The Micrometeorology of the Urban Forest [and Discussion]

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The micrometeorology of the urban forest

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Urban trees occupy a wide variety of habitats, from a single specimen competing in the urban jungle to extensive remnant or planted forest stands. Each is shown to produce distinct micro- to local scale climates contributing to the larger urban climate mosaic. These effects are discussed in relation to the radiative, aerodynamic, thermal and moisture properties of trees that so clearly set them apart from other urban materials and surfaces in terms of their exchanges of heat, mass and momentum with the atmosphere. Their resulting ability to produce shade, coolness, shelter, moisture and air filtration makes them flexible tools for environmental design.

1. Introduction

It is fair to say that the micrometeorology of the tree populations of urban areas has received scant attention. Meteorologists concerned with forests or built environments seem not to have considered the urban forest to be a target for basic research. There is little coordinated understanding based on field observation of meteorological processes or effects and hence the basis for physically sound modelling is not in place. This makes it difficult to address satisfactorily a growing demand for solutions to practical questions involving the use of trees to create more comfortable, safe, healthy and efficient communities.

This paper tries to bring together some of the scattered information available. It draws parallels between forest and urban 'canopies' and notes the importance of maintaining a sense of scale when studying the atmospheric interaction between trees and built environments. Because of the underdeveloped state of the subject there is considerable reliance on first principles.

2. The urban forest

Grey & Deneke (1978) stated that most cities are forests. Although this concept is surprising to most, Rowntree (1984) notes that if the definition of a 'forest' is that at least 10% of the land is stocked with trees (a threshold achieved by a basal area of 5.5 m^2 ha^{-1}† in the eastern U.S.A.) it is probably exceeded by 60–80% of the area of cities in temperate regions. It is also probably true for the majority of cities in the humid tropics. A review of the urban forestry literature shows that, except for some relatively arid regions, North American cities generally exhibit tree canopy coverage (plan area) of 20–40% on a city-wide basis. In many cases there are more trees in the city than its rural environs.

Urban trees are of diverse provenance. Some are remnant or at least derived from the pre-urban vegetation, others are planted or transplanted native or exotic species. Some grow without attention, others are intensively managed. They occur singly, in clusters, lines, strips (especially along road- and waterways), savannah-like parkland or in dense forest blocks.

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† 1 hectare (ha) = 10^4 m^2.

Intra-urban abundance of trees varies with land use. In typical North American cities the commercial core and industrial areas exhibit less than 10 % tree cover, residential areas have 15–40 % and parks 20–60 % cover. In this paper I consider the urban forest to be the complete assemblage of woody plants within and around cities.

3. URBAN CANOPIES

Just as the forest canopy layer is made of trees so the urban canopy layer (UCL) is composed of buildings and trees (Oke 1976). The analogy with a vegetation canopy is far from perfect but has provided a useful basis for conceptualization in urban meteorology and climatology.

Other than being large, trees and buildings share few characteristics of meteorological significance. Aerodynamically, buildings are true bluff bodies because of their impermeability, inflexibility and sharp edges. When exposed to airflow they create strong positive and negative pressure differences over their surface, leading to flow separation and vortex shedding. Trees are also good generators of mechanical turbulence but buildings have to be judged as more effective roughness elements. Radiatively, buildings are relatively simple when compared with trees. They are essentially opaque and monolithic, thereby precluding the need to consider transmission and internal radiative exchanges. The range of albedo and emissivity values is larger for buildings compared with vegetation. The thermal mass of buildings is vastly larger than the equivalent volume of trees, thereby providing a massive reservoir for heat storage and release. Moreover, because the building lacks the internal water supply and stomatal activity of trees, when dry it does not possess the thermal moderation imparted by evaporation. Both systems have a metabolic component. For the tree, photosynthesis is of little energetic impact but the associated physiological control is fundamental to its thermal climate. The ‘metabolism’ of the building involves anthropogenic heat release due to the activities of its occupants and the engineering controls necessary to maintain a comfortable interior.

These differences are very important, because they highlight the fact that the UCL is composed of dichotomous elements leading to very strong spatial variability of climates within the layer. This in turn dictates that horizontal interchange of energy and mass via radiation and convection (advection) is likely to be prevalent on all scales. It means that the environment for a tree in the urban canopy is very different from that in a conventional forest, and that there is considerable potential for trees to act as modifiers of the urban climate. I concentrate on the latter here.

Despite these obvious and marked differences between the primary elements of the building and urban forest canopies, the resulting urban canopy has sufficient similarities in general form to make analogies with forests appealing. Indeed, urban meteorology has borrowed theory and methods from the fields of forest and plant meteorology that are in a more advanced stage of development. Examples include the concept of the canopy itself, the use of tower-based micrometeorological techniques for evaluating areally averaged fluxes, methods for estimating heat storage in the canopy volume (cf. Stewart & Thom 1973), precipitation interception storage by the canopy (cf. Rutter *et al.* 1975), evaporation from a sparse heterogeneous system (cf. Shuttleworth & Wallace 1985), determination of the depth of roughness influence over arrays of tall roughness elements (cf. Raupach 1979: Garratt 1980) and the concept of canopy–airstream coupling (cf. McNaughton & Jarvis 1983). The best analogy for the urban canopy is probably with a dense savannah forest. The spaces between the primary elements are just as important as the elements themselves.

Scale is a very important consideration in urban meteorology (Oke 1984), just as Jarvis & McNaughton (1986) demonstrate for transpiration from vegetation. Here, the built analogues of the stoma, leaf, plant, canopy and region are the building, canyon, block (neighbourhood), land-use zone, and city (table 1). The concept of a discernible canopy probably only applies at the land use and city scales. Failure to recognize the role of scale in both forest and urban meteorology can lead to serious errors in the design of experiments, observation networks, model development, model validation and interpretation of results.

TABLE 1. SCALE CLASSIFICATION OF THE URBAN CANOPY[a]

unit	built features	tree features	climate phenomena	dimensions[b] H	W	L	scale[c]
1. building	building	tree, garden	wake, plume shadow	10	10	10 m	micro γ
2. canyon	street	avenue, boulevard, shelterbelt	street vortex, thermal climate, shade	10	30	300 m	micro β
3. block	city block, factory	park, wood	local breezes, cumulus, park cooling	—	0.5	5 km	micro α
4. land-use zone	residential, industrial, city centre	greenbelt, suburban forest	air quality and climate districts	—	5	5 km	meso γ
5. city	built-up area	urban forest	heat, humidity island, city breezes, smog dome, precip. modification	—	25	25 km	meso β

[a] Adapted from Oke (1984).
[b] Typical for city of one million inhabitants. H, height; W, width; L, length.
[c] Meteorological scales (Orlanski 1975).

4. STREET TREES

The isolated urban tree exists in a wide variety of habitats. It may be part of an urban parkland or garden underlain by other vegetation, perhaps even irrigated, or at the other extreme it may be in a street canyon or parking lot surrounded by dry building materials and having little obvious source of water. This latter case is very interesting but largely unstudied; the tree is potentially subject to several severe stresses due to water shortage, low humidity and both high heat and pollutant loading.

The daytime energy balance of an isolated street tree is illustrated in figure 1. Heat gain by the tree is particularly large because of three processes. First, the tree may receive large amounts of reflected short-wave radiation from the canyon walls and floor. Albedo values of urban material are larger than many anticipate (brick 0.20–0.40, stone 0.20–0.35, concrete 0.10–0.35, asphalt 0.05–0.20 (Oke 1987)). Second, the long-wave radiant energy input is greatly boosted. This is because of the screening out of part of the cold sky and its replacement by the considerably warmer surfaces of the buildings, plus the fact that all built surfaces are very much hotter than the tree. This more than compensates for the slightly lower emissivity of built materials. Third, although not always the case, it is possible for the air temperature in a street canyon to exceed the leaf temperature of the tree, subjecting it to the advection of sensible heat. This is micro-oasis-type advection and is likely to be most prevalent when the tree is well watered and able to keep leaf temperature moderate via transpiration.

The dissipation of this considerable heat load is fundamentally dependent upon the water balance and wind climate of the tree. Transpiration cooling will reduce the need for long-wave

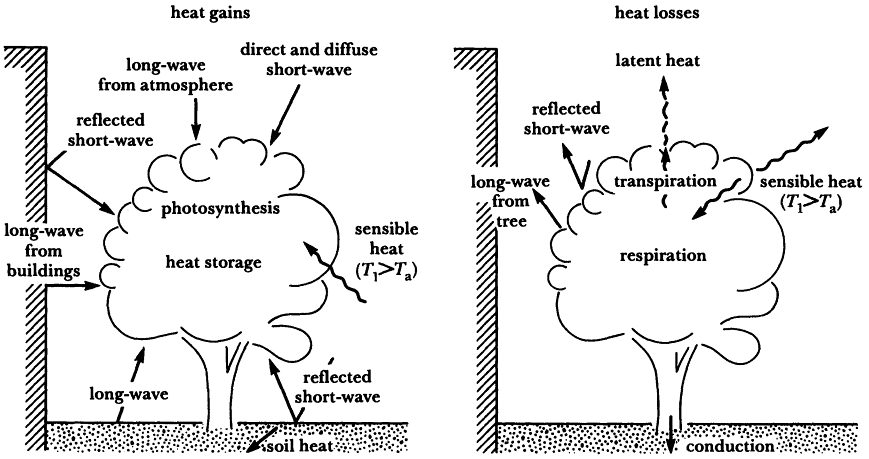

FIGURE 1. Scheme of the daytime energy exchanges between an isolated tree and its street canyon environment. (T_l, T_a, temperatures of leaf and air.)

emission and convective transfer of sensible heat. However, there are several factors that could act to limit water loss. First, water supply to the root system may be restricted. This is a major limitation in many instances. Second, the ground water may be contaminated (e.g. by road salts). Third, the stomata may be physically blocked by particulates or adversely reacting to gaseous pollutants. Fourth, the heat load may be so great that it leads to stomatal closure. Fifth, the wind shelter found in street canyons will reduce ventilation. On the positive side, it should be noted that there is often more soil moisture below 'impervious' urban surfaces than first anticipated. The sources include leaking water mains and sewers and excessive urban irrigation (Lerner 1988). Of course, although the outer leaves of the free crown may restrict transpiration by lowered stomatal conductance (leading to high leaf Bowen ratio values (Knoerr & Gay 1965)), those on the interior may continue to lose water at their lesser rate.

At night the reduced sky view, and the continued warmth of the buildings and street relative to the tree are likely to reduce the radiative energy loss compared with a tree in the open.

The climate of the isolated urban tree is deserving of study. The bewilderingly wide variety of environmental niches observed in the real urban case make modelling in combination with field validation attractive. Several urban canyon models are available to calculate the radiation and energy balance components at any location within the system (see, for example, O'Rourke & Terjung 1981; Arnfield 1982) and even the distribution of wind temperature, moisture and pollution (Sievers & Zdunkowski 1986). The output of these models could usefully form some of the input for models designed to calculate the radiation, water and carbon dioxide exchanges of an isolated tree (see, for example, Thorpe *et al.* 1978; Landsberg & McMurtrie 1984).

The impact of street trees on microclimate is a matter of considerable interest in urban design. Outside the meteorological community it is widely held that such trees exert significant effects on air temperature, humidity, wind, pollution and noise. The observed facts tend to confirm the sign but not the size of such expectations. For example, Herrington *et al.* (1972), Plumley (1975) and McGinn (1982) found little or no measurable effect on air temperature or humidity in the UCL. Widely spaced trees are also not very effective in providing shelter or noise reduction (Heisler 1977). Nevertheless, one must hasten to add that certain effects are important, but care must be taken to specify the scale and variable involved.

Lowry (1988) made a simple calculation of the transpiration cooling provided by a rather dense array of six trees, each with a leaf area of 25 m^2, placed along 10 m of a street canyon with a 10 m × 10 m cross section. Assuming an average leaf transpiration rate of about 70 W m^{-2} at midday and a canyon ventilation rate of 100 volume changes per hour, the resulting cooling rate is 0.3 K h^{-1}. For comparison, using the urban canyon observations of Nunez & Oke (1977) to characterize the sensible heat fluxes into a bare canyon (walls 25 W m^{-2}, floor 300 W m^{-2}) and the other conditions as before, gives a warming rate of about 1.0 K h^{-1}. The case in the real world is complicated by such features as the shading of the trees, oasis advection and the probability that much of the transpiration occurs from the top of the trees and doesn't mix throughout the volume, but the calculation helps to put the cooling effects in realistic perspective. A few saplings are certainly not effective; the case of large mature trees deserves detailed scrutiny. These conclusions should not be construed to deny the cooling effects of trees due to their shade nor to minimize the role of the cool foliage and shaded areas as radiant heat sinks for surrounding hot surfaces. Also, the collective impact of trees on heat fluxes at the mesoscale can be great (§6).

The use of trees in landscape design, especially to conserve energy use or to aid solar energy receipt by collectors on residential buildings, is well developed. In a full review, Hutchison *et al.* (1983) encapsulated recommendations for temperate climates in the statement 'provide shade from the summer sun, channel cooling summer breezes toward windows, allow winter sun to reach the structure and, particularly to penetrate Equator-facing windows, and provide protection from winter winds.'

The value of shade in summer is almost universal, but care is necessary in positioning the trees. Vegetation shading the east and west walls of a building is usually beneficial but the common practice of using deciduous trees on the equator-facing side can be negative. In warm climates the savings in summer air conditioning may be more than offset by increased winter heating needs, because leafless trees reduce the solar input by more than is appreciated generally (e.g. 30–45% on sunny winter days (Heisler 1986*a*)). Therefore it is important to consider the complete annual cycle. The economic value of shade trees in reducing cooling need, or the disbenefit of obstructing solar energy collectors, can be calculated for any given site configuration by using coupled models of tree shade and building energy use (see, for example, Thayer *et al.* 1983; Huang *et al.* 1987). Attention should also be paid to ensure maximum shade when planning the orientation, spacing and alignment of trees along avenues, walkways and parking lots.

The microscale shelter provided by trees is relevant to pedestrian comfort and safety, air pollution dispersion and energy conservation. In cold climates even small reductions of wind speed can provide welcome relief from wind chill. On the other hand denial of breezes in a hot humid climate can lead to stifling sultriness. Strong winds and turbulence, which may be augmented by the bluff body effects of buildings, can lead to problems with driving rain, blowing dust and snow, excessive loss of heat from buildings or water from plants and even cause damage to structures or buffetting of pedestrians.

Each application requires careful consideration. Tall shade trees open in the trunk zone may fit the need for comfort in tropical climates, whereas a dense, low hedge may protect from blowing sand. Clusters of woody plants around a house may reduce heat losses due to exposure to cold winds or interior to exterior leakage, but major shelterbelts may be necessary to protect from the hazards of strong winds. A solution that is geared to one problem may create another. For example, provision of shade by an avenue of trees may come at the expense of poorer air quality if the cross-canyon vortex circulation is hindered by the trees; in fact, they could act as a seal to the vehicle emissions if the canopy is very extensive. As already noted, the conflict between the positive influence of shade and shelter and the negative impact of reduced solar access, plus the role of climate in generating different energy demands, accounts for the fact that estimates of energy savings of trees vary from a 24 % saving to a 25 % increase in cost (Heisler 1986*b*).

5. Trees in parks

Considering the potential importance of parks in the urban climate, it is surprising how little research has been done beyond descriptive surveys of effects. Here I utilize first principles to deduce probable mechanisms in line with observation. I consider two simple cases: the 'garden park', which is the common recreational park with scattered trees (singly or in clumps) in association with grass or gardens, and the 'forest park', which is a dense wood.

During very light winds or calm at the meso- or synoptic scale a garden park establishes its own climate *in situ*. A review of results from park surveys in Mexico City (Jauregui 1973), New York City and Syracuse (Herrington 1977), London (Chandler 1965) and Montréal and Vancouver (T. R. Oke, unpublished results) covering parks from 29 to 500 ha suggests that the thermal pattern is usually most pronounced under the conditions that favour the largest UCL heat islands, i.e. calm, clear nights. The results in figure 2 show that under these conditions the nocturnal coolness of the park is established soon after sunset, following which the park and the urban area cool at similar rates. On the other hand, rural cooling rates are greater than those in the city in the first half of the night and equal or less in the second half. Results from the cities surveyed show temperatures inside the park perimeter are rarely more than 3 °C (more typically 1 or 2 °C) lower than in the surrounding UCL. However, a zone of larger influence often extends beyond the park, so the total impact is larger than these statistics first suggest (figure 3).

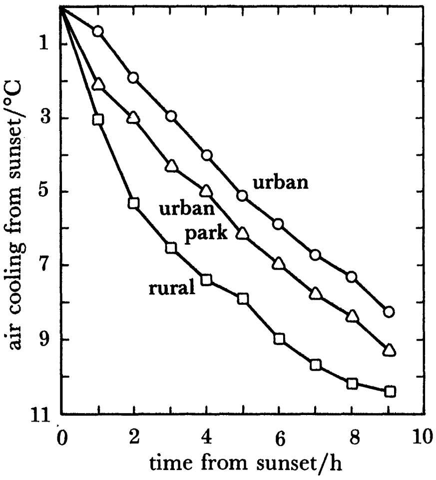

FIGURE 2. Cumulative cooling curves from urban (city centre), urban park and rural environments in Vancouver, British Columbia. Values are derived from automobile traverses on three near calm, cloudless nights in August 1971. Data for each environment are normalized to their respective sunset temperatures. The parks were 1.1 °C, and the rural area more than 5 °C, cooler than the urban centre at sunset.

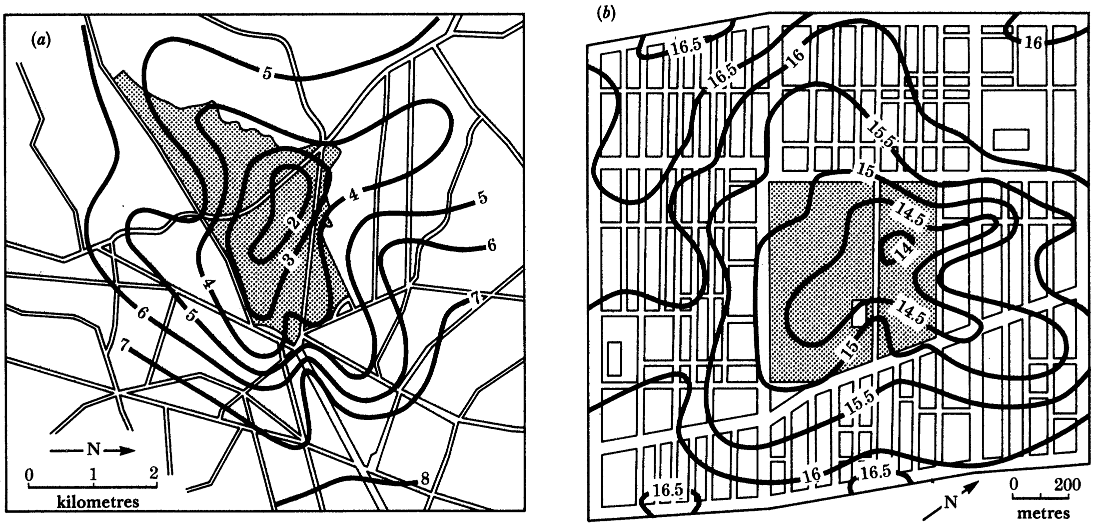

Figure 3. Distribution of near-surface air temperature (in degrees Celsius) in the vicinity of urban parks. (*a*) Chapultepec Park, Mexico City (500 ha) with calm cloudless conditions at 05h28–06h48 on 3 December 1970 (after Jauregui 1973). (*b*) Parc LaFontaine, Montreal (38 ha) with cloudless skies and winds of 2 m s^{-1} from the southwest at 20h15–21h15 on 28 May 1970 (Park area shaded).

These observations raise questions. Why is the within-park cooling not greater; why is it not similar to the rural case; and how does the park influence diffuse outwards? A hypothesis that fits most of these facts, but lacks field support, is that a large park induces a centripetal thermal circulation system. This was suggested by Whiten (1956) and Gold (1956) and implied by Wainwright & Wilson (1962) in relation to air pollution in the squares and parks of London, rather than the thermal evidence presented here. I envisage a thermally induced pressure gradient leading to a divergent outflow of cool air at low level (park breezes) and subsidence over the park. The circulation should be completed by ascending air over the surrounding warmer city and convergence over the park. The park breezes explain the outward diffusion of cool air from its source (figure 3). The continual supply of warmed urban air from above could explain the apparent upper limit to an urban-park temperature difference and the fact that park cooling is tied more closely to that of the city than of the rural area (figure 2). The circulation will also depend on vertical stability. This explains why Wainwright & Wilson (1962) found the rate of pollutant dilution was better explained by lapse rates than wind speed.

The primary process responsible for the park cooling is not simply explained. Parallels between urban-park, and urban-rural thermal differences in the near-surface layer make it appealing to refer to the causes suggested for the heat island of the UCL (see, for example, Oke 1982). The nocturnal timing of the maximum differential suggests that the relative failure of the urban system to cool is just as important as any special park cooling mechanism, and tends to downplay the role of evapotranspiration. Nevertheless, it is wise to await process studies before assigning energetic causes.

With moderate winds the park cooling is displaced towards the downwind edge and into the downstream neighbourhood. In Montreal (figure 3*b*), which has wind speeds of 2 m s^{-1}, the effect extends several hundreds of metres. This could be welcome relief to residents during a heat-wave. Nocturnal cooling of only a few degrees can be critically important to high-risk groups such as the elderly (Clarke & Bach 1971). The transport of the cooler air into the downstream neighbourhoods is probably both by simple advection down along-wind streets and by turbulent mixing from above (i.e. from above-roof level via the cross-canyon vortex). The latter is suspected because cooling was also observed along the length of streets aligned normal to the wind direction and located several hundreds of metres from the park. With wind speeds greater than 6 m s^{-1} the cooling effect was negligible in Montréal.

The near surface (sub-canopy) microclimate within a forest park is likely to be very similar to the natural forest, except for 'edge-effects' along the stand borders. These might include 'clothesline'-type heat advection (Oke 1987, p. 159) and pollution filtration as warm, dry, polluted air flows into the upwind border. On days with weak large-scale flow, a park–city centripetal breeze system should develop. Thermal contrasts both within and above the respective canopy layers dictate cool forest breezes emanating from the park by day and night.

The meteorology of urban parks deserves more study. Urban planners seek answers to many pertinent questions: what is the minimum size of park to impart significant climate benefit; is there an optimal size; are many small parks better than one large one; what is the best mix of trees and other vegetation? The answers are likely to depend on many factors (e.g. macroclimate, city morphology), making it unwise to extrapolate from descriptive case studies. What is needed is a comprehensive understanding of the underlying mechanisms, especially the energy and water balances, and the three-dimensional wind field, so that valid conceptual and numerical models can be constructed for application to specific built environments.

6. The urban forest

The spatially integrated conditions at the top of the UCL form the 'surface' boundary for the overlying urban boundary layer (UBL). It includes turbulent surface and mixed layers and may exhibit several internal boundary layers in response to distinct land-use zones (e.g. suburban, industrial). It is therefore a regional or mesoscale phenomenon (units 4 and 5 of table 1).

The assemblage of buildings and trees in a city creates a very rough surface. Typical values of roughness length for most urban terrain are of the same order as those for forests, say 0.5–5.0 m (Oke 1987, pp. 57 and 298). The introduction of tall trees to a single-family residential area usually increases its roughness, and deciduous trees create a seasonal variation with greater roughness when the trees are in leaf. Seasonal leaf change can also alter the roughness environment by removing some existing scales of geometric regularity (streets are lined by trees of similar height to the houses), establishing new regularities (tree lines taller than the houses) or creating irregularities (scattered tall trees and clumps in an otherwise uniform array of buildings). Presumably controls such as these are responsible for the otherwise conflicting results of Peschier (1973) and Clarke *et al.* (1982). The former show reduced variability of roughness with wind direction in summer whereas the latter indicates the reverse.

The combination of mechanical effects due to roughness, and thermal effects due to the heat island, create a highly turbulent atmosphere in the city on most occasions. This greatly facilitates the turbulent transfer of heat, mass and momentum. The presence or absence of vegetation is important for the dry deposition of pollutants in the city. Fibrous elements such as trees behave differently from bluff-rough bodies such as buildings. The processes acting at the mesoscale may, however, be counteracted by a wide range of microphysical processes acting immediately at individual surfaces. In general, it seems that vegetation surfaces are likely to be preferred sites for deposition (Hicks & Hosker 1987).

Intra-urban variation of radiation exchange is remarkably limited considering the wide range of surfaces found at the microscale. In a survey of Hartford, Connecticut, Brest (1987) reports ranges of monthly albedo from 0.085 to 0.117 for urban, and 0.114 to 0.156 for suburban, land classes in snow-free conditions. The averages for many cities are 0.14 for urban, and 0.15 for suburban, areas (Oke 1988). These values are quite similar to those of trees and hence in the mean their effect on albedo may not be large. Vukovich (1983) even notes that Forest Park in St Louis exhibits no difference in reflectivity (0.5–1.1 μm band) to its suburban environments. In the Hartford study, tree vegetation (deciduous and evergreen) values covered the range 0.093–0.177. Non-tree vegetation is potentially more important in altering spatial averages (Hartford values 0.078–0.203). In cities where the albedo of the trees and built elements are very different, or when snow lies on the ground but not on trees, the role of tree cover in producing spatial variation of urban radiation fields can be more significant than the preceding remarks suggest.

Given that surface emissivity is not thought to show great variability in cities (Oke 1988), the emission of long-wave radiation is largely determined by the surface-temperature distribution, and this is known to be strongly affected by tree cover and vegetation in general (see, for example, Carlson *et al.* 1981; Vukovich 1983; Roth *et al.* 1988). All studies stress that urban-rural and intra-urban surface temperature contrasts are greatest by day (the opposite of air temperature; see § 5) and in the warm season. Urban greenspace is relatively cool by day and night, thereby reducing its emission of infrared radiation.

Therefore we find that, although on average trees probably absorb slightly less solar radiation than built surfaces, they also emit less. This offsetting feature is a common attribute in the urban system leading to remarkably little spatial variability of net all-wave radiation. White *et al.* (1978) found less than 10% variation of net radiation across St Louis if water bodies were neglected, and closer to 5% if industrial areas were omitted (see also Oke (1988) and table 2).

TABLE 2. ENERGY FLUX DENSITIES AND HEATING RATES FOR DIFFERENT LAND-USES

	rural	suburban	urban	urban (bare)
green:built	100:0	50:50	15:85	0:100
energy/(W m^{-2})[a]				
$Q^* + Q_F$	535	554	546	530
Q_{HO}	150	216	240	370
Q_E	305	216	158	0
ΔQ_S	80	122	148	160
heating rate (K h^{-1})				
sensible heating	0.5	0.8	0.9	1.3
evaporative suppression[b]	0.9	0.7	0.5	0
net change[c]	−0.8	−0.6	−0.5	—

[a] Oke (1988); Q^*, net radiation; Q_F, anthropogenic heat; ΔQ_S, sub-surface heat storage, Q_{HO}, surface turbulent sensible heat; Q_E, turbulent latent heat.

[b] Thermal equivalent of energy used in evaporation which would otherwise contribute to turbulent warming.

[c] Difference from bare city case.

It is the hydrometeorological role of the urban forest that commands most attention. The fundamental problem in urban hydrology is storm runoff. Urbanized watersheds generate extremely large volumes of water very rapidly. Trees and other vegetation provide some short-term interception storage on their foliage, and because they occupy pervious sites, they provide a route to longer-term soil or ground water storage. In an emergency, parks and other stands of trees may provide a means of temporary retention of floodwater. All of these features help mitigate flood hazard. The other major hydrometeorological role of urban trees is their ability to act as conduits for water loss to the air. The mass and energy fluxes associated with transpiration are important controls on the moisture and thermal climate of the UBL.

Research in the past decade has demonstrated that cities are not the 'deserts' they were once thought to be. The urban forest, together with other greenspace (some irrigated) and a variety of smaller sources, provide a significant flux of water and latent heat to the UBL (for reviews see Oke (1982, 1988)). The results in figure 4 give an idea of the range of evapotranspiration experienced in a suburb of Vancouver (*ca.* 60% of greenspace, including 5–10% trees) in summer. Even in a very dry year, such as 1978 when soil water potentials in unirrigated grass were as large as -3 MPa, evapotranspiration continued at rates greater than one third of the equilibrium value. Irrigated gardens and trees tapping deeper soil water are probably the main sources. In more normal conditions evapotranspiration hovers around or just below the equilibrium value ($\alpha = 1$). When the system is saturated but energy availability is limited (e.g. cloudy after persistent rainfall), the maximum rate is close to the Priestley–Taylor potential value ($\alpha = 1.25$–1.30). However, when the suburb is well supplied with water and energy input is high, evapotranspiration can be remarkably large. For example, in 1980

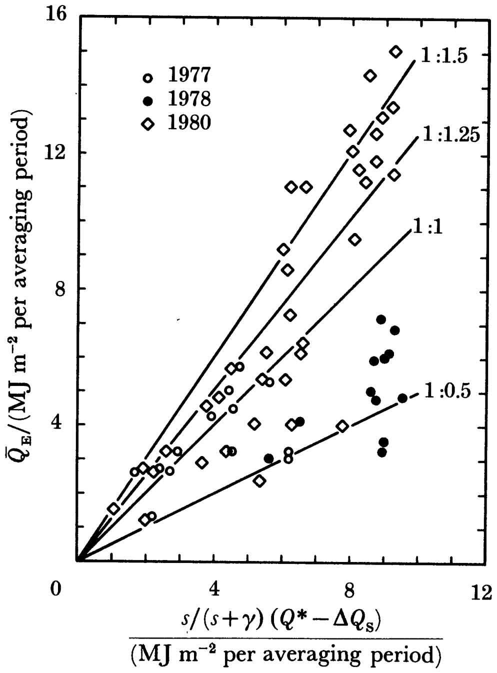

FIGURE 4. Measured daytime total evapotranspiration (ordinate) and its relation to the energy term of the combination model (abscissa) for a suburban site in Vancouver, British Columbia; sloping lines represent different values of the Priestley–Taylor parameter (α) s, slope of saturation vapour pressure versus temperature curve; γ, psychometric constant; Q^* and ΔQ_s, see table 2.

Vancouver was subject to alternation of rainy and sunny days, and on the latter values for α of up to 1.8 were encountered (figure 4). Such enhanced water loss may be the result of the evaporation of intercepted water from tree foliage and advection of sensible heat from impervious surfaces creating micro-oases. Shuttleworth & Calder (1979) reported similarly large values of α for forests.

The collective effects of vegetation on air temperature at the mesoscale are illustrated in table 2. Typical values of surface heat fluxes from a review of field observations are used to derive heating rates in a column of air. Calculations assume a dry convective mixed layer with no advection and a constant depth of 1 km. Sensible heat is input from the surface and by entrainment from a capping inversion. The relative impact of latent heat 'cooling' is compared with a hypothetical 'bare' city. It is clear that the rate of heating declines with greenspace; evaporative suppression is of the same order as the heating; and differences from the 'bare' city are large enough to generate significant intra land-use thermal differences.

Models of the UBL potentially provide a means of assessing the impact of different urban forest covers upon the atmosphere. McElroy (1970) used a cross-sectional steady-state numerical model to simulate the nocturnal thermal structure over a city, and found good agreement with observations over Columbus, Ohio. To study the effect of greenbelts he first simulated

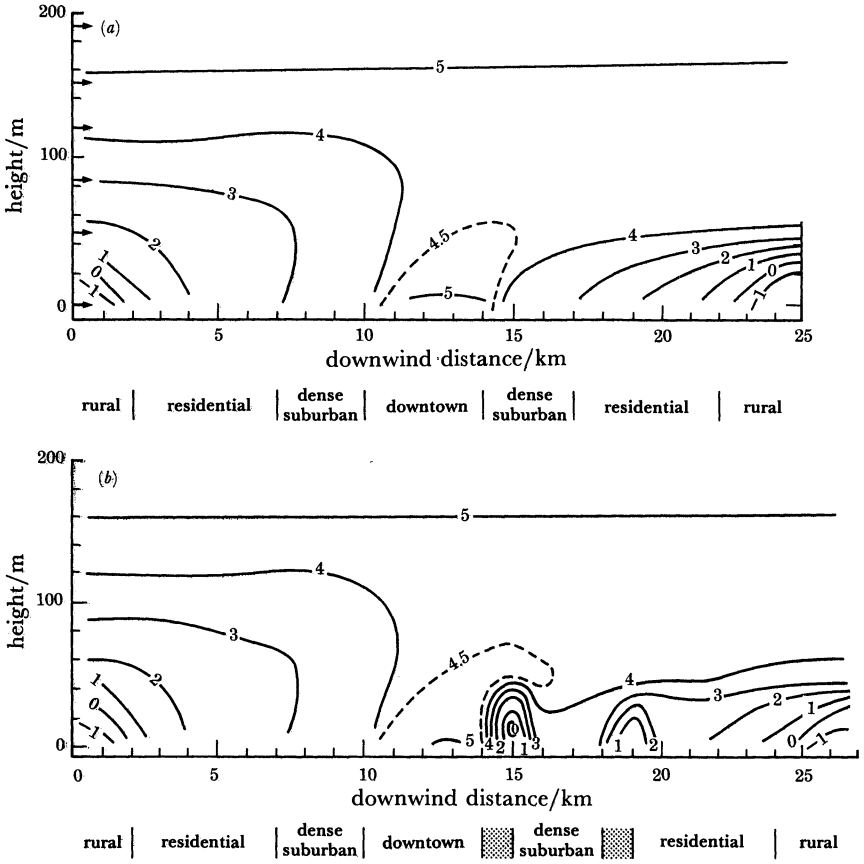

FIGURE 5. Simulated cross-section of nocturnal air temperature (in degrees Celsius) across a hypothetical city using land use, meteorological and other data for Columbus, Ohio. (*a*) Using actual conditions for 23 March 1969 near sunrise. (*b*) As for (*a*) except 1 km wide greenbelts added as indicated by the shading (after McElroy 1970). (Arrows on vertical axis of (*a*) indicate model grid spacing.)

temperatures across an hypothetical symmetrical city by using the observed Columbus data as boundary conditions (figure 5*a*). In a re-run greenbelts were added. They produced marked cooling but the effect remained localized, both horizontally and vertically (figure 5*b*). Unfortunately, the model was not extended to simulate the daytime thermal structure.

In their study on the role of vegetation in reducing cooling loads on residences in cities in the southwestern U.S.A. Huang *et al.* (1987) combined a simple expression for evapotranspiration and an advective mixing height model to calculate air-temperature effects associated with different amounts of tree cover. Adding a further 10–25% tree cover gave predictions of marked decreases in air temperature in some cities sufficient to suggest that important savings in energy use would accrue.

It must be noted that the potential value of UBL models is severely handicapped by the crude way in which evapotranspiration is handled. Ross & Oke (1988) concluded that none of the three models they tested against observations were able to simulate this essential term in the energy balance.

The movement for increased tree coverage in many cities is met by those who question whether the effects are all beneficial. Heat islands are not necessarily a negative attribute. Some argue that reduced sensible heat fluxes may decrease the strength of convective mixing and lower the depth of the UBL, thereby reducing dispersion. It is also suggested that smaller heat island intensities and increased vertical stability will weaken the centripetal city–country breeze circulation. This gives ventilation when it is most needed.

7. SUMMARY

Trees are important but little studied components of the urban canopy. They are responsible for distinct meteorological and climatic effects at all scales in the city. Knowledge of these effects can, and is, being used at the micro-scale to aid in building design. However, evidence of understanding and applications decline as the scale increases from the street canyon to the park, land use and city. There is scope and need for carefully designed research to improve knowledge in a field that seems to have lapsed between the interests of urban and forest meteorology.

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Discussion

J. M. Crowther (*Department of Physics and Applied Physics, University of Strathclyde, U.K.*). There is interest in various parts of the world, particularly in the Middle East and some parts of the U.S.A. in using belts of trees to try to reduce the effect of sand storms and dust storms on urban areas. Is there any observational evidence as the the effectiveness of these measures?

T. R. Oke. I am aware of the interest in the areas you mention as well as in northeastern China and Australia. A review of problems caused by aeolian processes and some suggested solutions are given by Cooke *et al.* (1982). The literature is almost silent, to my knowledge, on the question of assessing the effectiveness of such historical measures as the extensive shelterbelts around Beijing. There is also interest in the question of containing drifting snow.

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K. G. McNaughton (*Plant Physiology Division, Department of Scientific and Industrial Research, New Zealand*). Urban trees are there primarily to improve the comfort of city dwellers, so an appropriate measure of the effectiveness of the urban forest may well be the comfort indicies for people. Has Professor Oke considered this?

T. R. Oke. The text of my paper makes some reference to human bioclimate implications of urban trees. Comfort is a difficult state to define. An unpublished study we did in Vancouver showed that physiological comfort of pedestrians was best in shaded central city canyons and worst in exposed open grassed parks on hot summer days, but psychological comfort was worst in the city canyon because of factors such as glare, noise and air quality.

J. L. Monteith, F.R.S. (*International Centre for Research into Crops for the Semi-Arid Tropics, Hyderabad, India*). Would Professor Oke comment on the adverse effects that trees may have in tropical climates (i) by humidifying (as well as cooling) the air; (ii) by reducing the ventilation of houses round which they grow? (I lived recently in a flat-roofed house surrounded by tall eucalyptus where the maximum surface temperature was 85 °C!)

T. R. Oke. Yes, of course the increase in humidity has negative implications for sweating in human thermoregulation in hot, wet climates, and reduced turbulent transport may result in unacceptably large heat loads on organisms and buildings in all hot climates. These examples serve to highlight the danger of promulgating universal 'solutions' on the basis of limited experience. Each application requires intelligent evaluation. A study in Kuala Lumpur (Sham 1987) found a positive influence on a measure of human comfort (involving dry- and wet-bulb observations) because of shade trees. However, a fuller analysis of pedestrian energy budgets, including ventilation, would be desirable. Because of sun–earth geometry roofs are extremely important in tropical building climate. Therefore shade trees should be tall and have a broad enough canopy to shade the roof as well as the walls, otherwise the accompanying loss of ventilation will lead to the oppressive conditions Dr Monteith describes.

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B. Gardiner (*Forestry Commission Northern Research Station*, *Midlothian*, *U.K.*). Professor Oke mentioned that trees in an urban environment may have a modifying effect on pollution and also that trees increase evaporation. It is my understanding that in some cities such as the dry American southwest this increased humidity promotes the growth of haze particles, which can produce a reduction in visibility. Is this his understanding?

T. R. Oke. Yes, the potential for increased haze accompanies increased urban evapotranspiration, although I am not aware of the specific case to which Dr Gardiner refers. There is also the possibility that the extra natural hydrocarbon releases from the urban forest can exacerbate production of oxidants. There is evidence to suggest that summers with particularly high ozone concentrations follow relatively wet winters in areas of southern California. The stimulation of tree growth in this otherwise semi-arid area has been cited as a major contributor.