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The energetic basis of the urban heat island

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1. Introduction

The development of scientific enquiry into a natural phenomenon may be expected to follow a sequence such as the following:

	① Recognition and description of the phenomenon	→	② Linkage (e.g. statistically) of the feature to other factors
→	③ Study of processes causing the phenomenon	→	④ Construction of process-response models to predict behaviour of the phenomenon

In such a framework the field of urban meteorology may be judged to be at an early stage and to be evolving in a rather unbalanced fashion. The literature of the past 150 years is replete with studies of 'urban effects' carried out at levels 1 and 2. Usually they are concerned with simple description or statistical analysis based upon empirical evidence from a single city. With the exception of a very few notable studies, attention to the processes (i.e. the causes underlying the observed effects) and to physico-mathematical modelling has been restricted to the past decade. Of course it is not expected, nor indeed may it be desirable, that research in a field should progress in a simple manner through the sequence 1–4, but two important points should be evident. First. as time progresses the bulk of research in a field should move to higher levels of enquiry. Second, the predictive power of process-response models is limited by the extent to which the processes are understood.

Some special difficulties have contributed to this unsatisfactory state of the field including:

(1) the inherent complexity of the city-atmosphere system. The atmospheric state is a response to exchanges of energy, mass and momentum covering a wide range of space and time scales; in urban areas the sources and sinks for these exchanges are located in an extremely heterogeneous fashion and involve significant anthropogenic as well as natural factors;

(2) the lack of clear conceptual/theoretical frameworks for enquiry especially in the light of the complications placed upon conventional theory by (1);

(3) the expense and difficulty of observation in cities. Commonly one must deal with conditions within a relatively large volume of air (typically 10^2 to 10^3 km^3) containing significant spatial and temporal variability thereby creating sampling problems. Moreover there are restrictions on the use of observation systems (towers, aircraft, balloons, acoustic radar) not normally encountered in uninhabited terrain.

Here we will use the example of the urban 'heat island' effect to illustrate the state of urban meteorological research. This will include a condensed review of our understanding of the qualitative features of heat islands and their relation to meteorological and urban factors (levels 1 and 2); a summary of the results of recent research into urban energy and mass exchanges (level 3); and a first attempt to relate these energetic causes to their thermal effects (level 4), albeit under rather simple circumstances.

2. The nature of urban heat islands

Luke Howard was the first to provide evidence that air temperatures are often higher in a city than in its surrounding countryside (Howard, 1833). In the interim this fact has been demonstrated beyond doubt and the characteristics of this urban heat island effect have been documented for many villages, towns and cities (for a fairly complete listing see Chandler 1970, 1976 and Oke 1974, 1979). Based on this body of information it is now possible to draw some generalizations.

For the purposes of this paper such generalization will initially refer to the features of the screen-level heat island in a large temperate-climate city (population $\geqslant$ 100 000), located on flat open terrain, during a fine (cloudless skies and calm or very light winds) summer day. Later we will relax these constraints to show the vertical extent of the heat island and mention the effects of geographical location, city size, weather, season and climate.

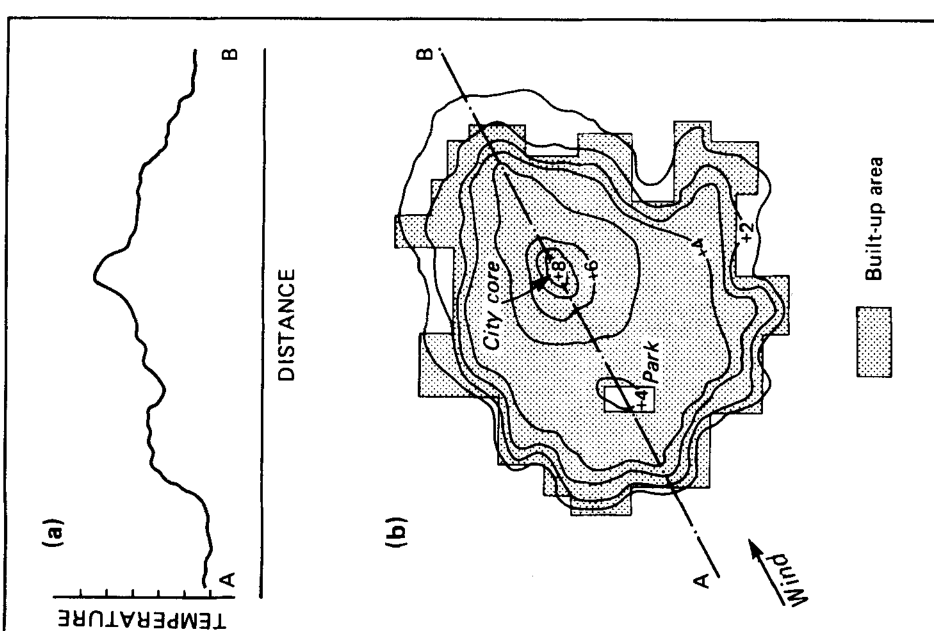
This division conforms to the concept of two distinct layers (Oke 1976): one, called the urban building or 'canopy' layer (UCL) extends from the ground up to about mean roof level, rather like a vegetative canopy layer; the other, called the urban boundary layer (UBL), is a mesoscale internal boundary layer whose characteristics are determined, at least partially, by the presence of the city beneath. This conceptual division has been given observational support recently (Taesler 1981).

(a) *The near-surface heat island under 'ideal' conditions*

Figure 1 depicts in idealized form the spatial and temporal features of urban and rural screen-level air temperatures giving rise to an urban heat island under the conditions specified above. The temperature cross-section and isotherm map in Figs. 1(a) and 1(b) respectively illustrate a number of common features of heat island morphology. Assuming the surrounding topography to be of minor significance the 'island' protrudes sharply above the background rural temperature field. The 'cliff' to the 'island' is especially marked on the windward urban/rural boundary and fairly closely follows the outline of the built-up area for much of the city perimeter. Most of the rest of the urban area is characterized by a much slacker horizontal temperature gradient but is interrupted by warm or cool spots associated with localized areas of anomalously high or low building density. A park or lake might be relatively cool whereas an industrial area, an apartment complex, a shopping node or the central city area might be relatively warm. With a light wind these thermal features may show evidence of being advected slightly downwind of their source areas. Similarly, the warmth of the city may be carried into rural areas to the leeward and the 'cliff' on that side may be less distinct.

Time-dependent aspects of the phenomenon are illustrated in Figs. 1(c) to (e) where 'rural' air temperatures represent the background values of the countryside around the city and 'urban' the highest sustained (usually city centre) values of the urban area. In a causal sense urban/rural energy balance and stability differences produce different rates of near-surface warming and cooling (Fig. 1(d)), giving rise to distinctive diurnal air temperature régimes (Fig. 1(c)), whose differences at given times define the urban heat island intensity, ΔT_{u-r} Fig. 1(e).

The rural sequence is a standard one. At about sunset there is relatively rapid cooling (typically 2 to 3 °C h^{-1}) as the surface experiences a net radiative energy drain and withdraws heat from the shallow layer of stable air immediately above it. As the surface temperature drops and the rate of radiative emission decreases, the cooling rate also declines (to about 0·5 °C h^{-1}) as the night progresses. As a result rural air temperatures at night exhibit



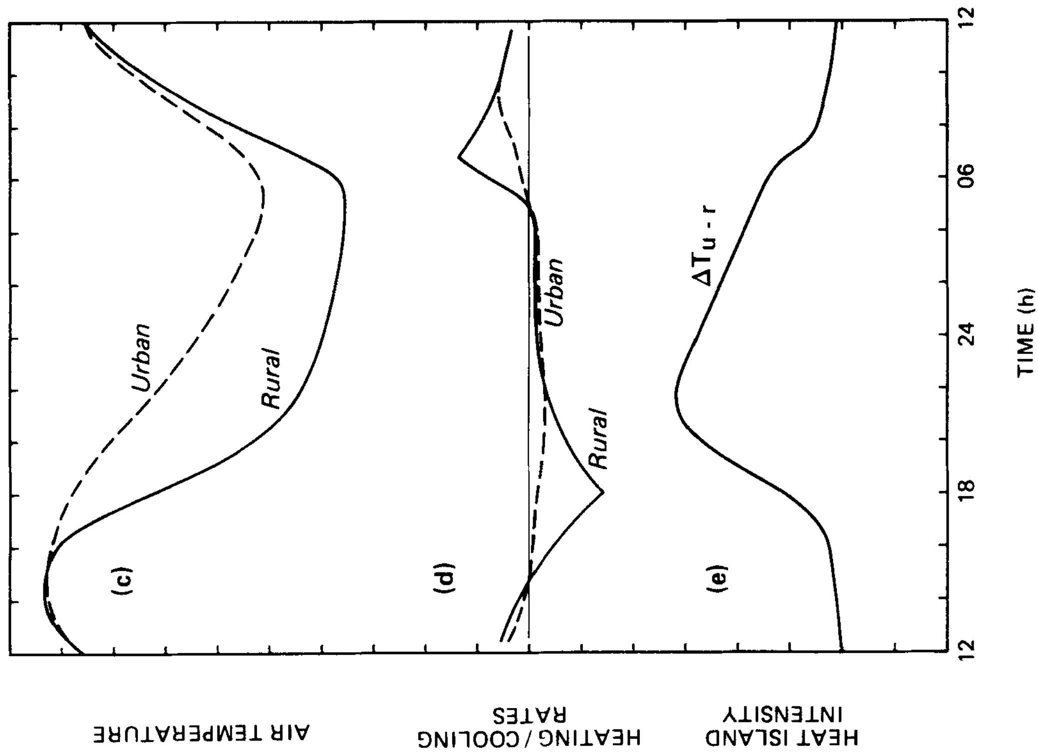


Figure 1. Hypothetical representation of the spatial and temporal features of the canopy layer urban heat island in a mid-latitude city with 'ideal' (calm, clear) weather. Spatial pattern (a) along cross-section AB and (b) in relation to the plan outline of the city. Temporal variation of urban and rural (c) air temperature (d) heating/cooling rates and (e) the resulting heat island intensity. Vertical scale units are approximately 2 °C for (a), (c) and (e) and 2 °C h^{-1} for (d).

a simple exponential decay curve until just after sunrise, when the pattern is abruptly interrupted by warming. Solar heating of the surface generates a turbulent sensible heat flux which converges in the surface layer, whose depth is limited by the remnant nocturnal radiative inversion above. As the mixed layer grows the rate of warming declines into mid-afternoon at which time the maximum temperature occurs.

Without at this point invoking any physical explanations it is clear from Figs. 1(c) and (d) that the urban régime is very different. Warming and cooling rates are generally smaller (except in the latter half of the nocturnal period) and noticeably lack the sharp peaks around sunrise and sunset thereby producing a damped diurnal temperature wave.

As a consequence of the above the heat island intensity undergoes a marked diurnal variation (Fig. 1(e)). Diverging rates of cooling between the urban and rural environments around sunset produce a sharp increase in intensity to a maximum a few hours (typically 3 to 5 h) later. Thereafter slightly greater urban cooling reduces the intensity until the early daytime rural heating virtually erases the heat island. In some cities there are even reports of slightly lower temperatures in the central area in comparison with the countryside ('cool' islands). Based on this account the spatial distribution of the heat island given in Figs. 1(a) and (b) obviously relates to the time of maximum intensity. The spatial pattern by day tends to be less well defined.

In summary, the canopy heat island is largely a nocturnal phenomenon attributable to urban/rural cooling (rather than heating) differences especially in the period around and following sunset. Its spatial pattern conforms closely to the distribution of surface cover characteristics. The very general features emphasized in this discussion are well illustrated by studies in individual cities: for examples of spatial features see Sundborg (1951); Duckworth and Sandberg (1954); Takahashi (1959); Chandler (1965; 1967) and Oke and East (1971); for temporal features see Chandler (1965); Hage (1975); and Oke and Maxwell (1975).

(*b*) *Vertical structure of the heat island*

The influence of the canopy heat island extends into the overlying atmosphere. If the 'ideal' constraints used in Section (a) apply, the thermal modification takes the form of a self-contained urban heat 'dome'. In reality, winds are unlikely to remain totally calm throughout the lower atmosphere for very long and hence the more normal form of the thermally-modified layer is that of an internal boundary layer, entrained in the direction of the wind (Fig. 2(a) and (b)). By day (Fig. 2(a)) the UBL increases in depth with time in accord with the growth of the rest of the mixed layer in the lower troposphere (e.g. Smith and Hunt 1978). Thus by mid-afternoon the UBL may be 0·5–1·5 km in depth, depending upon the strength of the surface sensible heat flux and the stability of the air mass. The presence of the city and its UBL may be evident by a slight doming of the normal mixed layer (by up to approximately 0·25 km, Fig. 2(a)) (Spangler and Dirks 1974). Downwind of the city the development of a new rural internal boundary layer leaves the urban-affected air aloft, as a heat 'plume', often extending for tens of kilometres.

At night, because of the usually well-developed heat island, the city retains a surface mixed layer whilst the surrounding rural areas have none, due to the presence of a surface-based radiative inversion (Fig. 2(b) and (c)). The stability of the rural air is eroded to a depth of 100–300 m (Fig. 2(c)) as it advects across the warm, rough city and again an elevated heated 'plume' is found in the lee (Clarke 1969; Oke and East 1971). A plot of the urban heat island intensity with height for the city centre (Fig. 2(d)) thus shows the heat island intensity to decline rapidly with height from its value at screen-level often becoming negative (rural warmer than urban) near the top of the UBL in the so-called 'cross-over effect' (Duckworth and Sandberg 1954; Bornstein 1968).

(*c*) *Other heat island controls*

Relaxing the constraints originally imposed on our discussion of the heat island we

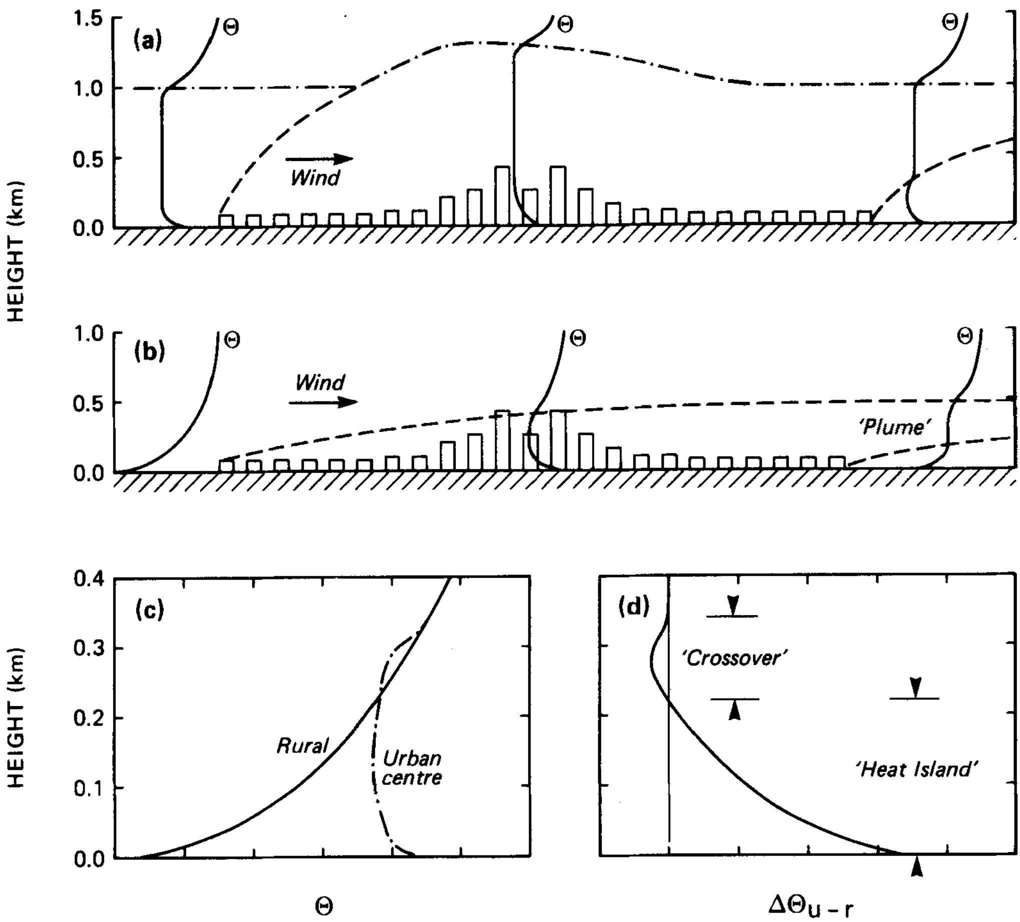


Figure 2. Generalized form of the UBL thermal structure in a large mid-latitude city during fine summer weather (a) by day, including schematic profiles of potential temperature (θ) and the depths of the urban and rural internal boundary layers (- -) and the daytime mixed layer (-·-) and (b) at night. Comparison of (c) rural and urban vertical temperature profiles and (d) the resulting vertical profile of heat island intensity in the city centre at night.

can note briefly the role of other controls. For example the geographical location of a city imposes a wide range of possible effects especially related to the presence of water bodies, topographic features, and the nature of the soils, vegetation and land use in the region. The combinations possible are almost as great as the number of cities and to some extent this explains the preoccupation with descriptive heat island studies described earlier.

Possibly more amenable to generalization than that for location is the relationship between heat island intensity and city size. Such relationships have been shown to exist (e.g. Fig. 3), but current interest lies in an elucidation of the critical physical factors implicit in measures of 'size' such as population. Is the appropriate measure one of city diameter, which might be seen to be related to distance of fetch and therefore the accumulation of heat, or is it one of architecture, building materials or anthropogenic heat which might also be correlated with size? Similarly we wish to know why the European and North American P vs. $\Delta T_{u-r(max)}$ relationships are different.

Weather controls on the heat island have been studied in some detail. Statistical studies

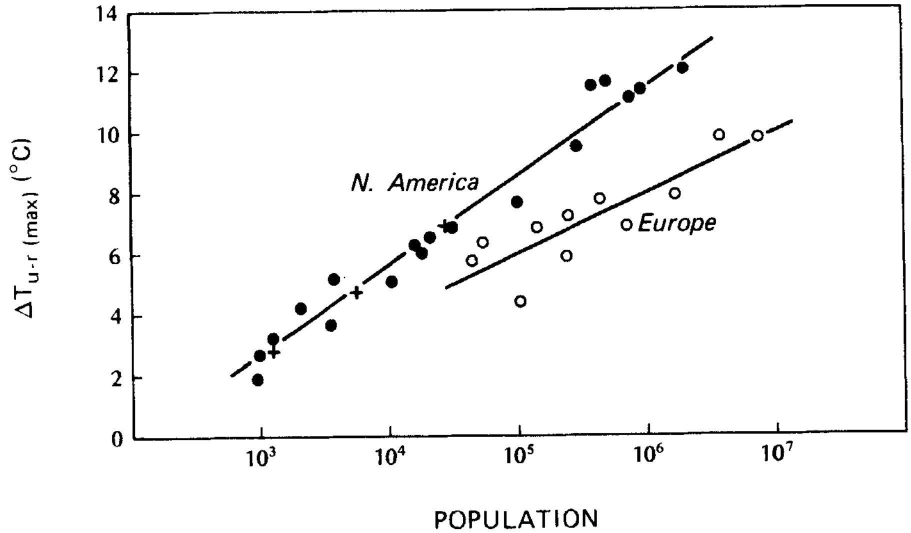


Figure 3. Relation between maximum heat island intensity ($\Delta T_{u-r(max)}$) and population (P) for European and North American settlements. The crosses are for the growing new town of Columbia, Maryland reported by Landsberg (1979). Figure modified after Oke (1973).

agree that the most significant meteorological variable governing heat island intensity is the wind speed and next is cloud cover (Sundborg 1951; Duckworth and Sandberg 1954; Chandler 1965). Closer study reveals that the wind speed relationship is non-linear (approximately inverse square root, Oke 1973) and that cloud type, as well as amount, is important since low cloud is more effective than an equal quantity of high cloud in limiting the heat island intensity. Wind and cloud are clearly surrogate variables related to the relative roles of turbulent and radiative transfer in producing temperature change. These roles are combined to some extent in the single variable of atmospheric stability, which has also been shown to bear a good correlation to heat island intensity (Ludwig 1970; Lee 1975).

In temperate latitude cities there is often a seasonal variation of the heat island with the greatest frequency of occurrence and greatest intensities being registered in the warmer half of the year, especially summer and autumn (Chandler 1965; Lee 1979; Unwin 1980). This is tied in part to the seasonality of the weather controls (wind, cloud and air mass stability) just discussed, but it probably also reflects variations in surface cover, such as snow and vegetation, and in solar influences, such as angle of incidence in relation to urban canyon geometry and attenuation by aerosols. The fact that the heat island is best displayed in summer, whereas peak heating requirements are in winter, may indicate that anthropogenic heat is not a primary cause.

Whilst there is a relative abundance of research on the nature of heat islands in temperate climates, there is a dearth regarding those of equatorial, tropical, sub-polar and polar settlements. In broad outline the results available from low latitude cities bear a resemblance to those discussed previously (Tyson *et al.* 1972; Daniel and Krishnamurthy 1973; Jauregui 1973), but at high latitudes the picture is altered by the seasonally extreme radiation climate. In winter there is little or no solar radiation input so the normal cycle of energy receipt is absent. It is replaced by a daily cycle of anthropogenic heat releases, related to human activities (especially space heating demand), to which the heat island is tied directly (Nicol 1976; Bowling and Benson 1978). The converse situation, involving continuous daylight in summer, has not been studied in detail but we may anticipate very little diurnal variation in the heat island. Observations in the spring and autumn transition periods show the heat island features to approximate the temperate case.

In summary, the urban heat island is a thermal anomaly having both horizontal, vertical and temporal dimensions, which has been observed in virtually all settlements, large and small, where it has been sought. In the mid-latitudes, where it has been most studied, its characteristics are found to be related both to the intrinsic nature of the city (e.g. its size, building density, land-use distribution) and to external influences (e.g. the climate, prevailing weather and seasons).

3. Urban/rural energy balances

The urban heat island effect clearly must be the result of urban/rural energy balance differences. This has been realized for many years yet we still await the first observational study to demonstrate this fact and to pinpoint the critical term(s). Here we suggest that if progress is to be made it is important not to confuse the two principal scales of urban meteorological enquiry, viz: the micro-scale characterizing exchanges and climates in the UCL, and the meso-scale of the UBL. However neither layer should be considered in isolation, since conditions in the UCL are often modulated by those in the UBL which, in turn, represents both an areal integration of UCL effects and its own intrinsic qualities.

We will deal first with the diurnal energy balance of a typical rural surface in the summer. This will be brief since it is well known, but is important, because it forms the basis of comparison for the surface energy balances appropriate to the urban canopy and boundary layers which follow. Discussion is limited to the case of a fine summer day in a temperate climate.

(a) *Rural energy balance*

The rural energy balance illustrated by Fig. 4 is well understood (e.g. Sellers 1965; Oke 1978a) as is its relationship to planetary boundary layer characteristics (e.g. Smith and Hunt 1978). The heat energetics of the system are driven by the surface net radiant flux density (Q^*) which is dominated by short-wave radiation exchange by day and solely due to long-wave radiation at night. The surface radiant energy surplus (deficit) is dissipated (supplied) by heat conduction to (from) the underlying soil (Q_G) and by convection of sensible and latent heat to (from) the air (Q_H and Q_E respectively). The actual sharing of heat between the soil and the air depends upon many factors including the nature of the surface, the thermal properties of the soil and the state of the atmosphere (especially the level of turbulence). A surface covered by short vegetation such as that in Fig. 4 apportions about 80–90% of the daytime radiant surplus to the air but, at night, the radiative deficit is balanced largely by conduction of heat from soil storage with only 10–50% drawn from the atmosphere due to the relatively suppressed state of turbulent activity.

The partitioning of the turbulent transport between the sensible and latent forms (Bowen's ratio, β) largely depends upon surface moisture availability. When the surface is wet, evapotranspiration is at the *potential* rate and is dependent only on energy availability and temperature (Priestley and Taylor 1972). When the surface is moist, rather than wet, the rate drops to about 80% of the potential value, a condition known as *equilibrium* evaporation where typical rural values of $\bar{\beta}$ (based on daily energy totals) are in the range 0·4–0·8. In the case of the irrigated crop in Fig. 4 Q_E is close to potential and $\bar{\beta}$ is about 0·3. Following a period of drying it is quite possible to find rural $\bar{\beta}$ values of 1·5 or greater in the mid-latitudes (e.g. Bailey 1977).

(b) *Urban canopy layer energy balances*

The myriad of surfaces present in the urban canopy layer make it impossible to draw generalizations. Every surface facet has a unique combination of both its intrinsic properties: radiative, thermal, moisture and aerodynamic, and those contributed by the rest of the surrounding site environment: radiation geometry, position in flow field, adjacency to

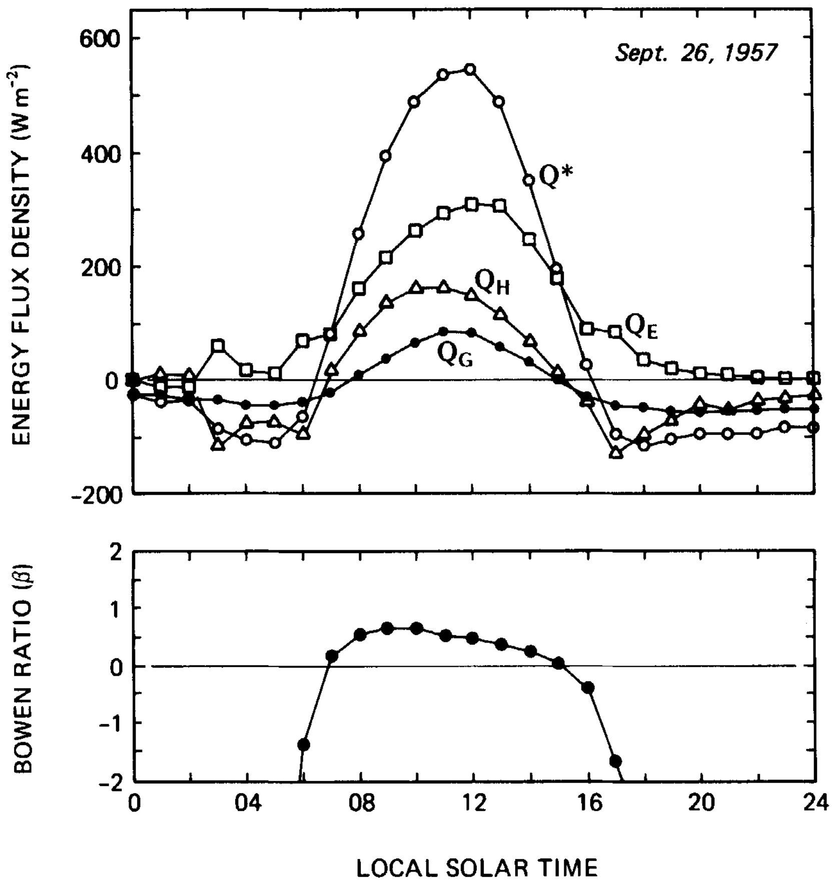


Figure 4. The diurnal variation of the energy balance and the Bowen ratio (β) of an irrigated field of grass at Hancock, Wisconsin (data from Tanner and Pelton 1960).

contrasting surfaces likely to contribute to advective interaction, etc. This produces an almost limitless array of energy balances and therefore microclimates. Despite this apparent chaos, there are studies concerning a few of the more dominant surface units including lawn (Oke 1978b) courtyard (Noilhan 1980) street canyon (Nunez and Oke 1977, 1980) parking lot (Landsberg and Maisel 1972) and road (Terjung *et al.* 1971) environments.

Any attempt to produce a climatic classification of these surface units would have to recognize moisture status (water storage capacity and surface moisture availability) to be the primary criterion. Storage capacity is important in that water retention provides a buffering or moderating influence, because gradual moisture depletion allows for evaporative cooling to extend over a period of days or more. On the other hand, impervious elements of the urban landscape experience an almost dichotomous wet/dry behaviour, wherein the climatic effects of rain may be present for only a few hours before run-off and evaporation dry the surface.

A surprisingly large proportion of the surface area of European and North American cities is occupied by vegetation (40–70%), especially in their suburbs. These surfaces are likely to have water storage capacities equal to those of rural areas and many of them are irrigated in summer (depending on climate, abundance of water supply and local custom), making water easily available to the atmosphere. Thus irrigated lawns, gardens, parks, golf courses, and cemeteries lie at one end of the wide spectrum of urban surface types.

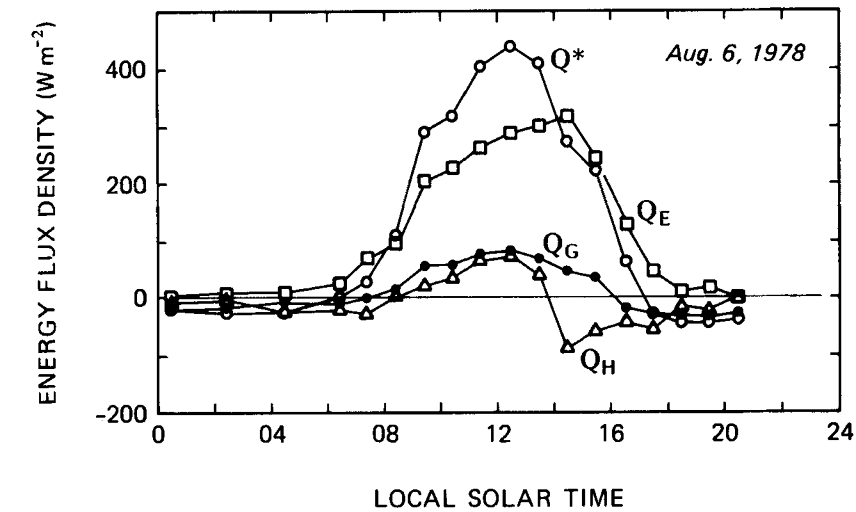


Figure 5. Energy balance of an irrigated suburban lawn (160 m²) in Vancouver, B.C. (after Oke, 1978b)

An example of an energy balance for just such a surface (an irrigated suburban lawn) is given in Fig. 5. The pattern is somewhat similar to that of the moist rural surface (Fig. 4) but there are significant differences. In particular Q_E can be seen to assume an even more dominant role in daytime energy use. Evapotranspirative losses exceed even the potential rate by about 30% on a daily basis. Probably this is made possible by the advection of warmer, drier air from surrounding impervious surfaces. They act as additional sources of sensible heat capable of forcing the lawn evaporation at a rate in excess of that supportable by $(Q^* - Q_G)$. Such an 'oasis'-type condition can persist only if the natural water budget is supplemented by irrigation.

As long as un-irrigated urban vegetation has available moisture it will also be in receipt of advective energy. Following rain such surfaces may be expected to behave like the lawn already discussed but their drying cycle is likely to be accelerated in comparison with non-advective rural vegetation.

At the other end of the spectrum of urban surface types are impervious areas: paved roads, parking lots and buildings. These systems are characterized by almost exclusively partitioning their radiant energy into sensible heat. They are the sensible heat source regions for the microscale advective interaction with moist areas. One very common arrangement of these relatively dry surfaces is the street canyon formed by a roadway between two adjacent buildings. This unit consisting of three active surfaces (the walls and floor) introduces the influence of geometry. Geometry is significant in a number of ways: for example, it increases the surface area exposed to exchange processes; it controls and complicates the spatial distribution of direct-beam solar radiation and precipitation inputs; it gives rise to radiative interaction between surfaces; it influences the loss of long-wave radiation to the sky and it controls the mean and turbulent flow structure. As a result, even for a single canyon constructed of materials possessing relatively uniform radiative, thermal, moisture and aerodynamic properties, the radiation and energy balance régimes of the component surfaces exhibit a great deal of spatial and temporal complexity. This is amply demonstrated by the results from an urban canyon given in Fig. 6. The canyon is oriented with its longitudinal axis in a north-south direction, has dry walls but a slightly moist floor and a height/width ratio of 0·86. Measurements were taken during fine weather with cloudless skies and light winds. In terms of geometric scaling and moisture availability, the canyon is probably a fair analogue of a street in the centre of a moderate-size city with a few scattered moisture

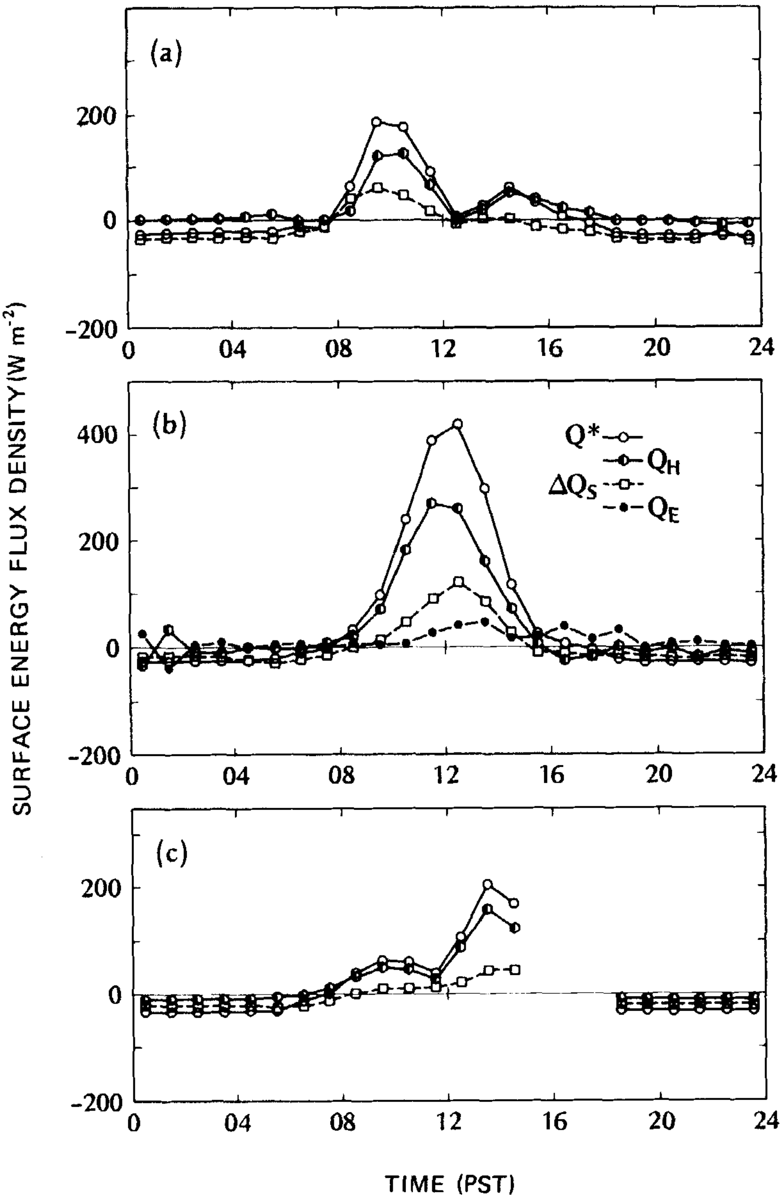


Figure 6. Energy balances for each surface of a north-south oriented canyon in Vancouver, B.C. (a) West (east-facing) wall, (b) floor and (c) east wall of the canyon. Data are averages for a 3-day period in September 1973 (after Nunez and Oke 1977).

sources (e.g. trees). The spatially-averaged energy balances for the three canyon surfaces in Fig. 6 show their primary peaks to occur at quite different times of day, due to differing times of maximum solar irradiance. The walls also show secondary peaks associated with reflection from the other wall, but overall the floor is the most active energy exchange surface. Note that, in absolute terms, the magnitudes of the energy flux densities are rather small (e.g. by comparison with the rural values). This is especially the case at night. By day this is primarily dictated by the lack of illumination of one or more surfaces due to horizon obstruction and the rather unfavourable angle of solar incidence on east and west

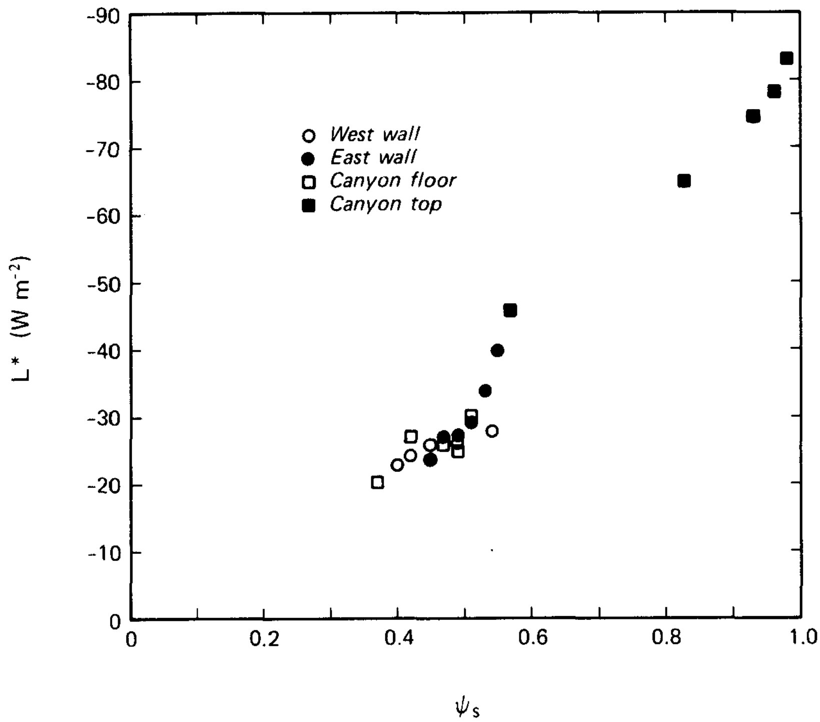


Figure 7. Relationship between net long-wave radiation (L^*) and sky view factor (ψ_s) for different positions around the perimeter of a canyon cross-section. Average results for two nights with cloudless skies and light winds in September 1973. Values of $\psi_s < 1$ at the canyon top are due to the walls being of different height (data from Nunez 1974).

walls. At night the low rates of radiative emission are largely a consequence of the reduced sky view factor (ψ_s) inside the canyon. (The sky view factor of a point is proportional to the area of the overlying hemisphere which is open to the sky). The relationship between ψ_s and net long-wave radiation (L^*) for different locations in the same canyon is given in Fig. 7.

When one considers that the complete UCL morphology is composed of such relatively simple canyons, having complex internal workings, as well as many others having totally different orientations to the Sun, wind and rain, different height/width geometries and different material properties, the situation becomes rather bewildering. On the other hand, some solace is gained from the evidence provided by the available canyon observations (Nunez and Oke 1977, 1980) and models (Terjung and Louie 1974; Terjung and O'Rourke 1980) which show that total canyon systems experience a relatively smooth diurnal energy régime. For example, the results in Fig. 8 show the integrated energy fluxes calculated to pass through the top of the canyon considered in Figs. 6 and 7. For each heat flux (Q) the conversion of fluxes from walls and floors to an equivalent flux through the top of a symmetric canyon is accomplished with

$$Q_t = 2Q_w(H/W) + Q_f$$

where H/W is the canyon height/width ratio and the subscripts t, w and f refer to the top, walls and floor respectively. In most respects the daily pattern of energy sharing shown in Fig. 8 is similar to that of a flat surface with a severely restricted water supply. One minor discrepancy is the rather short day length brought about by horizon obstruction. The daytime peak net radiation is very similar in magnitude, and the nocturnal values are only

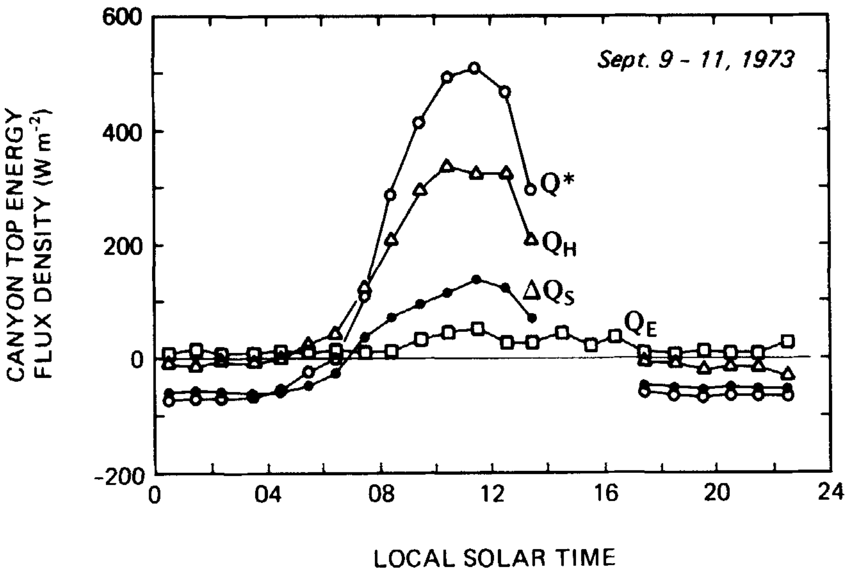


Figure 8. Energy balance of a complete urban canyon system. Exchanges are expressed as equivalent flux densities passing through the canyon top using mean hourly data for a 3-day period in September 1973 (after Nunez and Oke 1977).

slightly less negative, than those for typical rural surfaces (e.g. Fig. 4). Energy partitioning is predominantly into sensible heat. In the canyon studied, approximately 60% of the daytime radiant surplus is removed by the convective sensible heat flux and a further 30% is conducted into storage (ΔQ_s) by the canyon system. This gives a canyon β value of approximately 6 by day. At night, when turbulent activity is weak, almost all (approximately 90%) of the net radiative (long-wave) drain is drawn from storage.

Presumably, when dry, paved surfaces, such as roads and parking lots, dissipate radiant surpluses and make good radiant deficits purely by sensible heat transfer to and from the air and ground. When wet, they may evaporate water at at least the potential rate, but this is usually short-lived because of efficient run-off to sewers. Therefore, as mentioned earlier, the energy régime is probably of a rather 'flashy' nature but it should be recognized that there is the possibility that water storage in such materials has been underestimated (Lacy 1977).

The UCL energy balances considered have not explicitly included anthropogenic heat releases due to space heating, industrial operations or automobile use. If such heat releases enter the UCL (e.g. walls, windows, doors, vehicle exhausts, etc.) they may form an important, even dominant, component of the *local* energy balance but in general they are small (see the following section).

In summary, the UCL consists of a wide range of energy balance systems. Moisture availability is one of the key variables controlling local partitioning of daytime radiant energy. The range even includes the possibility that some surfaces may show no evaporation at a time when others are losing water at a rate in excess of potential. Site geometry is another crucial parameter because of its importance in determining the receipt and loss of radiation. A third must be the thermal properties of the surface and building materials, but with the exception of Kawamura's pioneering study (Kawamura 1964) little information is available. Locally anthropogenic heat may also become important.

(c) *Urban boundary layer energy balances*

At the scale of the whole UBL we are concerned with the spatially-integrated heat exchanges between the city and its overlying air. Here the 'surface' of the city corresponds to the level of the UCL/UBL interface. The fluxes across this plane comprise those from the individual UCL units (such as roofs, canyon tops, trees, lawns, roads, etc.) integrated over larger land-use divisions (e.g. suburban). In the centre of such a division, where meso-scale advective effects may be neglected, the 'surface' balance becomes:

$$Q^* + Q_F = Q_E + Q_H + \Delta Q_S$$

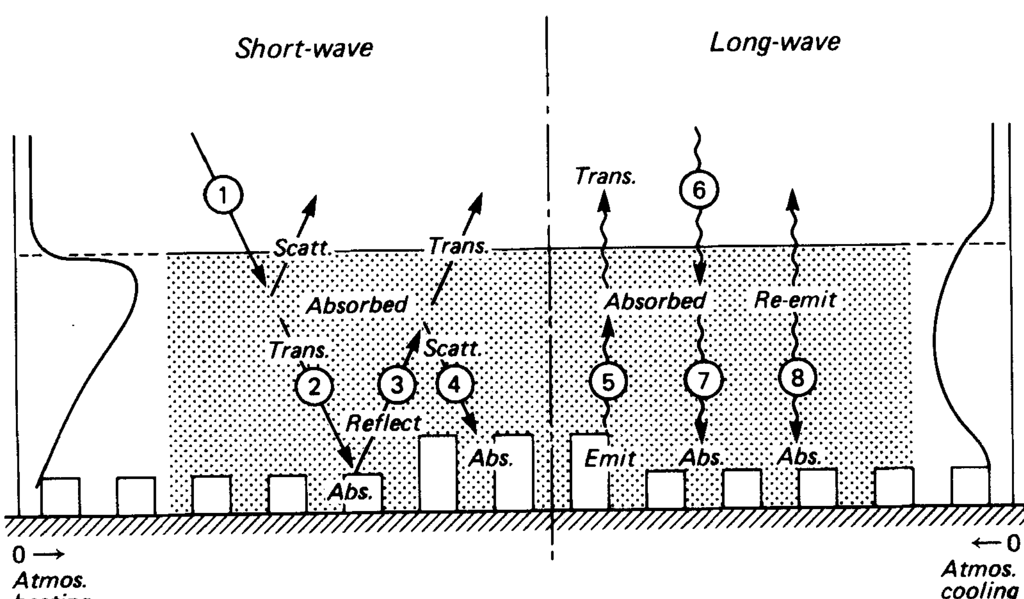
where Q_F is the anthropogenic heat flux density entering the UBL via chimneys and roofs and the other symbols are as defined earlier. All are spatial averages and the storage term refers to heat change in a volume whose depth extends to the level where vertical exchange is negligible, and is expressed as an equivalent flux per unit horizontal surface area.

Although Q_F can be readily calculated, if a fuel use inventory on appropriate space and time scales is available, it cannot be directly measured in the field. Observed energy balances therefore cannot show this term separately but its influence is contained in one or more of the other fluxes. Under the conditions specified for discussion (temperate climate, summer) typical daily average values of Q_F range from about $5\,\mathrm{W\,m^{-2}}$ in a suburb to $50\,\mathrm{W\,m^{-2}}$ in the city centre, and show about a three-fold increase from night to daytime (e.g. Kalma *et al.* 1972 for Sydney, Australia). On most occasions such figures will lie within the precision to which the balance can be evaluated and can therefore be neglected.

The city has a marked impact upon the short- and long-wave components of the net radiation budget due both to the presence of radiatively-active pollutants in the air and to changes in the surface radiative properties. The nature of these impacts has been reviewed elsewhere (Oke 1974; 1979). Here we will restrict consideration to a summary of the aspects most closely related to surface and atmospheric temperature changes. Discussion may be aided by referring to fluxes according to the scheme of Fig. 9.

In its path through the UBL the incoming short-wave radiation (Flux 1) and that reflected from the city surface (Flux 3) are subject to greater attenuation than the equiva-

Figure 9. Schematic depiction of radiative exchanges in a polluted urban boundary layer including generalized profiles of short-wave radiative heating (left) and long-wave cooling (right) due to the aerosol layer (shaded). Numbered fluxes referred to in the text (modified after Atwater 1971).



lent fluxes in the rural case. The amount received at the surface (direct-beam and diffuse, Flux 2 plus net back-scattered, Flux 4) is typically 2–10% lower in the city (Peterson and Stoffel 1980). On the other hand urban albedo values are typically 0·05 to 0·10 lower than for the countryside in the mid-latitudes (Oke 1974). As a result urban/rural net short-wave radiation differences are considered to be rather small. The sign of any differences will depend upon the relative strengths of the pollution attenuation and albedo factors. A similar off-setting of effects occurs in the long-wave radiation budget where exchanges are not only perturbed by the increased pollutants and the probably lower surface emissivities of cities but also by a feedback with the heat island warmth. The higher surface temperature of the city appears to outweigh the emissivity change thereby producing an enhanced emission (Flux 5). However, a relatively large part of this is absorbed by the polluted layer and re-radiated back to the surface along with that portion of the incoming sky radiation (Flux 6) transmitted to the surface (Flux 7), and that emitted by the warm heat island air (Flux 8). At night these combined long-wave radiative inputs are slightly larger in the city (Oke and Fuggle 1972), and by day the excess may be greater still, due to emission from solar heated pollutants (Rouse *et al.* 1973). In summary both long-wave input and output are increased by urbanization so that urban/rural net long-wave differences are not large. From the above it follows that urban/rural net all-wave radiation (Q^*) differences are small, probably less than 5% (Oke 1974; 1979; Probald 1975; White *et al.* 1978).

Our knowledge of the radiative processes *within* the polluted layer is far from complete. The mathematical treatment of scattering and absorption by pollutants is reasonably well developed (Atwater 1975; Coakley and Chýlek 1975), but there are few studies of urban atmospheres which combine information on both the physical properties of the aerosols and their radiative effects. The profile of atmospheric warming produced by shortwave absorption given in Fig. 9 is probably a reasonable consensus based on both observations and model calculations. The corresponding profile for the long-wave region is less certain. Most models (e.g. Atwater 1971; Bergstrom and Viskanta 1973) and nocturnal observations (Fuggle and Oke 1976) show cooling to predominate but some daytime observations suggest warming (Berlyand *et al.* 1974). The net radiative impact of urban pollutants probably is to warm and therefore increase stability in the UBL by day, but at night they act to cool and destabilize the layer.

If we assume, as seems reasonable for most mid-latitude cities in summer, that urban/rural radiative and anthropogenic heat flux differences are relatively small at the surface, then most of any energy balance differences must stem from a different sharing of heat between the turbulent and storage and/or between the sensible and latent terms. Here we will consider these possibilities using data from studies in suburban and urban terrain. The former may be considered to consist mainly of 1–2 storey houses with gardens in the fairly uniform, but dispersed, pattern often characterizing the dominant land-use of modern cities. The latter is a more dense agglomeration of taller (2–4 storey) buildings including residential, commercial and light industrial uses with less vegetation.

Simple consideration of the impact of urbanization on the water budget suggests that the city is subjected to partial waterproofing which leads to decreases in both subsurface water storage and evapotranspiration (Mather 1978; Oke 1978a). The available data clearly support this view but show that the city is by no means to be considered a 'desert'.

Consider the example suburban energy balance shown in Fig. 10. These results are judged to be fairly typical of summer conditions in Vancouver (Kalanda *et al.* 1980; Oke 1978c; Yap and Oke 1974) and probably a number of other mid-latitude cities including Adelaide, Australia (Coppin 1979) Los Angeles and St. Louis, USA (Carlson *et al.* 1981; Ching *et al.* 1978) and Uppsala, Sweden (Oke 1978c). Note that the sensible and latent heat flux densities are of similar magnitude during the daytime so that $\bar{\beta}$ is about 1·0. The rate of evapotranspiration is approximately 80% of the equilibrium value and therefore far from insignificant. Such relatively high rates (considering that about 34% of the surface is impervious) probably are due to 'micro-oases', such as the lawn in Fig. 5, whose exception-

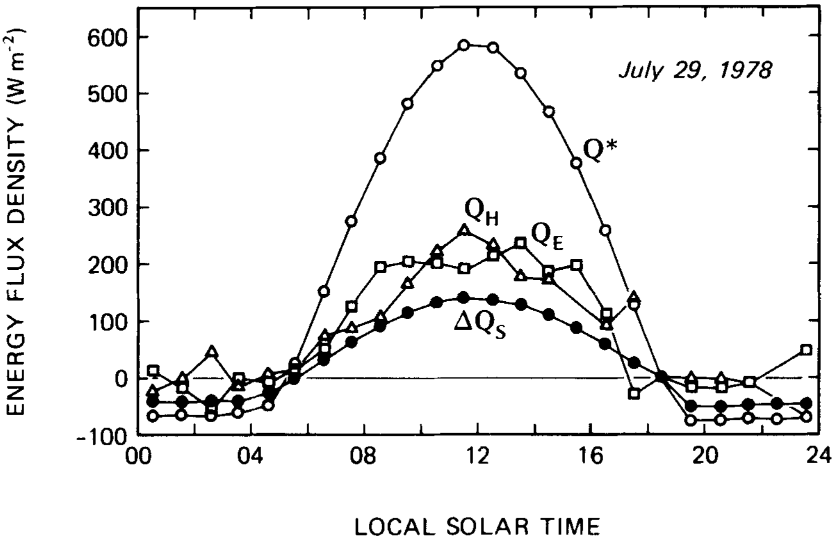


Figure 10. Energy balance of a suburban area in Vancouver, B.C.

TABLE 1. Average daytime partitioning of heat by by rural, suburban and urban landscapes.[1] Consensus of observed values of Bowen's ratio (β), estimates of $\Delta Q_S/Q^*$ and resulting typical values of the ratios Q_H/Q^* and Q_E/Q^*.

Land-use	$\bar{\beta}$ Observed range[2]	Typical	$\Delta Q_S/Q^*$ Estimated range[3]	Typical	Q_H/Q^* Typical	Q_E/Q^* Typical
Rural	0·1–1·5	0·5	0·05–0·25	0·15	0·28	0·57
Suburban	0·25–2·5	1·0	0·20–0·25	0·22	0·39	0·39
Urban	0·5–(>4·0)	1·5	0·25–0·30	0·27	0·44	0·29

[1] Temperate climate, summer, non-advective conditions.
[2] Sources: Bailey (1977), Carlson *et al.* (1981), Ching *et al.* (1978), Coppin (1979), Kalanda *et al.* (1980), Oke (1978c), Sellers (1965) and Yap and Oke (1974).
[3] Sources: Oke *et al.* (1981) and Sellers (1965).

ally high rates compensate for the removal of other transpiring surfaces. The range of values for suburban terrain under summer conditions is however reasonably large, extending from about 0·25 following rain to greater than 2·5 at the end of a dry spell (Table 1).

Data from urban sites are more sparse (Carlson *et al.* 1981; Ching *et al.* 1978; Yap and Oke 1974) but are consistent in that they show a further decrease in the role of latent heat compared with rural terrain. Nevertheless Q_E is still far from negligible (Table 1). Within the daily pattern two interesting features have been noted. First, the mid- to late afternoon decrease of Q_H often tends to lag behind that of Q^*; and second, Q_H may remain positive (directed into the atmosphere) at night (Yap and Oke 1974). These features can result in β being relatively large in the late afternoon and positive at night. The timing of these features corresponds to that of most rapid heat island growth (Section 2(a)) but any direct linkage has yet to be shown.

Therefore as summarized in Table 1, suburban and urban surfaces are characterized by rather variable energy partitioning. This is largely controlled by moisture availability. When both the city and countryside are wet, differences will be small; in drier conditions the city tends to become a relative source region for sensible heat, although urban irrigation can mitigate (perhaps even reverse) this tendency.

It is usually assumed that heat storage (ΔQ_S) in the city is significantly larger than in its surrounding areas because of the greater thermal conductivity (k) and heat capacity (C) of some building materials. The appropriate parameter which combines these properties is the thermal admittance, μ (viz. $(kC)^{1/2}$), sometimes called the thermal inertia. It is a measure of the thermal responsiveness of a surface for a given heat flux. *Ceteris paribus* surfaces of large μ, such as cities, should accept (release) heat to (from) storage with relative ease, and register relatively small surface temperature changes. Especially at night, when storage assumes a more important role in the total energy balance of both urban and rural environments, this factor may be important in maintaining warmer urban temperatures. The daytime situation is more complex (Bryson and Ross 1972).

Confirmation of this increased heat storage is hard to obtain because direct measurement of ΔQ_S at the city scale is not possible at present. Probably the most practical, but over-simplified, approach is to parametrize ΔQ_S in terms of Q^* (e.g. Oke *et al.* 1981). The method relies on a series of empirical equations relating these two fluxes for a variety of urban materials and surface units (including canyons). These are weighted according to the fraction (α_i) of the urban landscape covered by each of the i surface types:

$$\Delta Q_S = \sum_{i=1}^{n} \alpha_i(a_i Q^* + b_i)$$

where a_i and b_i are statistically determined coefficients. Values derived in this manner are included in Fig. 10 and Table 1 where it is seen that cities do appear to be better heat stores than their environs.

The cause of such heat storage differences is not yet clear because urban/rural thermal admittances do not appear to show the contrasts expected (Carlson *et al.* 1981; Oke 1981). The apparent discrepancy may be accounted for by considering, in more detail, the roles of such influences as geometry (increased area for exchange in the city); and moisture availability (greater daytime heating in the drier city).

In summary, our knowledge of meso-scale urban/rural energy balance differences, although less precise than is to be desired, tends to confirm intuition. The impact of urbanization is to favour partitioning of energy into sensible rather than latent heat and to increase the importance of heat storage by the system.

4. Urban heat island genesis

(*a*) *Urban canopy layer*

Starting with the first study of a heat island by Howard, urban meteorologists have continued to forward their favourite set of causative factors. Table 2 presents a list which includes most of those suggested (it may be of interest to note that Howard proposed no less than five of the seven). It should be realized that, until the past decade, the basis of such lists rested almost entirely upon intuition and reasoning from indirect evidence. Now it is fair to say that each of the seven mechanisms has been shown to be capable of operating in the direction required (Section 3), but still we are unable to assign a definite rank ordering of their contribution to heat island development except in a few special cases.

One extreme case is represented by an arctic settlement in mid-winter (i.e. during polar night, Bowling and Benson 1978). The energy balance is greatly simplified due to the absence of solar radiation, evapotranspiration and heat conduction between the buildings and the ground. The balance in calm conditions essentially reduces to that of a net long-wave drain upon an anthropogenic heat source. Complications are introduced by increased wind speeds (giving convective exchange) and if the air is polluted (especially with water in the form of ice fog). Nevertheless in comparison with most other urban climates, the energetic controls involved in this special case are defined fairly well.

The best opportunity to understand the causation of mid-latitude heat islands relates

TABLE 2. SUGGESTED 'CAUSES' OF THE URBAN HEAT ISLAND (Not rank ordered)

Altered energy balance terms leading to positive thermal anomaly	Features of urbanization underlying energy balance changes
A. Canopy layer	
1. Increased absorption of short-wave radiation	Canyon geometry – increased surface area and multiple reflection
2. Increased long-wave radiation from the sky	Air pollution – greater absorption and re-emission
3. Decreased long-wave radiation loss	Canyon geometry – reduction of sky view factor
4. Anthropogenic heat source	Building and traffic heat losses
5. Increased sensible heat storage	Construction materials – increased thermal admittance
6. Decreased evapotranspiration	Construction materials – increased 'water-proofing'
7. Decreased total turbulent heat transport	Canyon geometry – reduction of wind speed
B. Boundary layer	
1. Increased absorption of short-wave radiation	Air pollution – increased aerosol absorption
2. Anthropogenic heat source	Chimney and stack heat losses
3. Increased sensible heat input-entrainment from below	Canopy heat island – increased heat flux from canopy layer and roofs
4. Increased sensible heat input-entrainment from above	Heat island, roughness – increased turbulent entrainment

to the 'ideal' case illustrated by Fig. 1. This is because it is a fortunate coincidence that the phenomenon is best displayed (has its greatest magnitude) under conditions when the energetic controls are simplest. Our task is to explain a phenomenon which finds its best expression in large mid-latitude cities on calm, clear summer nights and whose morphology shows a marked conformity with that of the city's structure. We will therefore concentrate initially on consideration of differences of urban/rural surface energy exchange at night which may lead to the observed differences in cooling rates. The following simple conceptual framework is offered as a starting point.

On the basis of observation, (as summarized in Section 3) or as a result of the constrained conditions, we may effectively eliminate 'causes' A1, A2, A4, A6 and A7 in Table 2 from further consideration. Thus urban/rural energy balance and cooling rate differences will depend simply upon the relative strengths of the net long-wave radiative sink and the sub-surface heat store in each environment (i.e. 'causes' A3 and A5). *Ceteris paribus* the relevant and therefore critical properties governing these differences are the radiation geometry (ψ_s) and the surface thermal properties (given by the thermal admittance, μ). Some indication of the importance of ψ_s differences is given by comparing L^* values on the canyon floor in Fig. 7 with those for locations near the canyon top where ψ_s tends to 1·0 (the latter being of similar magnitude to those typical of open rural sites e.g. Fig. 4). Recent work using scale models, where ψ_s is varied while holding μ constant, shows that the influence of radiation geometry is capable of simulating the temporal features of the 'ideal' nocturnal heat island (Fig. 1(c) to (e)) well (Oke 1981). The same study also shows that in the absence of ψ_s differences an increase of μ is also able to replicate these features. Thus in the real world both effects are probably in operation, their relative roles depending on the size of urban/rural ψ_s and μ differences. Whereas the former are easily demonstrated it is difficult to obtain truly representative values of the latter, which depend on the multitude of materials involved and are complicated by vegetation, snow-cover and soil moisture differences.

Further general support for this simplified view of 'ideal' heat island causation is provided by Fig. 11. It shows the relationship between the maximum heat island intensity (i.e. 'ideal' conditions) observed in a large number of cities and the sky view factor of their central area. The good correlation achieved answers many of the questions posed in relation to Fig. 3: the use of geometry alone attests to the importance of local site factors rather

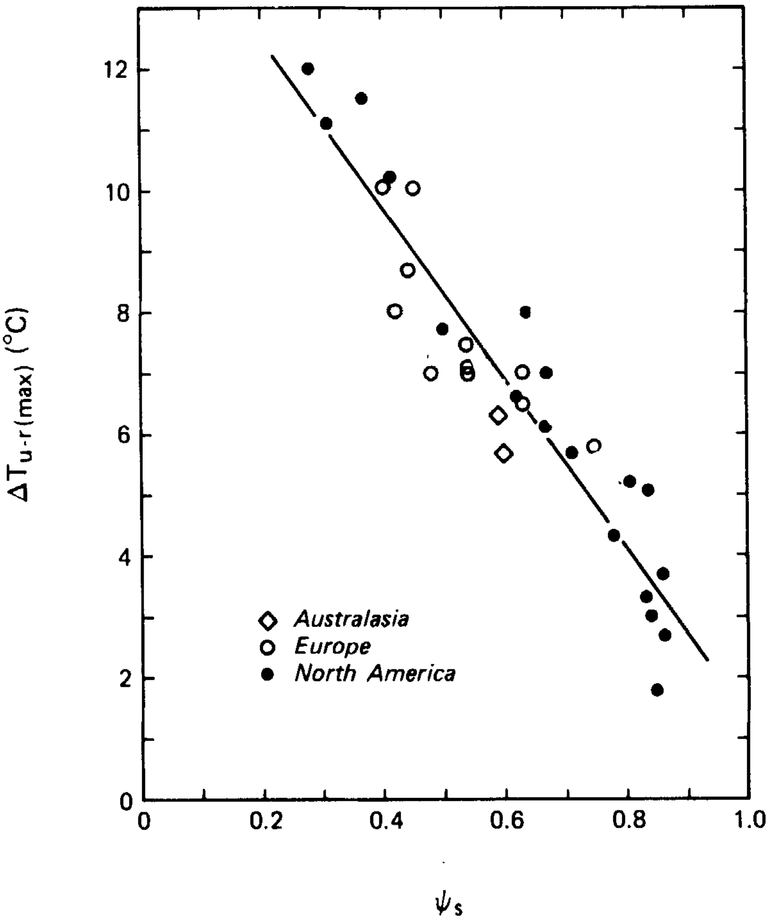


Figure 11. Relationship between maximum heat island intensity ($\Delta T_{u-r(\max)}$) and the sky view factor (ψ_s) in the centre of 31 settlements (after Oke 1981). All data refer to canopy layer measurements on calm, clear summer nights.

than advective heat accumulation; the restriction to summer data greatly reduces the possibility that anthropogenic heat is significant; and the merging of the European and North American data suggests that geometry is the common underlying control (22 of the cities used in Fig. 3 are included). The relationship of course does not exclude the possibility that thermal admittance differences are also involved, but the similarity of building materials used in constructing the centres of large cities may diminish their effect in Fig. 11.

These arguments refer to *surface* energetics and cooling and we are left to infer that they are reflected in *air* temperature change. In detail, atmospheric cooling occurs as a result of vertical and horizontal divergence in the transport of heat by radiation and/or turbulence as given by the thermodynamic equation. Under perfect 'ideal' nocturnal conditions when turbulence is suppressed and there are no phase changes in the air, the cooling rate for an open rural site will be given by the vertical divergence of the radiative flux:

$$\frac{\partial T}{\partial t} = \frac{\partial L^*}{\partial z} \Big/ \rho c_p$$

where ρc_p is the heat capacity of air. The equivalent rate for air within the urban canopy layer is given by the volume divergence:

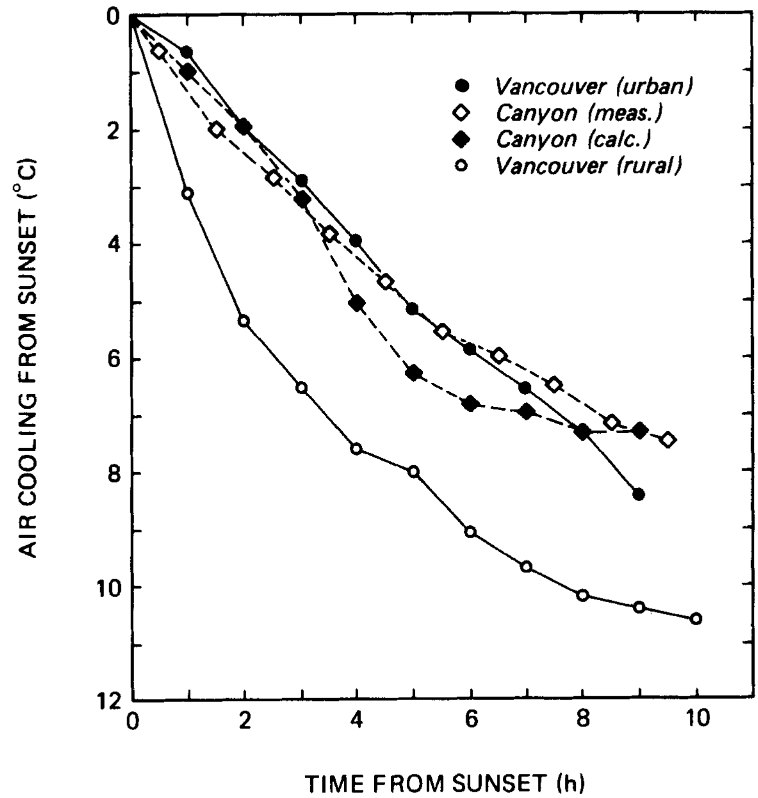


Figure 12. Cumulative cooling curves for canyon, city centre and rural environments on cloudless nights with light winds. Canyon results from Nunez and Oke (1976), for explanation of calculations see text.

$$\frac{\partial T}{\partial t} = \left(\frac{\partial L_x^*}{\partial x} + \frac{\partial L_y^*}{\partial y} + \frac{\partial L_z^*}{\partial z}\right)\Big/ \rho c_p = \nabla.\mathbf{L}^*/\rho c_p$$

thereby accounting for the existence of net horizontal exchanges. In the real world turbulence is rarely absent, but in the case of a canyon where the air may be almost stagnant, due to greater frictional retardation, cooling may be approximated by this simple divergence model. This is verified in Fig. 12 which shows the agreement between measured cooling of the canyon air volume and that calculated from radiative divergence observations from a three-dimensional array of net pyrgeometers (Nunez and Oke 1976). Although not strictly comparable, the Vancouver urban cooling curve for 'ideal' conditions is also included in Fig. 12 along with the corresponding rural curve. Similarity between the canyon and urban cooling curves is evident.

In summary the observed features of the UCL nocturnal heat island under 'ideal' conditions are reasonably accounted for by the available energy balance information involving only 'causes' A3 and A5 from Table 2.

There is very little information on which to base an explanation of the daytime features of the 'ideal' heat island. In general terms, just as the evening heat island growth is produced by the slower cooling rate of the city, so its early morning disappearance is the result of sluggish warming in the canopy layer. The absence of a sharp peak in warming, such as that experienced in the countryside (Fig. 1(d)), probably is due to the combined effects of canyon shading at low Sun angles, higher thermal admittance and the lack of a capping inversion within the lowest few hundred metres of the urban atmosphere. The existence of a 'cool' island in the middle of the day usually is attributed to canyon shading in the city centre but full explanation awaits further detailed study.

In other than 'ideal' weather conditions the analysis becomes complicated especially by the impact of increased turbulent transfer. The well established inverse relationships between nocturnal heat island intensity and cloud and wind speed, and the direct relation to increasing atmospheric stability, are clearly to be interpreted as reflecting a diminution in the relative roles of radiation and heat storage in comparison with convection and advection, the former tending to enhance differentiation of microclimates whereas the latter tend to promote mixing and homogeneity.

(*b*) *Urban boundary layer*

Study of the mechanisms underlying the thermal excess in the boundary layer over cities has been restricted largely to modelling efforts (both numerical and scaled flow) with relatively little direct observation. The models are helpful in providing insight but they require field verification not only in terms of their output but also their process underpinnings. Such work might reasonably start by investigating the four suggested 'causes' in Table 2, although full treatment of 'cause' B3 requires a canopy layer sub-model which, as we have just discussed, is not yet available.

The increasing depth and temperature of the daytime mixed layer are the result of heat flux convergence: both radiative due to aerosol effects and convective due to horizontal and vertical transport and mixing. Both mechanisms are likely to be enhanced in the UBL (Table 2). However whereas the net radiative impact ('cause' Bl) clearly seems to produce increased warming (Section 3(c)), the convective impact is more complex. The greater upward sensible heat flux from the city ('causes' B2 and B3, Section 3(c)) combined with increased urban turbulence intensities (Counihan 1975) are likely to produce greater bombardment of the base of the UBL capping inversion by convective plumes. This will create an enhanced downward heat flux ('cause' B4). Therefore the UBL heat budget benefits by increased convergence of heat both from above and below. On the other hand, it should be mentioned that this process, plus the increased uplift experienced in the UBL as a result of frictional retardation of airflow over the rougher city (Angell and Bernstein 1975; Auer 1975), is responsible for the doming of the layer over the city (Fig. 2(a)). This tends to reduce the possible heat island intensity by increasing the volume of air affected. Therefore all four UBL 'causes' listed in Table 2 are probably in operation by day, but their relative roles remain to be evaluated.

At night all 'causes' except the radiative one are capable of explaining the UBL heat island. However, if we take the summer fine weather case, 'cause' B3 would appear to be the most important mechanism. Urban-rural surface energy balance comparisons point to larger sensible heat input to the urban atmosphere in the late afternoon and a suppression or even reversal of the return flux at night (Section 3(c)). This is due, at least in part, to the development of the UCL heat island which is likely to generate instability between the below- and above-roof levels. This certainly would fit the lower portion of the observed temperature profile in the urban area at night (Fig. 2(b and c)). The upper neutral or stable portions of that profile may be due to roughness rather than buoyancy effects resulting in entrainment at the elevated inversion base. The 'cross-over effect' (Section 2(b)) might then correspond to the layer from which heat has been removed, although it is possible that it also might be due to long-wave radiative flux divergence at the top of the polluted UBL.

One of the few reasonably clear examples of boundary layer heat island causation concerns the high latitude settlement in winter. With calm and little or no solar heating, the heat input to the UBL is dominated by anthropogenic releases (Bowling and Benson 1978). It can be shown also that even without a heat source the advection of stable air over a rougher area will result in a positive thermal anomaly.

Perhaps the most important point regarding heat island causation is that the mechanisms responsible for the canopy layer anomaly are not the same as those in the boundary layer. The former is largely the result of the immediate site character (especially building geometry and materials), whereas the latter probably represents both an advective accumulation of this warmer air with that entrained from above, and internal radiative effects.

5. Conclusion

We conclude from the foregoing that in meteorological terms urban heat islands are well described but rather poorly understood. Further descriptive studies of heat island morphology in more towns and cities are likely to be of only local or applied interest, though there are some exceptions. For example, present evidence is meagre, or even conflicting, for the cases of daytime heat and 'cool' islands; UBL structure and down-wind urban 'plumes'; and heat islands of tropical cities, the latter being of special practical, and perhaps scientific, importance.

Understanding will be enhanced by greater attention to process. The present review has shown that only the rudiments of the fundamental energy and water balances of cities have been investigated, whereas those of most natural environments are far more advanced. As a result, it is possible to provide little more than hand-waving arguments to explain UCL and UBL heat islands under other than very idealized conditions. The major challenge is to identify relevant processes and scales of activity in the urban atmosphere and to provide consistent generalizations and syntheses as a basis from which to develop and test numerical models. In the case of the heat island it would seem that this may require separate canopy and boundary layer sub-systems with appropriate coupling.

Much of what has been said with respect to the heat island applies with equal or greater force to research into urban wind and humidity effects and to the very complex question of urban cloud and precipitation modification. If the challenge is not taken up quickly urban meteorology will be a long time in approaching the goal of becoming a predictive science.

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