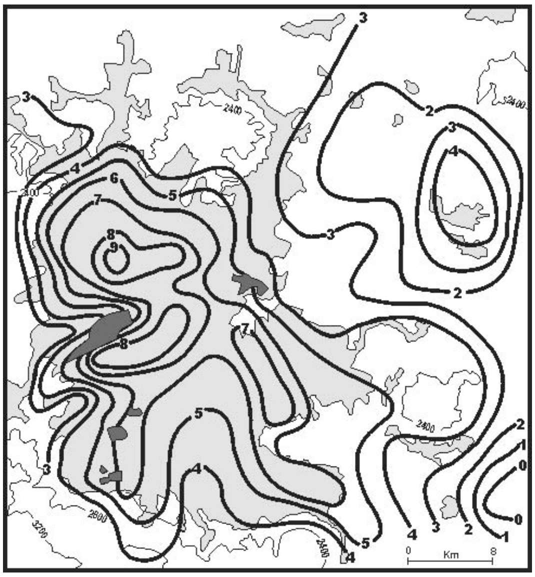

Fig. 1. The urban heat island of Mexico City as measured in the minimum temperature November, 1981. (Redrawn from [5]).

The usefulness of much of the data gathered by this research was limited in a number of respects:

a. The inability to identify a standard meteorological station that could represent the background climate. Thus, the 'urban' effect was almost certainly a result of changes occurring jointly in the urban and the non-urban observations.
b. Whereas the analyses of these data were suggestive, they did not allow causative processes to be studied. This limited the research to individual case-studies and statistics rather that modelling was employed to obtain general results.
c. The absence of an experimental structure linked to meteorological theory made it difficult to abstract from results obtained at one place.

These problems can be seen in the research on the urban heat island (UHI), which has been variously identified from satellite surface measurements (roofs and streets), aerial thermal imagery (sides of buildings, parts of streets, etc.) and air temperature readings using stationary and mobile stations often at different heights. The result has been a great deal of data that has proved difficult to compile into a coherent body of useful knowledge.

The field has advanced considerably in the last two decades owing to changes in how urban climates are studied.

2.1 Focus on Process

Changes in air properties (e.g. temperature, wind speed, etc.) are the result of exchanges of energy and momentum. The energy exchange at the urban surface is given by:

$$Q^* + Q_A = Q_H + Q_E + \Delta Q_S$$
$$Q^* = K\downarrow + K\uparrow + L\downarrow + L\uparrow = K^* + L^*$$

Where Q * is net radiation and is comprised of incoming (↓) and outgoing (↑) shortwave or solar (K) and longwave or terrestrial (L) radiation. Also available in urban areas is energy produced by humans (Q_A). This available energy drives exchanges with the atmosphere in terms of sensible (Q_H) and latent (Q_E) fluxes and results in changes in heat stored in the solid substrate (ΔQ_S). These exchanges provide a foundation for understanding the urban 'effect' and how urban design can ameliorate undesirable impacts [6]. For example, Fig. 2 examines the role of surface coatings in regulating surface-air temperature differences. Increasing the surface albedo increases K↑ and reduces the absorption of solar radiation.

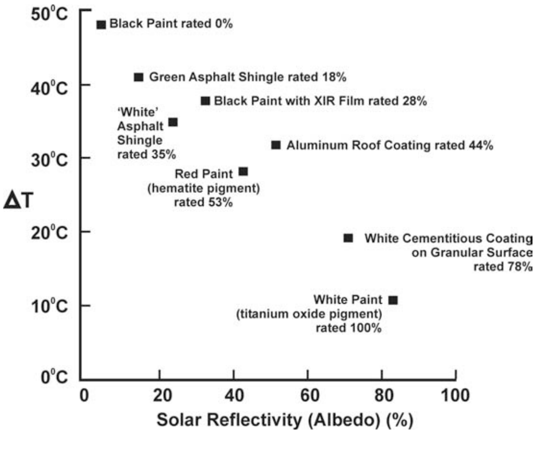

Fig. 2. The relationship between the surface-air temperature difference (ΔT) and the albedo of selected paints and roofing materials facing the sun. Redrawn from [7].

The energy budget framework allows the UHI to be better understood. The evidence suggests that the UHI is strongest at night ($K^*=0$) in near calm conditions ($Q_H+Q_E \approx 0$). Moreover, Q_A has been found to be small in comparison with the natural fluxes, except in extreme circumstances. Thus, the relevant equation becomes,

$$L^* = \Delta Q_S$$

In other words, as the warm urban surface cools at night (due to the loss of longwave radiation), heat is withdrawn from storage. What characterises the urban effect is the nature of heat loss at night, which occurs more slowly than in surrounding areas. This is as a result of the unique materials and geometry of urban areas.

2.2 Urban structure

While it may appear obvious in retrospect, much research on urban climates has been carried out without due consideration for the horizontal and vertical scales that affect the interpretation of measurements and allows abstraction of results from the specific to the general [9].

From a planning and design viewpoint it is the urban 'surface' that is of interest. It is this surface (and the activities thereon) that can be managed to exert some control on the climate experienced. The zone of human occupation corresponds with the urban canopy layer (UCL). This consists of the volume below roof-level and includes that contained within building envelopes and those in the intervening spaces (Fig. 3). The properties of the building volumes are strongly regulated for the purposes of its occupants. Our interest here is on the weakly regulated outdoor climate. At this micro-scale, the urban effect is controlled by the immediate environment.

The UCL occupies the lower part of the Urban Boundary Layer (UBL), a distinctive envelope of air that forms as air passes across a new (urban) surface and begins to interact. The height of the UBL grows from the upwind edge of the city at a rate that is determined by the intensity of the vertical exchanges (Fig. 3)

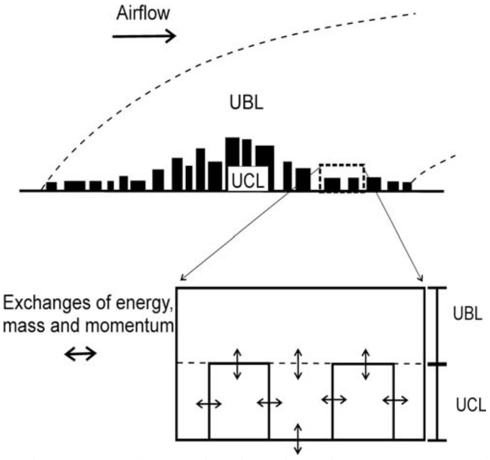

Fig. 3. A schematic showing the structure of the urban atmosphere. .

The geometry of building placement, orientation and material composition has a great impact on the indoor and outdoor climate. Much design-focused research has examined the urban effect caused by the interaction between buildings and specifically their access to solar radiation (K↓). To deal with the complex urban form, simple model geometries have been used to explore relationships. The cube (individual buildings) and the canyon (to represent streets) have been employed since the early twentieth century by urban designers [10] (Fig. 4).

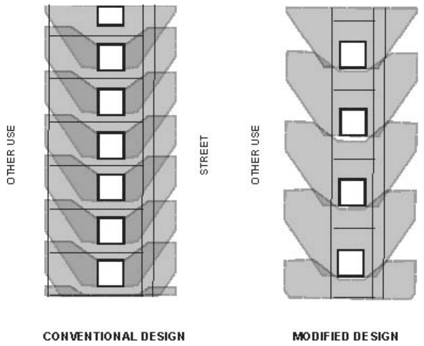

Fig. 4. Arrangements of cube shaped buildings to ensure access to solar radiation. (Redrawn from [11])

From a climatology viewpoint the urban effect is a boundary-layer problem. The aerodynamically rough and warm urban surface generates considerable vertical exchange that generates the UBL. At the lee side of the urban surface, a new boundary layer begins to form, so that an elevated urban plume extends downwind.

The lowest part of the boundary layer (known as the surface layer) is most closely linked to underlying surface(s). The buildings within the UCL generate considerable turbulent activity up to about 1½ times their height (referred to as a roughness sub-layer). Sometimes this activity can resolve itself into coherent standing eddies between buildings [12] however, these tend to be short-lived. Rather, exchanges between the UCL and the immediate overlying air are characterised by random 'expulsions' of UCL air and its properties. It is only above this sub-layer that fluxes exhibit stable statistics. Urban observations made above sub-layer may be compared with observations made above the roughness sub-layers of other surfaces, such as grass. A major aspect of recent urban meteorological measurements has been to establish links between observations at this elevation and different types of underlying urban land cover(s) [13].

3. Deriving design guidelines

In urban climate research these simple models are also used to explore urban climates more comprehensively. For example, Fig. 4 shows that observations of the UHI can be well explained by a simple physical ratio describing the narrowness of streets.

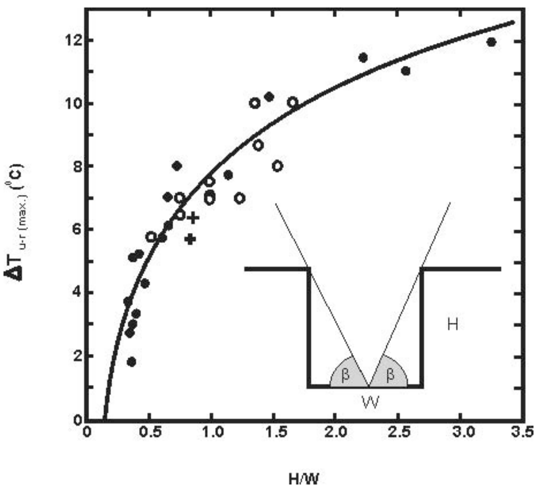

Fig. 4. Relation between the maximum heat island intensity ($\Delta T_{u\text{-}r(max)}$) and the height to width ratio (H/W) of the street canyons in the centres of the settlement. Redrawn from [14].

The observed UHI is now amenable to explanation. We have already observed that the heat island is strongest when $L^* \approx \Delta Q_S$ and the relationship above clarifies the role of the micro-scale circumstances in managing L*. In narrow streets (large values of H/W) characteristic of city centres, the loss of radiation to the sky is impeded by the presence of the surrounding surfaces, which absorb and re-emit the incident longwave radiation. This relationship is captured in Fig. 4 where $\Delta T_{u\text{-}r(max)} = 7.45 + 3.97 \ln(H/W)$.

Because radiation exchanges are based on geometrical relationships, their role in urban design has been relatively easy to study. The availability of three-dimensional urban databases and conventional software now allows these radiation issues to be explored in some considerable detail for extensive parts of cities [15]. Moreover, unlike many other aspects of the urban climate, there are many case-studies to draw upon for illustration purposes.

By comparison, the urban effect on airflow, which has an impact on all atmospheric transfers (momentum, heat and pollutants) has proven more problematic to study and to abstract general rules.

Meteorological theory suggests that the distinct properties of a 'surface' can be obtained through observations made above the roughness sub-layer and sufficiently far from the upwind edge of that surface. In a neutral atmosphere, the vertical wind profile is takes a logarithmic shape and wind-speed (u) at any height (z) can be obtained from,

$$u_z = \frac{u_*}{k} \ln \frac{(z-d)}{z_o}$$

where u_* is the friction velocity, k is the von Karman constant (0.4) and z_o is roughness length (m) and d is the zero plane displacement (m). The friction velocity is most often obtained from observations of u within the boundary layer but z_o and d are properties of the surface itself. The roughness length represents the height at which u_z in the above equation equals zero. The zero plane indicates the elevation of the momentum sink (located at approximately two-thirds the height of the roughness elements).

This is true for conventional meteorological measurements made over short grass surfaces (with $z_o \approx 0.05$) and for measurements made above the urban surface (with values of z_o varying from 0.4 for low-density suburbs to 10 for high rise, closely spaced buildings). Thus, to estimate airflow properties for an urban site from measurements made at a conventional meteorological site requires that windspeed is first estimated for a reference height (z_{ref}) above the urban surface.

The link between urban form and aerodynamic roughness can be gauged from Fig. 5. This shows the result of wind tunnel research exploring the effect of urban building density on turbulent exchanges with the overlying atmosphere [15]. Using identical cube-shaped buildings arranged in a grid, density is increased by bringing the building units closer together (thus increasing the fraction of built-up area). At the limit of 1.0, the cubes have merged forming a single roof surface with no intervening spaces. Although in real-world situations the uneven height of buildings would not give rise to a smooth surface, the results are informative nonetheless.

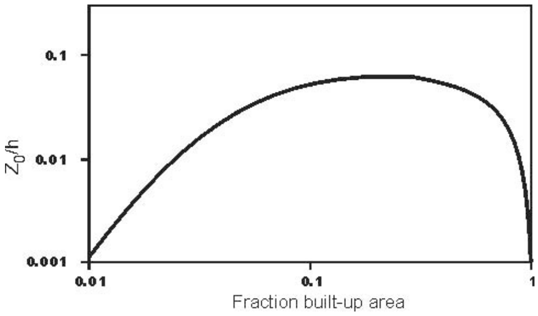

Fig. 5. The relationship between surface roughness (zo) and urban building density. Redrawn from [16].

This curve in Fig. 5 shows that building density can be modified to enhance or suppress interaction between the urban 'surface' and the overlying air. Of course, what lies below this aerodynamic surface is the UCL. For a rough surface, vertical movement will quickly replace air within the streets with air from above. On the other hand, when this surface becomes smoother, the air below becomes increasingly separated from the airflow above the street. This has implications fro street-level air quality where the bulk of transport emissions arise.

There has been a considerable amount of research into the nature of airflow within the UCL when it becomes aerodynamically separated. From a design perspective it would be useful to be able to evaluate the degree of exchange between the street and the overlying atmosphere. A simple means of linking the average wind-speed within streets (Uc) and the exchange rate (UE) between the street air volume and the air above has been proposed [17].

$$\frac{U_C}{u^*}=\left[\frac{z_o}{2H}\right]^{-0.5} \qquad \frac{U_E}{u^*}=\left[\frac{1}{k}\ln\left(\frac{z_{ref}-d}{z_o}\right)-\frac{U_C}{u^*}\right]^{-1}$$

As can be seen from the above equations the key urban factors are roughness length and zero plane displacement, each of which is the product of neighbourhood decisions on building height and separation.

4. Case-studies

The study of urban climates is now well established as a scientific discipline and its experimental approach has yielded considerable insights. Real-world case studies are needed to complement these experiments. Ideally, these studies would be available for a range of climates and be placed within a suitable scaling framework that corresponds with their meteorological impact (Table 1).

Table 1: A summary of the tools employed at the building, building group and settlement scales to achieve climatic objectives at those scales.

Objective	Scale	Tools
Indoor comfort Shelter	Buildings	Location, materials design (e.g. shape, orientation, etc.)
Outdoor comfort Outdoor health	Building groups	Building placement, landscaping, materials, street dimensions & orientation
Energy use Air quality Protection from extremes	Settlement	Zoning, overall extent and shape. Transport Policy

Currently, there are relatively few published case-studies that can be used to illustrate the value of climate based design at different scales. I have chosen two to illustrate design intervention at two distinct scales.

Fig. 6 shows the planning outcome of an analysis into the value of night-time winds to air quality in Graz, Austria. Under clear skies, cool and clean air moves down-slope along the valleys and 'ventilates' settlements. Land-use zoning is employed to ensure that this air can move downslope unobstructed by developments. On this diagram, the darkest areas have the greatest restrictions.

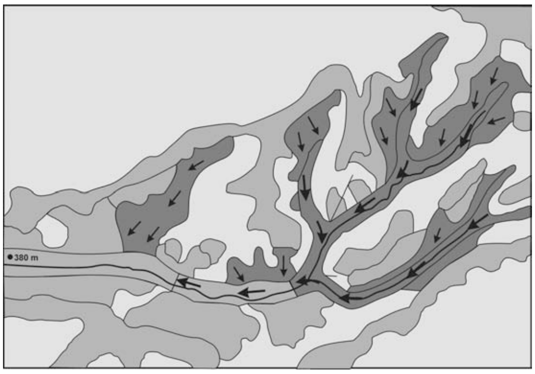

Fig.6 Areas of restricted development in Alpine valleys above Graz, Austria. Arrows show the direction of night-time valley winds. Redrawn from [18].

Of all the tools available to the planner, vegetation is the most flexible and plays a role in: surface and air temperature modification; hydrological control; removal of airborne pollutants; noise control and; the sequestration of carbon emissions. Fig. 7 shows the benefit of trees to moderate a pedestrian environment in a hot and arid climate. In addition to providing direct shade for the pedestrian, the trees cool the micro-scale environment through shading of the underlying surface and evaporation.

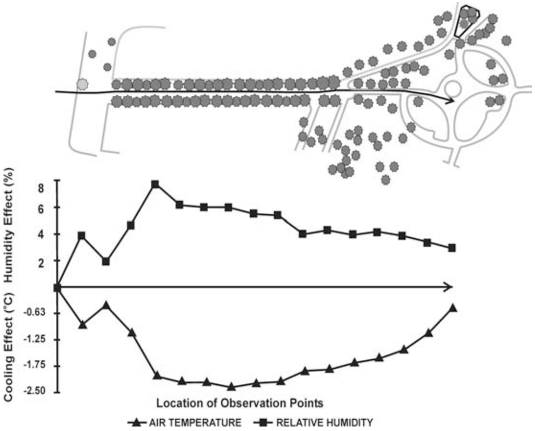

Fig. 6. The cooling and humidity effects of vegetation measured along a transect at 3pm. Measurements correspond with the path shown above in which the tree canopy is shown by shaded circles. Redrawn from [19].

5. Conclusions.

There has been a substantive increase in the body of knowledge on urban climates since the 1970's. Much of this advance has come about through the application of meteorological theory and greater precision in defining urban surfaces and their atmospheric effects. However, while this has generated a great deal of information much of it remains hidden in the scientific, non-applied literature. Part of the reason for this is that urban climate studies often emerge from a research agenda set by the urban science, rather than urban design/planning, community. In addition, even when potential design information is available, its potential is not recognised.

Despite progress in the last thirty-years, some significant gaps remain in our knowledge base. These include:

1. With few exceptions, there is little information available on city climates in tropical regions, where much of the urban growth is occurring [20].
2. While there has been considerable work completed using the cube and canyon forms, other forms (e.g. courtyards) have not received the same attention.
3. There are very few case-studies available that demonstrate the value of incorporating urban climate knowledge into decision-making.

Nevertheless, there is sufficient information in many areas to demonstrate (through theory and practice) the value of urban climate knowledge to design/planning in the urban environment. The completed WMO report should provide a coherent picture of the state of the field and identify where gaps remain.

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