

Urban thermal diversity

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Abstract: This paper introduces the interrelationships between urban form, microclimate and thermal comfort. It draws on recent research of monitoring, surveying and modelling urban thermal characteristics and proposes a method of mapping urban diversity. Because the urban context provides a rich and varied environment that influences the way we use urban spaces (movement, sequence, activity) and how we feel in them (stimulation, thermal comfort), the aim here is to highlight the notion of diversity. Thus thermal diversity is used as a measure of the urban environment, rather than more conventional spatially or temporally fixed average values.

Keywords: urban; comfort; microclimate; outdoor space

1. Introduction

In environmental terms our cities are frequently described negatively and associated with pollution, poor health, stress and overcrowding. In practice, many cities have developed in a piecemeal and evolutionary manner, planned and designed over many centuries – though some, like Chongqing, are developing far more rapidly – and involving countless individuals. Although the result is that planning has typically been **incremental** and ineffective to adapt to new pressures, such as for example transport, the result is a richness and variety of urban environments – both in positive and negative terms. These qualities affect our perception of urban spaces and how we use them. The purpose of this paper is to explore the nature of this environmental diversity with a particular focus on the thermal conditions, by defining the links between urban form and microclimate, and to demonstrate how our perception is influenced by it.

The first part of this paper addresses the urban microclimate with a particular reference to its diversity rather than the absolute conditions. This is achieved primarily by the study of monitored data. The second part reveals how users of outdoor spaces respond to the urban microclimate, as exposed through a combination of surveys and environmental monitoring. Finally, the paper concludes by proposing a mapping of environmental diversity, showing how this can be used to understand and inform urban design.

2. The urban microclimate

It is well understood that the urban climate varies significantly from the synoptic climate, and that this is caused by a combination of anthropogenic and physical factors. The reduction of vegetation, the increase of thermally massive and non-porous surfaces, the presence of drainage systems and the emission of heat and pollution all contribute to altering the urban microclimate. Most interesting, at least from a planning and design perspective, is that the geometry of urban form also has an important effect. Geometric factors include density, surface-to-volume and height-to-width ratios of urban buildings and spaces. What is perhaps surprising is to find that such complex sets of interactions, between form and microclimate, are typically reduced to a discussion of temperature difference - by way of the 'urban heat island effect' - or pollution levels, etc. Such metrics are expressed as the difference between the rural environs and the urban areas. Thus the heat island effect will typically be measured on still and clear summer evenings when maximum values can be recorded.

There are three issues related to such analysis of the urban microclimate: 1) it gives the impression that the urban environment is on average different (warmer) without revealing the dynamic range, 2) the relative significance of this overall difference compared to smaller scale variations is not clear, and 3) the effects are almost always discussed as negative terms. Technically, the 'urban canopy layer' relates to the spaces in the streets and between buildings, and is of particular interest in terms of conditions experienced by people and buildings. The boundary layer above the

urban canopy is typically well mixed[6] whereas the canopy layer “is characterised by considerable complexity, mainly deriving from the convoluted nature of the active surface” [6]. It is this complexity that we are interested in here.

In his seminal book ‘The Climate Near the Ground’, Geiger states that “Taken over the year as a whole, a city is warmer than the surrounding countryside, the difference being in the order of 1 deg.” [3]. More recent studies refer to maximum values of as high as 12 to 14 degrees [6]. How are we as planners and designer to use this kind of data? Further unravelling is needed to understand the implications with respect to urban form and perception.

The measurements and predictions of the urban heat island are typically carried out to reveal *peak* differences, in order to demonstrate the physical forces and extent of the effect. Oke refers to the “maximum heat island intensity” in his correlations between the heat island and urban geometry, as follows:

$$T_{\max} = 7.54 + 3.97 \ln (H/W)$$

Oke’s assessment shows that the narrower a street canyon, or the larger the height to width ratio (H/W), the greater the maximum heat island intensity ($T_{\max}$). He concludes that “the urban geometry is a fundamental control on the urban heat island” [6]. On the same page he goes on to state that “Humans however find the added warmth to be stressful if the city is located in an already warm climate”. The conclusion would seem to be that narrow streets are the wrong approach for hot climates as this would increase already high air temperatures. And yet we know that traditional hot-arid cities are very compact with deep streets and courts (Fig. 1). The reason for this apparent contradiction is that the use of maximum heat island intensity is overly simplistic, and that it is in fact the dynamic diurnal and spatial effects that are critical.

The maximum heat island intensity typically occurs after sunset – at about 9pm. Yet there is also the potential for a ‘negative heat island’ at the hottest time of the day at about 3pm. At this critical point in the day it is possible for the urban temperature at the bottom of the urban canopy layer to be cooler than the rural temperatures, providing much needed protection in a hot climate. By the time the heat island intensity (i.e. the increment above ambient) is at a maximum the ambient temperatures will be lower and thus less critical in terms of comfort or stress. This argument

clearly suggests that the variations in *temporal* terms are critical, offering the potential for cooler conditions at the hottest time of day in return for a temperature increment when air temperatures are cooling down.

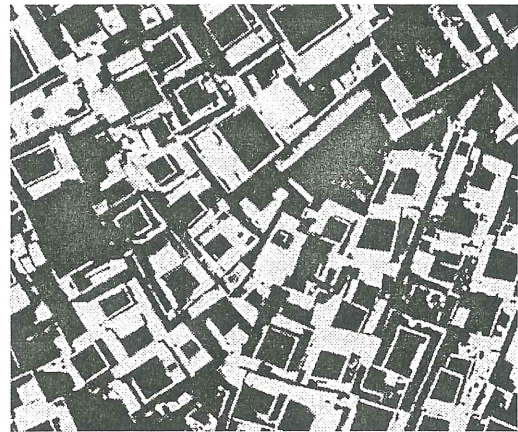


Fig. 1 The deep streets and courts of Marrakech seem to contradict the logic of urban heat island effect where narrow streets create higher urban temperatures

If we again take the scenario of the hot-arid climate, then a simplistic appreciation of the heat island intensity might lead us to assume that it is better to provide wide, open streets to minimise thermal stress. However, in the context of human thermal comfort, the presence of shade will be significant. The opportunity to walk out of intense sunlight may offer greater benefits to comfort than the disadvantage of some increase in the average air temperature. A change of 1 °C in air temperature can be compensated for by an inverse change in horizontal radiation of approximately 70 W/m² [10]. Considering that 1000 W/m² of direct solar radiation would not be uncommon, this equates to a 14 °C air temperature increase. Thus shade is a more significant factor than heat island. It is also evident that shade is determined by built form and solar geometry. A similar case could be made for cold climates where the heat island benefits of a compact form are offset by a lack of access to solar radiation. This demonstrates that *spatial* diversity can play a significant role in terms of the urban environment.

3. Form and diversity

Having shown how both *temporal* and *spatial* factors will influence performance of the urban environment, the next stage is to explore the extent and significance of diversity within the urban fabric. The study of temperature variations through cities has been part of

the investigations in to the urban heat island effect. Such work not only reveals that temperature increases tend to be maximum in the urban core and reduce more or less concentrically out, but also shows variations in temperature differences. Such variations are particularly pronounced near parks where temperature reductions of approximately 3 °C compared to adjacent urban conditions have been measured [8]. This is confirmed with computer analysis, showing not only similar reductions but also subtle variations across a park and adjacent urban context in relation to wind effects [2], [5]. One might suspect more diversity when one looks even more closely at urban form. Some urban spaces may be exposed to direct sunlight for a large part of the day, whilst others may be shaded or vegetated, so that in the same street a diverse range of thermal conditions might be found.

The key questions are: what is the nature and extent of this diversity, and what is the relationship to built form? The work of Oke (1987) and others has already indicated that the temperature conditions in streets and squares is related to the degree of enclosure, expressed as height-to-width ratios or sky view factors. A similar definition might be used to define the thermal characteristics of semi-enclosed spaces such as colonnades and loggia.

For the purpose of this paper we will look at two urban contexts: Kastro on the Island of Siphnos in Greece and Cambridge in the UK. Kastro has a fairly high density urban grain with street height to width (H/W) ratios of between 2.0 and 6.0 (average of about 3.0). Using Oke's correlation[6] this would result in a maximum heat island intensity of 10.0 to 14.5 °C. By comparison, Cambridge has H/W ratios typically ranging from 0.5 to 2.0, averaging at about 0.8 and results in a maximum theoretical temperature increase of 6.5 °C.

Looking more closely at the two urban areas one can identify a range of intermediate spaces: loggias, passage-ways, cloisters and colonnades of different proportions and orientations. Their spatial characteristics, having opaque overhead surfaces, immediately make it clear that a simple H/W ratio is not an appropriate indicator of their forms, but that an alternative measure is required in order to compare form with thermal performance. The measure that we propose is the 'Degree of Enclosure' (DoE). This is

defined as the ratio of the sum of all surfaces (closed and open (A_{total})) to the sum of the opening areas (A_{open}).

$$DoE = A_{total} / A_{open}$$

A series of spaces with different degrees of enclosure were monitored in Kastro during the summer period. Initial results suggest that the extent of the diurnal temperature fluctuations correlates inversely with the degree of enclosure. Thus, the less enclosed an intermediate space is the greater the temperature variations. This makes sense and follows the trends that have been found at the larger scale related to the urban heat island effect.

Recent monitoring of urban spaces in Cambridge UK by the authors has shown that a temperature range of 6.4 °C was measured on a Spring morning, with the coolest being in an open park (2.1 °C) and the warmest in a cloister (8.5 °C). The ambient temperature at the time was 0.4 °C. This suggests that different types and combinations of spaces provide an increase in thermal diversity.

The next step in the analysis is not simply to measure differences but gain an insight in to the physics in order to explain principles of the diversity that has been measured. A model was developed, based in the CIBSE Admittance Method, to explore the temperature implications of intermediate space design characteristics. The temperature swings predicted by the model are compared to the monitored data from Kastro and Cambridge intermediate spaces of various DoE in Fig. 2. The trendline drawn through the monitored dataset shows a modest correlation, with an r-squared value of 0.53. More significant is the fact that the monitored trendline very closely matches the theoretical data produced in the model, resulting in the following equation:

$$T_{swing} = 17.3DoE^{-0.48}$$

So, on the one hand there is a fairly wide diversity of thermal conditions found in the monitored spaces, but on the other hand there is a clear trend showing that DoE affects temperatures.

As ambient conditions get cooler, an intermediate space with a high Degree of Enclosure will provide a warmer environment. Conversely, as ambient temperatures increase, the space may be expected to remain cooler.

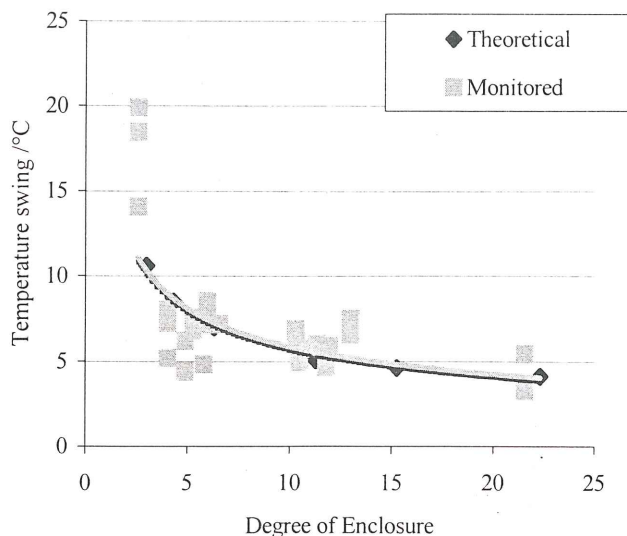


Fig. 2 Predicted and measured temperature swings as a function of the degree of enclosure.

The theoretical curve matches the average monitored curve so well, it provides a good opportunity to explore what causes the deviations from the trendline. One factor will evidently be the ambient conditions. However, it is more interesting in design terms to explore the thermal diversity generated by built form: specifically the scale of the space, its proportions and its orientation.

A change in the volume of a space, whilst maintaining all other variables constant, has an effect on the theoretical temperature swing. The volume becomes more influential for small spaces, but overall only a modest 2 °C alteration can be modelled.

Changing the proportions has very small effects, nearly undetectable within a range from 1:1 to 1:5 of the height-to-width proportions of an arcade where the DoE is kept constant. However, altering the orientation of an arcade does indicate that this variable is an important factor. Orientation influences the temperature swing by 3.5 °C, with a West-East orientation creating the largest range of temperatures. One could imagine that an open-sided, West-facing loggia would provide yet greater variations to the temperature swing.

Even based on the theoretical studies presented here, one can see that the basic formal characteristics of streets, squares and intermediate spaces will result in significantly diverse thermal conditions. This is supported by the monitored data. The next question that is raised is how do people respond to the thermal conditions and diversity in an urban environment?

4. Outdoor comfort

It is, in theory, possible to predict thermal comfort as a function of environmental parameters (such as temperature and air speed) and personal variables (such as clothing level and metabolic rate). However, as comfort has been defined as “that *state of mind* which expresses satisfaction with the thermal environment” (ASHRAE, 1992) it is suggested that comfort is related to both physiological and psychological variables. It would thus be arguable that the perception of the users of spaces, as opposed to only the physical parameters, is an appropriate measure of comfort. Carefully constructed questionnaires, alongside detailed monitoring in a range of urban spaces, are used here to reveal people’s perception of comfort and subsequently compared with theoretical predictions of physiological comfort with reference to ISO 7730 (1994).

For the purpose of this paper we will discuss survey results from two urban spaces in Cambridge, UK, and one urban park in Manila, Philippines. The reason for discussing these case studies is that they represent a range of conditions from compact urban square in a temperate climate, to more open space in a hot humid context.

The key results, comparing the actual with the predicted comfort votes, immediately highlights a discrepancy between the two (Figure 3). During warm conditions, particularly noticeable from the Manila surveys, the theoretical figures, based on ISO 7730 calculations using detailed monitored and observed data, suggest that the users of the spaces should be far too hot. Conversely, during cooler summer weather the theory indicates that people should be colder than they actually report. Another way of presenting this information is that the percentage of people expressing dissatisfaction was far lower than one would predict from the environmental data recorded. For Manila the predicted percentage dissatisfied (PPD) is 100% whereas the actual percentage dissatisfied (APD) is 43%. For Cambridge the figures are 43% and 6% respectively, confirming the discrepancy between the theoretical model and actual comfort perception. Intriguingly, in both Cambridge and Manila the actual comfort vote peaks at +1 (defined as “slightly warm” or “comfortably warm”) despite the very different climatic conditions.

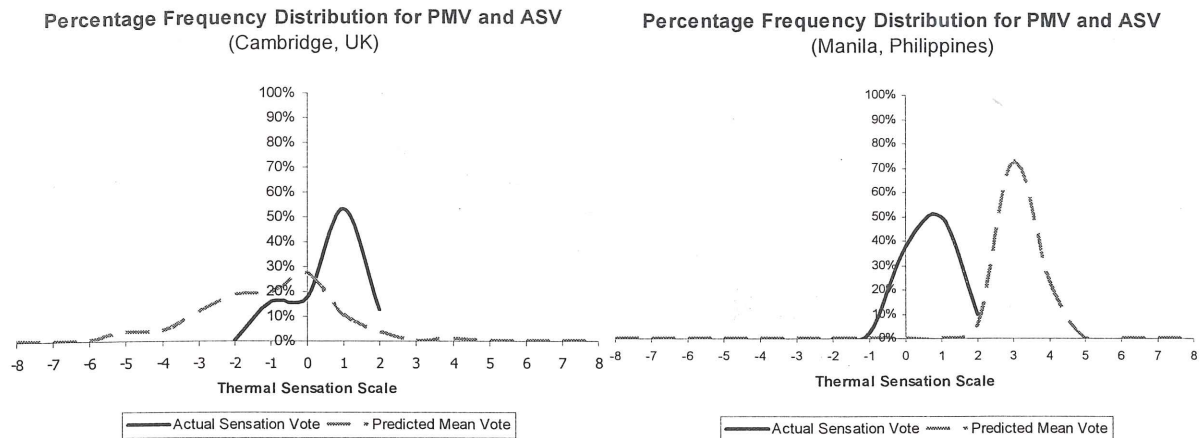


Fig. 3 Comparisons of the Predicted Main Votes (PMV) and Actual Sensation Votes (ASV) for Cambridge (left) and Manila (right).

So we have two issues here: 1) the theory diverges significantly from the responses, and 2) the responses are similar for quite different climatic conditions. The first point is the most important because we speculate that offering diversity is a more significant parameter than ensuring optimum thermal conditions in physiological terms. This is discussed further below. The second issue may also be influenced by the greater degree of freedom of choice found in urban environments compared to internal environments, on which conventional comfort theory is based. It is, furthermore, likely that acclimatisation is a critical factor explaining why the Cambridge and Manila responses are similar. Assuming monthly average temperatures, in England during the summer the neutral temperature at which most people will feel comfortable – neither too cold nor too warm – is 21 °C. In Manila the neutral temperature is in the order of 27 °C. This goes some way to explaining why in two quite different climates the comfort responses can be broadly similar: slightly warm. Further explanation for the discrepancies may be attributable to cultural differences, though this remains a speculative point here.

The key question remains: why are the predicted physiological comfort levels so different from the actual responses? Or, putting it another way, why do most people say they are comfortable when technically they should be too cold or hot? The assertion here is that increased freedom of choice available outdoors is a fundamental factor. This assertion correlates directly with the research on “adaptive opportunity” in the indoor comfort field. The ability of building occupants to regulate their thermal conditions to suit their

preferences will influence the comfort temperature range: more choice results in a wider comfort range. With respect to the interior context, adaptive opportunities range from interactions with the building fabric (opening windows, adjusting blinds, etc.) to personal variables (altering position, adjusting clothing, taking warm or cold drinks, etc.). In the urban environment the “occupants” have the same, if not a wider range of personal variables. These include the choice to be in a particular place (which is typically not available to an office worker); the ability to move within a space (e.g. to find shade); the metabolic rate (e.g. from lying on the grass to jogging); the potential availability of hot or cold drinks (i.e. a café); greater freedom in clothing (office dress tends to be more constrained); etc.

Most important amongst the urban personal variables is the choice to be in any one particular space. This is confirmed by survey data which demonstrates that perceived outdoor comfort is related to the degree of choice people have to be there: those needing to wait (e.g. for a friend or public transport) express twice the amount of dissatisfaction with thermal comfort compared to those with a choice to move. Interestingly, whether such choices are exercised is not critical; simply the knowledge that choice exists creates a sense of control and therefore a greater tolerance. Nikolopoulou and Steemers [2] have suggested that “perceived control” is the most significant psychological parameter determining outdoor comfort. Clearly, in order for choices to be perceived and potentially exercised there must be a sufficient diversity of environments available.

The importance of choice and diversity is supported

by psychologists who claim that “higher organisms engage in an active process of seeking this variability if not found in the immediate surroundings” [9] and that “in any situational context, the individual attempts to organise his physical environment so that it maximises his freedom of choice” [7]. Biologists too support the notion that the optimum environment should not be constant but should provide an optimum range and frequency of change to be desirable for health and well being [11].

5. Mapping environmental diversity

So far we have suggested that the urban environment is potentially more diverse in thermal terms, and particularly that intermediate spaces offer an opportunity to extend diversity. We have also discussed how diversity is a particularly important factor in terms of increasing thermal comfort in outdoor spaces. What this section presents is a way of mapping spatial environmental diversity in cities.

As thermal comfort is dependent on air temperature, radiant conditions and air movement, the starting point for plotting the urban environment is to use temperature variations, sunlight and wind as the key parameters. We have already demonstrated that temperature fluctuations can be related to the “degree of enclosure” of an urban space. In this instance, we will use an equivalent metric: the “sky view-factor”, which is a relatively simple geometric parameter to determine. In terms of solar radiation it is a simple exercise to map shadows in relation to urban geometry. Finally, the urban wind field presents a much more complex condition that, for the purpose of the exercise we will simplify using the notion of wind shadows in relation to prevailing wind directions. So now we have, at least in principle, the ability to map temperature, radiant and air movement conditions. For the latter two we will determine the presence or lack of sun and wind in an urban space. For temperature variations the gradations are more subtle, dependent on the sky view factor, though it is possible to introduce artificial thresholds or bands in the data for ease of discretisation. Each is discussed below.

Thermal analysis can be based either on the maximum heat island intensity ($T_{\max}$) defined by Oke, or by a comparison of globe temperature swings, as discussed earlier. As Oke’s correlation represents extreme conditions, the proposal is that temperature

swings are a more useful metric to relate to diversity, particularly as the monitored data has demonstrated the spatially local effects. A correlation between SVF and temperature swing has been derived from the data presented above which, for urban situations with SVFs less than 0.85, is as follows:

$$T_{\text{swing}} = \ln(1 + \text{SVF}/0.02) / 0.35$$

Using image processing analysis it is possible to plot the SVFs graphically on a pixel-by-pixel basis, allowing a degree of resolution that is appropriate for studying spatial diversity between urban spaces. The image below (Fig. 4) shows the SVFs for a part of Cambridge, where darker areas indicate lower SVFs and thus a lower temperature swing compared to the ambient conditions. This area of Cambridge has an average SVF of 0.7 which, using Oke’s correlation, creates a maximum heat island intensity ($T_{\max}$) of 5.5 °C. However, it is clear that the variation in SVFs across the urban area is significant, ranging from approximately 0.9, equating to a $T_{\max}$ of 2.8 °C in the most open areas, to 0.2 in the deep courtyard spaces and narrow alleys, where $T_{\max}$ is 12.4 °C. For that range of SVFs the range of temperatures swings would be between 7 and 11 °C, which means that one in theory would expect a peak temperature difference of 4 °C to be available to the user. This compares with the 6.4 °C range measured in Cambridge. The theoretical figure of 4 °C excludes intermediate spaces because the graphical analysis technique cannot model open spaces under opaque roofs. Nor does it include an assessment of orientation or scale. A value of 4 °C can thus be taken to be significant in terms of thermal comfort, particularly as further diversity resulting from solar radiation and air movement have not yet been taken into account.

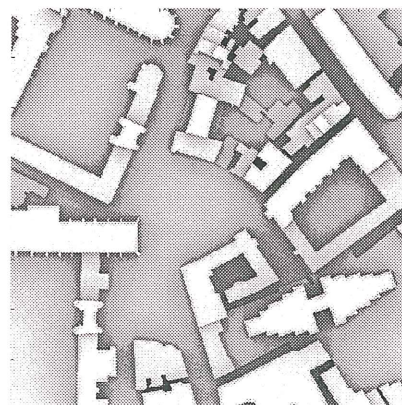


Fig. 4 Sky view factor distribution for a part of Cambridge.

Using a digital elevational model (DEM) of an urban

area it is a relatively simple procedure to project shadows for any time of the day and day of the year. Figure 5 shows the accumulated shadows for the site in Cambridge for a midsummer day. From the shadow casting image it is possible to show how many hours of sun any part of the urban area receives. In order to simplify the image one can generate contour maps, establish threshold values and from this define zones of predominantly sunny or shady conditions. Because solar radiation has a significant impact on thermal comfort as discussed earlier, the degree of availability of sun and shade as represented by a threshold value for hours of shade is a simple indicator of spatial diversity.

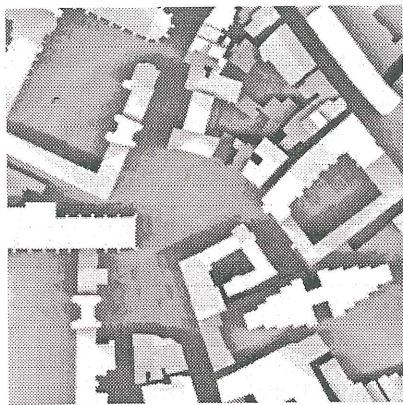


Fig. 5 Shadow casting on 22nd of June for the Cambridge site.

The final environmental parameter that is discussed is wind. In order to simplify the analysis for the purpose of demonstrating the notion of diversity, we have used the notion of wind shadows created by the sheltering effects of buildings. The length of the wind shadow is a function of the form and orientation of the building in relation to the wind direction. Because the wind direction changes we have used a wind rose to determine the frequency and direction of the wind in order to inform the relative 'intensity' of the wind shadow. Thus, a wind shadow generated by the prevailing wind direction will be more significant than a wind shadow created from a less significant direction. These overlapping shadows are then used to determine those areas predominantly still compared to those predominantly exposed to wind in order to produce an aggregated yet simplified map (Fig. 6). It would clearly be possible to produce much more detailed and time dependent wind analysis, using for example CFD (computational fluid dynamics) analysis. However, in this context our approach is used to demonstrate a methodology for deriving a diversity map which can

combine simple thermal, solar and wind parameters.

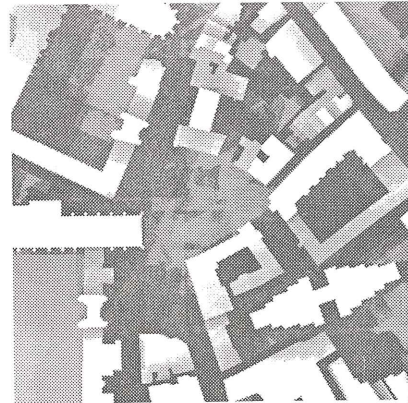


Fig. 6 Cumulative summer wind shadow casting for the Cambridge site.

The final stage in the mapping of environmental diversity is to overlay some or all of the notional maps of thermal, solar or wind conditions. For example, the combination of the solar and wind maps will indicate the relative amount of space that is: sunny and still; sunny and windy; shady and still; and, shady and windy. For the Cambridge site on a summer's day Figures 7a and 7b shows that the site has a predominance of sunny-still conditions: quite appropriate for the English climate, particularly as there is significant availability of still-shady as well as windy-sunny areas. For a climate which is temperate, the almost complete lack of windy-shady areas is not of great concern, but on exceptionally hot days, which are predicted to increase as a result of climate change, it may present noticeable limitations on comfort.

Remedial measures such as the introduction of shading and evaporative cooling from trees and water features will be a way of improving the situation. Additionally, one could conceive of enabling access to intermediate spaces with the appropriate thermal characteristics such as: high thermal mass, orientated to prevailing winds to encourage air movement, northerly aspects, etc.

The final figure shows the mapping of solar, wind and SVF (Fig. 8). SVF can be expressed as summertime resultant temperature swing and shows the more stable thermal environments (black areas have a lower T_{swing}) compared to those that follow ambient conditions more closely (higher T_{swing}). In the more stable environments, particularly the deep courtyards, the summer daytime temperatures have been measured as cooler than ambient, confirming the presence of urban cool islands. However, night time temperatures in such occluded spaces are warmer than ambient and

adhere to the urban heat island intensity as defined by Oke.

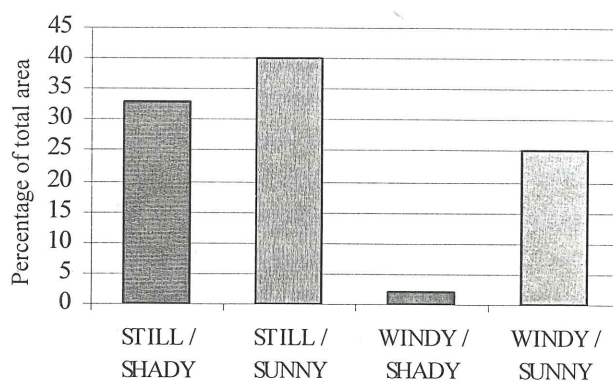


Fig. 7 (a) Diversity mapping of sun/shade and windy/still areas; and (b) chart of relative distribution of environmental characteristics

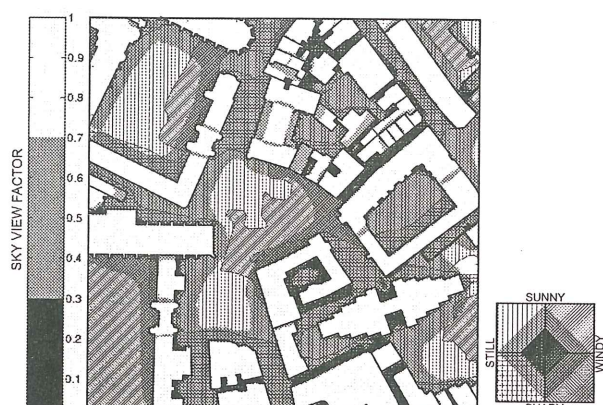


Fig. 8 Diversity map showing solar, wind and SVF/temperature characteristics of the Cambridge site.

Such environmental diversity maps can be produced for any site, climate or season in order to explore relative characteristics. The analysis can be more or less detailed, although the amount of information contained even in the relatively simple maps presented here is probably at the limit of practical value. The main purpose of such maps is to indicate the degree of environmental diversity as a function of urban form. The range and amount of diverse thermal conditions available will need to reflect the climatic and seasonal context. One might refer to 'appropriate diversity' where negative factors are reduced and positive ones are increased. For hot-arid conditions shade and thermal stability; in a warm-humid context wind and shade; for cold weather, sun and still conditions should predominate. Common to all climates or seasons is that there is an advantage in having an appropriate range of conditions available in order to increase choice.

The conclusion of this study is that there is limited value in defining or attempting to achieve optimum thermal conditions in the urban environment.

More importantly, the success of an urban environment can be assessed in terms of environmental diversity, both spatially and temporarily. The aim is thus to maximise appropriate diversity and thereby maximise choice in relation to the climate, activities and preferences of the user. This can be achieved by the manipulation of urban form.

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