IAUC Teaching Resources
The Urban Canopy Layer Heat Island

The urban heat island (UHI) is the most studied of the climate effects of settlements. The UHI refers to the generally warm urban temperatures compared to those over surrounding, non-urban, areas. It is important, however, to distinguish between the 'types' of UHI (for example, one defined by surface or air temperatures) as the observations and responsible processes will differ.

Surface heat islands have been detected using satellite and aerial imagery. At sufficient heights, the urban surface that is 'seen' consists of contributions from roofs, streets, car-parks, etc. At lower heights, observations from an oblique viewpoint will contain contributions from walls and the UHI assessment will depend on how representative these observations are. However, most UHI studies examine air temperatures in urban areas. If these are observed in **Urban Boundary Layer** (UBL) above the average height of the buildings (Figure 1), the sampled air has interacted with the rough 'surface' below. More commonly, UHI studies have focussed on air temperatures within the **Urban Canopy Layer** (UCL), below the roof tops in the spaces between buildings (Figure 1). It is this UHI and the responsible processes that are discussed here.

The Canopy Layer UHI

The UHI is typically presented as a temperature difference between the air within the UCL and that measured in a rural area outside the settlement (ΔT_{u-r}). Research strategies have examined the temporal and spatial characteristics of ΔT_{u-r} by using observations at fixed sites (representing urban and rural locations) and measurements made on mobile platforms (using cars and bicycles) [15]. In both cases, the selection of sites and routes is critical to establishing the form and behaviour of the UHI. Moreover, the choice of the non-urban, rural, sites is crucial.

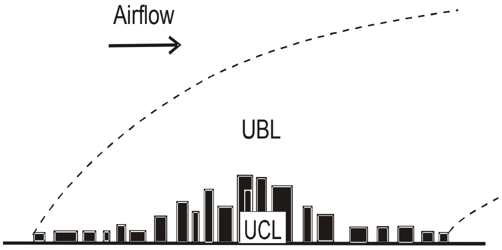

Figure 1: A vertically exaggerated cross-section of the urban atmosphere and its two main layers. The slope of the UBL is between 1:100 and 1:200 in reality.

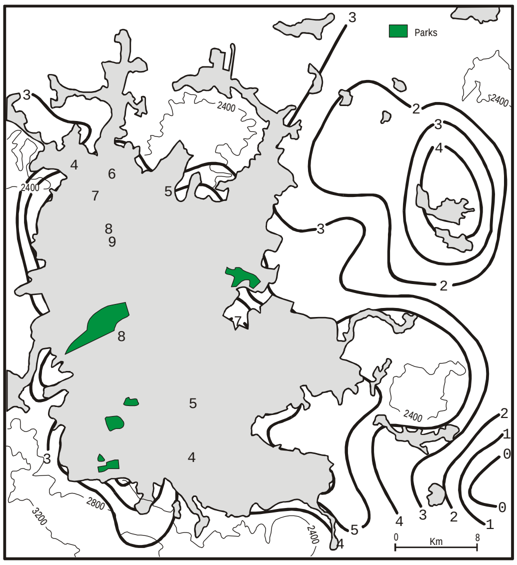

Figure 2: Mean minimum temperature for November 1981 in Mexico City. Redrawn from [4].

Description: Every settlement is capable of generating an UHI, regardless of its size. Observations for a host of UHI studies display common characteristics. ΔT_{u-r} reveals itself as a pool of warm air with largest values closest to the urban centre (Figure 2). At the urban edges, temperature changes are rapid, thereafter, ΔT_{u-r} increases more slowly. However, in the vicinity of green parks lower temperatures are observed (Figure 3). The strength of the UHI is referred to by the maximum difference recorded. The magnitude of ΔT_{u-r} is greatest at night, under clear skies and with little wind. Under such conditions, surface cooling is associated with radiation exchange. While exposed rural sites cool rapidly after unset, urban sites cool more slowly. The difference between urban and rural sites grows with time after sunset and reaches a maximum difference after about 4 hours (Figure 4). The maximum ΔT_{u-r} value recorded is usually found in the centre of the settlement is generally larger for bigger settlements.

Relevance: The UHI has a significant and unintended impact on the climate experienced in cities. However, whether it is desirable or not will depend on the background climate. Warmer

Figure 3: Isotherms in Chapultec Park on December 3, 1970 (5:28 to 6:48), with clear sky and calm air. Redrawn from [5].

night-time temperatures will require less (more) domestic heating (cooling) in cold (warm) climates. In colder climates, fewer snowfall and frost events will occur and surface snow will melt earlier (altering the surface hydrology). In warmer climates, the UHI, particularly when accompanied by other urban effects (such as poor air quality) may produce stressful conditions [7].

The UHI has relevance for the study of regional and global climates that rely on accurate assessments of climate. The global network of stations is unevenly distributed; most are located in the developed world, over land, and near urban areas. As settlements have grown in extent, stations located nearby may have been affected. Thus, the urban temperature 'effect' needs to be removed so that global trends can be examined [1].

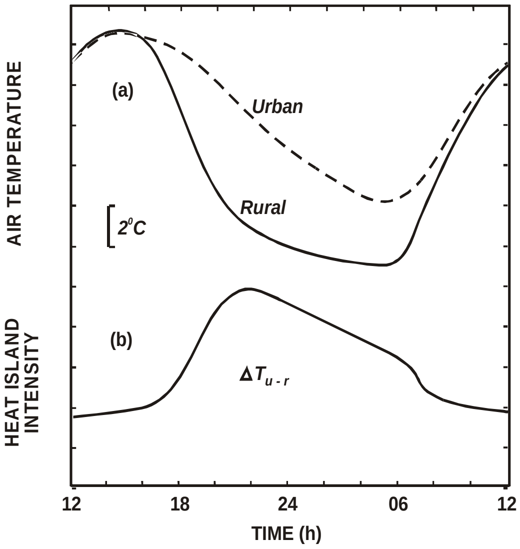

Figure 4: Typical temporal variation of urban and rural air temperature under clear skies and weak airflow. The UHI is produced by the difference between the cooling rates. Redrawn from [13].

History: The study of the UHI encapsulates the history of the field of urban climatology, which since the late 19th century can be divided into periods characterised by different research approaches. The earlier period was dominated by a descriptive approach that began with Luke Howard's pioneering examination of London's climate [2]. This type of research continues and there is now a large body of data on UHI characteristics from cities globally.

From the late 1960's onwards, research shifted toward an understanding of the processes that produce urban effects through the application of micrometeorological theory. The explicit recognition of the scales of urban climate (Figure 1) has become an essential part of research design, which is now characterised by the measurement and modelling of energy, mass and momentum fluxes [9]. The UHI is treated as a response to changes in surface geometry and materials and in atmospheric composition. Concurrently, an 'experimental' approach has developed that isolates elements of urban form whose unique effects can be explored. For example, the climate of city streets is examined by considering the properties of symmetrical 'canyons' characterised by their length, building height (H) and street width (W) and orientation [10]. This approach has permitted the discovery of general relationships linking street geometry and climate effect.

The formation of the UHI can now be understood from the viewpoint of the energy balance of an urban area.

The UHI energy balance: The surface energy balance accounts for all the exchanges of energy. These include radiative fluxes (both shortwave (K) and longwave (L)), turbulent sensible (Q_H) and latent (Q_E) fluxes with the atmosphere and energy stored or withdrawn from the substrate (ΔQ_S). An additional term that must be considered in the urban setting is the heat added by human activities (Q_F). However, with few exceptions, Q_F is a small component of the urban energy balance.

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

Net radiation (Q^*) is composed of radiation arriving at (↓) or exiting from (↑) a surface each component of which can be sub-divided into radiative sources and sinks. For example, incoming radia-

Table 1: Suggested causes of canopy layer Urban Heat Island [12]

Energy Balance term	Urban features	Urban effect
Increased K^*	Canyon geometry	Increased surface area and multiple reflection
Increased $L\downarrow_{sky}$	Air pollution	Greater absorption and re-emission
Decreased L^*	Canyon geometry	Reduced sky view factor
Q_F	Buildings & traffic	Direct addition of heat
Increased ΔQ_S	Construction materials	Increased thermal admittance
Decreased Q_E	Construction materials	Increased water-proofing
Decreased (Q_H+Q_E)	Canyon geometry	Reduced wind speed

tion at a surface can be divided into that derived from the sky and that from the surrounding terrain,

$$L\downarrow = L\downarrow_{sky} + L\downarrow_{terrain}$$

The contributions from these sources will depend on both their emittance and the proportion of the 'view' of the surface occupied by those sources.

Each energy balance term will be altered in the urban environment and contribute to the formation of the UHI (Table 1). The lower albedo of many urban materials results in greater absorption of solar radiation during the daytime (Table 2). Multiple reflections within the canopy layer lowers the albedo of the urban 'surface' (when viewed above the rooftops) still further. Lower average wind speed within the UCL suppresses turbulent exchanges while impervious, unvegetated surfaces hinder evaporative cooling. However, it is important to recognize that the physical geography of individual settlements may not fit this pattern. For example, urban areas in desert areas may be wetted through irrigation.

Much can be learned by examining 'ideal' meteorological conditions for UHI formation. ΔT_{u-r} is greatest at night, under clear and calm skies. In these circumstances, the energy balance can be approximated as,

$$L^* = \Delta Q_S$$

This suggests that the UHI can be examined as the result of differential surface cooling governed by rates of radiative exchange and of heat storage.

Although urban materials are known to have a high thermal admittance (ability to store and release heat), there is little evidence that urban areas are distinguished by their thermal properties [2]. As typical urban materials are impermeable, their moisture content and thermal properties do not vary greatly (Table 2). Outdoor materials (e.g. asphalt road and parking lots) are thick and in contact with a solid substrate. However, building materials are selected for their strength, and are formed into a relatively thin envelope that separates indoor and outdoor air. Much of the diurnal heat exchange is confined to this layer, which has a large specific heat capacity but a limited volume. As a result, the replacement of natural cover by urban materials is not a sufficient explanation for the formation of the UHI.

Under clear night-time skies, the rate of surface cooling is driven by net longwave radiation loss. The magnitude of this loss is proportional to its exposure to the sky, which may be measured as the proportion of the viewing hemisphere that is occupied by sky; this is the sky view factor (ψ_{sky}). Thus, the three dimensional structure of the urban area (its geometry) is a good measure of

Table 2: Properties of materials

Material	ρ	C	k	μ
Dry clay soil	1.60	1.42	0.25	600
Saturated clay soil	2.00	3.10	1.58	2210
Asphalt	2.11	1.94	0.75	1205
Dense Concrete	2.40	2.11	1.51	1785

Thermal properties of selected materials: Density (ρ) in kg m^{-3} x10^3; heat capacity (C) in J m^{-3} K^{-1} x 10^6; thermal conductivity (k) in W m^{-1} K^{-1} and; thermal admittance (μ) in J m^{-2} $s^{-1/2}$ K^{-1}. Compiled from [13].

Surface	α	ε
Asphalt	0.05-0.20	0.95
Concrete	0.10-0.35	0.71-0.91
Urban areas	0.10-0.27	0.85-0.96
Soils: wet to Dry	0.05-0.40	0.98-0.90
Grass: long to short	0.16-0.26	0.90-0.95

Radiative properties of selected materials: Albedo (α) and emissivity (ε) are non-dimensional. Compiled from [13].

night-time radiative loss (Figure 5). Oke [11] has shown that under these ideal conditions the maximum observed UHI is found in the central, densest part the settlement and that it is strongly correlated with ψ_{sky}, which can be approximated as the ratio of building height to street width (H/W). This formulation is suitable for ideal conditions and city centres, where the surfaces are dry and materials can be assumed to be largely the same.

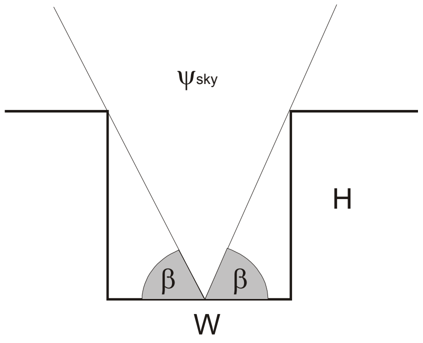

Figure 4. A depiction of the sky view factor in a symmetrical street canyon, described by its width (W) and its height (H), $\psi_{sky} = \cos\beta$. [12]

Measuring the urban effect: Ideally, the urban effect would be assessed from a continuous set of observations that begin prior to urban settlement [5]. Over a stable climatic period, the unique contribution of the urban area could be extracted. However, most UHI studies are based on comparisons between observations made at existing ‘urban’ and ’rural’ sites. This places a great onus on the selection of these sites.

Lowry [7] identifies three components in a set of measurements (M):

1. The ‘background’ climate (C),
2. the effects of the local climate (L) and
3. the effects of local urbanization (E).

Values of M are observed, but the contributions of C, L and E are not. Moreover, these are likely to vary with time depending on the frequency and duration of weather types experienced. The situation is further complicated in that we cannot, at the outset of a UHI study, identify the spatial limits of the urban effect (Figure 6). In the absence of pre-urban observations, the urban effect may be only be estimated. Observational studies of the UHI must give careful consideration to the selection of measurement sites and to the ‘background’ climate that is likely to enhance or diminish $\Delta T_{u\text{-}r}$ and the spatial extent of the urban effect.

Applied Climatology: The UHI is an unintended outcome of urbanization. Climate-conscious urban design seeks to modify climate processes to achieve a particular end. For the UHI, a starting point would be a consideration of the energy balance to decide which term(s) could be readily altered (Table 1). Figure 5 indicates that the maximum potential value for $\Delta T_{u\text{-}r}$ can be managed by modifying the geometry of the UCL (that is, the building heights and street widths). However, opportunities for changing the physical form of existing settlements are rare.

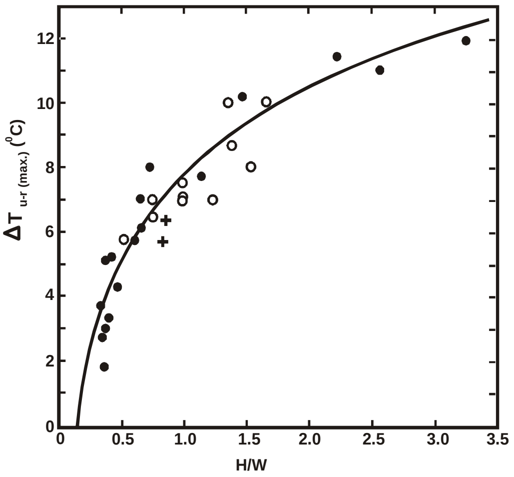

Figure 5. Relation between the maximum heat island intensity ($\Delta T_{u\text{-}r(max)}$) and the height to width ratio (H/W) of the street canyons in the centres of the settlement (Based on observations for 31 cities in N. America (●), Europe (○) and Australasia (+)). Redrawn from [11]. The relationship can be expressed as

$$\Delta T_{u\text{-}r(max)} = 7.45 + 3.97 \ln(H/W)$$

or

$$\Delta T_{u\text{-}r(max)} = 15.27 \text{—} 13.88\, \psi_{sky}$$

Another approach is to select surface materials

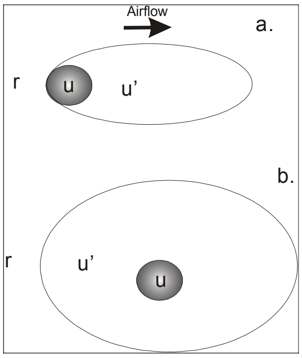

Figure 6. The urban effect is present in the urban area (u) and in a surrounding area (u’), whose shape and size depends on synoptic conditions. In a., the shape and size of u’ is regulated by a particular weather event. In b., u’ is defined by the sum of all weather events, that is, the climate of the area. Redrawn from [7].

with desirable properties. Increasing the surface albedo will reduce the amount of heat stored during the daytime and limit the surface-air sensible heat flux [14]. Increasing the vegetated area of the city will have a similar effect, as much of the available energy at the surface will be expended as latent (rather than sensible) heat energy. In addition, the leafy canopy will shade surfaces during the daytime. However, at night this canopy will limit radiative heat loss from the surface and could contribute to the night-time UHI.

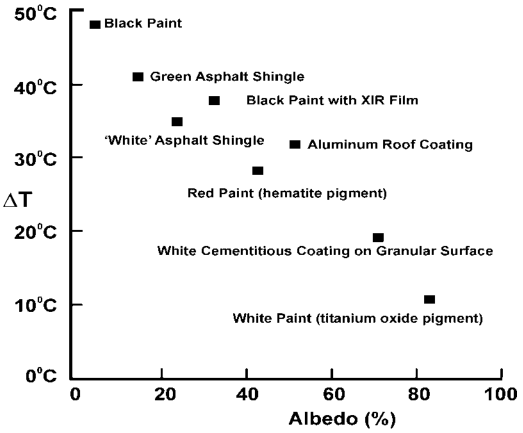

Figure 7. The relationship between the surface-air temperature difference (ΔT) and the albedo of selected paints and roofing materials facing the sun. Redrawn from [14].

Selected Readings

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