Satellite-derived urban heat islands from three coastal cities and the utilization of such data in urban climatology

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Abstract. NOAA AVHRR satellite infra-red data are used to display the surface radiant temperature heat islands of Vancouver, British Columbia, Seattle, Washington, and Los Angeles, California. Heat island intensities are largest in the day-time and in the warm season. Day-time intra-urban thermal patterns are strongly correlated with land-use; industrial areas are warmest and vegetated, riverine or coastal areas are coolest. Nocturnal heat island intensities and the correlation of the surface radiant temperature distribution with land-use are less. This is the reverse of the known characteristics of near-surface air temperature heat islands. Several questions relating to the interpretation and limitations of satellite data in heat island analysis and urban climate modelling are addressed.

1. Introduction

The capability of satellite-based sensors to provide Sun-synchronous, high spatial resolution thermal imagery is potentially very attractive and valuable to the field of urban climatology. Their data provide an opportunity to study aspects of the urban heat island which is one of the most clearly established examples of inadvertent modification of climate with significant practical implications regarding energy and water conservation, human health and comfort, air pollution dispersion and local air circulation.

The form of the urban heat island has been well documented using observations of air temperature from standard networks of climate stations and mobile surveys using automobiles and aircraft (Chandler 1976, Landsberg 1981, Oke 1982). There is also continuing research to understand the energetic basis of this phenomenon through field observations and numerical and scale modelling of the energy exchanges of urban and rural environments (Oke 1982, Bornstein 1986).

Observations of remotely-sensed urban heat islands using aircraft and satellite-based systems exhibit different features from those measured from air temperature directly and their interpretation is often difficult (Price 1979, Vukovich 1983).

The present study demonstrates the nature of satellite-derived heat islands in three coastal cities of western North America and compares them with those observed by more conventional means. This provides the basis for a discussion of the need to distinguish clearly between the two, the problems of interpreting remotely-sensed signals and the usefulness of such data in urban climate models.
2. Nature of the urban heat island

Urban development is accompanied by significant, often radical changes in the nature of the surface and atmosphere. The attendant transformation of the radian, thermal, moisture and aerodynamic properties leads to a set of distinct micro- and mesoscale climates. Almost universally, the modified thermal climate is warmer, giving rise to the urban heat island. When studying such effects it has been found to be important and useful to divide the urban atmosphere into two layers: the urban canopy layer (UCL) and the urban boundary layer (UBL) (Okc 1976). The former lies below mean roof level and consists of the myriad of microclimates spawned by the heterogeneous nature of the individual elements (houses, trees, roads, lawns, etc.) of the urban system. The latter is the overlying layer whose characteristics are modified by the integration of the UCL effects into a regional or mesoscale climate.

The UCL heat island is normally associated with air temperatures observed from fixed climate stations or automobile surveys. The magnitude of the urban warmth (usually expressed as the difference between the highest urban and the background rural temperature, which is called the heat island intensity, \( \Delta T_{u-r} \)) for a given city is closely tied to the prevailing weather. It is greatest when skies are cloudless and winds are absent. If conditions permit, the intensity follows a daily cycle, being greatest at night (a few hours after sunset) and least near midday. The daily temperature wave for the city is both higher in the mean and reduced in amplitude compared with the rural case. Some cities also exhibit a seasonal variation of intensity which may be due to the cyclical changes of solar angle, synoptic weather type, plant phenology, moisture availability or fuel use. Other things being equal, larger cities have greater heat island intensities but the relation is more tied to the degree and type of urban development in the city centre than to simple measures of size such as population or diameter. Intra-urban patterns of air temperature in the UCL are also strongly correlated with those of the density of urban development—warmest in areas of greatest conversion to urban uses, especially those densely built-up with deep street canyons and high fuel use. Under ideal conditions values of \( \Delta T_{u-r} \) of up to 12°C have been recorded.

The UBL heat island is an extension of that in the UCL. The intensity decreases in magnitude with height and is subject to the same weather controls. Thermal influences of a large city may be discernible up to about a kilometre away by day but contract to a layer only tens or a few hundred metres deep at night. The impact is advected downstream as an elevated urban thermal ‘plume’.

The surface heat island has been studied using aircraft-borne infrared scanners (e.g. Stock 1975, Pease et al. 1976, Winiger 1984, Hoyano 1984). Often the analysis is restricted to intra-urban variation. A summary of satellite-based heat island studies is given in table 1. Although the number of cases is still rather small, some interesting generalizations are beginning to emerge. In particular they show that heat island intensities based on satellite-viewed surface temperatures are greatest during the day and least at night (Carlson et al. 1981, Vukovich 1983, Lombardo 1985, Kidd and Wu 1987). This is the reverse of the UCL air temperature pattern already described. Lombardo (1985) reports a maximum day-time heat island for São Paulo, Brazil, of 14°C and Price (1979) gives 17°C for New York. Further, both Carlson et al. (1981) and Vukovich (1983) note that the spatial distribution of temperature is much more strongly tied to land-use features such as parks, water bodies, industry, etc. by day than at night. Industrial areas seem to appear as particularly warm areas.
<table>
<thead>
<tr>
<th>Author</th>
<th>Satellite</th>
<th>Thermal sensor</th>
<th>Resolution (km)</th>
<th>Target location</th>
</tr>
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<tbody>
<tr>
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<td>ITOS-1</td>
<td>SR</td>
<td>7.4</td>
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</tr>
<tr>
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<td>1.0</td>
<td>Los Angeles</td>
</tr>
<tr>
<td>Carlson and Augustine</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Matson et al. (1978)</td>
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<td>1.0</td>
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<tr>
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<td>HCMR</td>
<td>0.6</td>
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</table>

3. Data analysis

3.1. Data set

The satellite infrared data used in the present study come from NOAA-7, -8 and -9 which carry an Advanced Very High Resolution Radiometer (AVHRR). In all cases signals from channel 4 (10.5-11.5 μm) were utilized. The ground resolution at nadir is 1-1 km and the swath width is 2700 km. The time, location, satellite and weather data associated with each heat island case are listed in table 2. The study focussed upon Vancouver, British Columbia, but representative cases from Seattle, Washington, and Los Angeles, California, are also included. All cases were characterized by anticyclonic weather, with cloudless skies and no precipitation for several days previous.

3.2. Image processing

The satellite data were navigated to centre the image over the city of concern and to correct for geometric distortion. In order to extract small-scale features the 512 × 512 pixel images were enlarged (without improvement of resolution) thereby reducing the area to a 64 × 64 pixel working display, corresponding to a square with sides of 50 km for Vancouver and 83 km for Seattle and Los Angeles.

The image contrast was enhanced to produce the best heat island image. This was achieved by stretching the contrast of the temperatures across the urban area to fill the full dynamic range of the display scale. A linear transfer function giving equal weight to all pixel values regardless of their frequency of occurrence was applied to convert the measurement to the display scale. A colour rainbow was generated. The brightness temperature values were calculated using look-up tables computed for each satellite pass.

3.3. Errors

The accurate determination of surface temperature using remote sensing requires knowledge not only of the emissivity but also of the emissivity of the radiating surface and the interaction of the radiation with the intervening atmosphere. The data used in the present study were neither calibrated for emissivity nor corrected for atmospheric interference. A statement of anticipated errors is therefore necessary.

Spatially-averaged surface emissivities for typical urban and rural areas suggest that the city has a lower value by about 2 per cent (e.g. Arnfield 1982). If neglected this could mask or produce urban-rural temperature differences of up to 1.5 deg K. The tendency here is always to underestimate any urban heat island effect. Intra-urban emissivity variations of the same order are also to be anticipated (Arnfield 1982) but the effect is likely to be reduced by the spatial averaging inherent in the 1-1 km pixel size.

Even though the radiation sensed lies in the window region of the atmosphere the brightness temperatures need to be corrected for the effects of scattering, absorption, refraction and re-radiation. The atmosphere acts as a complex filter that varies spatially, temporally and spectrally. In this study we are not interested in absolute values only relative ones. We want to use the satellite data to define the spatial thermal pattern of the heat island. By neglecting corrections we are assuming that atmospheric effects are spatially uniform. In fact water vapour and pollutant concentrations in urbanized regions show significant horizontal variability. Carlson (1986) estimates that errors due to this effect are of the order of 1 deg K.
<table>
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<tr>
<th>Date</th>
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<th>City</th>
<th>Satellite</th>
<th>Pass Number</th>
<th>Angle of elevation†</th>
<th>Wind speed/direction (m s⁻¹/degrees)</th>
<th>Air temperature (°C)</th>
<th>Dew-point temperature (°C)</th>
<th>Visibility (km)</th>
<th>ΔΤₐₚ,ₜ (°C)</th>
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<td></td>
<td></td>
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<td>N9</td>
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<td>89</td>
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<td>50</td>
<td>2.7</td>
</tr>
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</table>

V = Vancouver, (population ≈ 1.3 × 10⁶ persons), S = Seattle, (≈ 1.1 × 10⁶) and LA = Los Angeles, (≈ 7.5 × 10⁶). ΔΤₐₚ,ₜ = heat island intensity.

† Angle of elevation of the satellite viewed from the target.
Hence, in the worst case when these errors act together we may expect spatial temperature errors of up to 2.5 deg K.

4. Results

The results presented from the three cities of Vancouver, Seattle and Los Angeles are comparable because they were gathered under roughly similar conditions. All are coastal cities of Western North America and they exhibit strong land/sea thermal contrasts. This, in turn, leads to land/sea breeze systems with a marked diurnal wind reversal. Day-time winds are onshore at 3–5 m s\(^{-1}\) (table 2). As stated earlier, all images were taken under anticyclonic conditions (i.e., weak synoptic pressure gradients and almost cloudless skies).

4.1. Day-time

Examples of day-time thermal images in the three cities and their corresponding land-use distributions, are given in figures 1–4. The striking feature of these images is the close correspondence between land-use and temperature patterns.

4.1.1. Vancouver (figures 1 and 2)

The geographical setting of Vancouver (figure 1(a)) includes mountain slopes extending from sea level to peaks of almost 1.5 km elevation near the top of the images. The range is dissected by fjords (Indian Arm and Pitt Lake) and drained by numerous, often deeply incised, rivers. Certain of the lower slopes have been urbanized, the rest are largely covered by coniferous forest. The cities of Vancouver, Burnaby and New Westminster are located on hilly terrain whereas the municipalities of Richmond, Delta and Surrey lie on the deltaic flatlands of the Fraser River terminating at the Strait of Georgia. This area lying south of the Fraser River is mainly agricultural, interspersed with farm/commuter towns often located on sandy, tree-covered hills. (Note: in the following discussion specific locations of interest are referred to by letters printed on the corresponding land-use map, e.g. figure 1(b).

In the warm season image (figure 1c) the sea and mountain areas are very cool (off-scale). The main channel of the Fraser River and the Pitt River are both visible as cool ribbons despite the coarse pixel resolution. The coasts all show sharp temperature gradients. The largest warm area is clearly centred over the main urban area of Vancouver. Numerous other hot spots are readily associated with areas of dense urban or industrial development. For example, the most densely built-up areas of the municipalities of North Vancouver (A), New Westminster (B), Port Coquitlam (C), Richmond (D) and Surrey-Whalley (E) are easily demarcated as are the towns of White Rock (F), Cloverdale (G) and Langley (H). The thermal signatures of such areas are not surprising. Perhaps less expected is the prominent warmth of certain areas of light industrial activity, often including rather large buildings (in plan area) and extensive areas of paving. Examples include the False Creek (I), Central Valley (J), the north arm of the Fraser River (K), Tilbury Island (L), Newton (M) and Fraser Mills industrial areas (N) and the Vancouver International Airport (O).

The coolest areas are easily correlated with the open farmland of south-east Richmond (P) and the moist pasturelands of Pitt Meadows (Q) and south Surrey (associated with the Nicomekl and Serpentine Rivers) (R) and the Burns Bog peatland (S). It is also worth noting that the commercial core of Vancouver (T), consisting of many densely-packed tall buildings, is not the warmest area. Even
accounting for the 'contamination' of some pixel temperature values by the surrounding water the lack of warmth is notable.

The overall heat island intensity of Vancouver for the warm season image (figure 1(c)) is about 7.5°C, the largest of the case studies surveyed here. Surprisingly, the intensities for most of the other warm areas (the towns and industrial zones) are of a similar magnitude (approximately 4–6°C).

In the cold season day-time image (figures 2(a) and (b)) the land is cooler than the sea and a sharp coastal gradient is again evident. The river waters are cooler than the sea giving rise to a distinct thermal cold plume at the mouth of the main channel of the Fraser River (A) and in the coastal waters off West Vancouver (B) and Burrard Inlet (C) which receive the discharge of the rivers draining the snow-covered mountains. The absolute range of land temperatures is considerably less than in the warm season case. Upland areas are cooler than the average, e.g. Burnaby Mountain (D) and in the vicinity of Tsawwassen (E) and White Rock (F). The urbanized areas are definitely warmer than the rest of the land but heat island intensities are smaller (Vancouver 1.6, most other areas less than 1.0°). The warmest area in Vancouver is
Figure 1. (a) Location and (b) land-use maps of Vancouver, and (c) the surface radiant temperature distribution for the same area at 13.56 (LST) on 16 August 1985. The letters on (b) identify locations noted in the text and the rainbow brightness temperatures on (c) and other images are in °C.

Figure 2. (a) and (b) same as figures 1 (b) and (c) except at 14.18 (LST) on 16 January 1984.
centred on the industrialized zone along the north arm of the Fraser River (G) and extending northwards to cover an area of fairly dense residential development on the south-facing slope of South Vancouver and east to New Westminster (H). Relatively warm urban zones are also evident on the steep, south-facing slopes of West (I) and North Vancouver (J).

4.1.2. Seattle (figure 3)

Seattle is located near the south end of the Puget Sound on hilly terrain interspersed with numerous lakes (figure 3(a)). The largest of these, Lake Washington and Lake Sammamish play an important role in shaping the pattern of urban development. Strong control is also exerted towards the east due to the steep topography of the western slopes of the Cascade Mountain Range and the deep valleys of the Snoqualmie, Cedar and Green Rivers which drain from the south-east to the north-west. Most of the numerous suburban communities are situated in hilly areas and carved out of coniferous forest (e.g. Kirkland, Redmond, Bellevue, Renton, Kent, Auburn).

The autumn afternoon image (figures 3(b) and (c)) shows the water bodies (sea and lakes) to be much cooler than most of the land, except that at high elevation to the east of Greater Seattle. The correspondence of warm signatures with urban development is quite remarkable. Centres of conspicuous warmth are associated with the University district (A), downtown Seattle (B), Kent (H) and Auburn (I), Bothell (C), Kirkland (D), Redmond (E), Bellevue (F), Renton (G) and the town of Issaquah (J). In correspondence with Vancouver there are a number of clearly identifiable warm sites associated with industrial activity or large areas of pavement. For example, the Boeing Space Center (factory and airfield) (K) and Seattle-Tacoma International Airport (L) are both clearly identifiable warm spots in areas with otherwise relatively low population density. Major commercial and industrial areas within Seattle are also prominent. The heat island intensity of Seattle is difficult to estimate because of the complicated rural terrain, but the value for this image is about 5°C.

4.1.3. Los Angeles (figure 4)

The urban region of Greater Los Angeles occupies a coastal basin bounded by hills and mountains on three sides (figure 4(a)). There are also hills within the urbanized basin. The extensive urban development is characterized by relatively low density with scattered commercial and industrial centres. The natural vegetation on the hills is largely mesophytic grass, shrub and scattered trees.

The thermal image (figures 4(b) and (c)) shows all the features noted for the other two cities. On this autumn afternoon, the water and the upland areas are cool. Notice the strong influence of the San Gabriel Mountains to the north, the Santa Monica Mountains wedging in at the north-west corner, the Rolling Hills (A), the San Joaquin Hills (B) and the line of Chino Hills extending north-eastward from the centre of the right-hand edge. The warm areas are clearly related to mainly urban land uses. The pattern is somewhat more evenly distributed than the other city regions probably due to the merging of once-separate towns into an almost continuous conurbation. Virtually all of the warm spots are industrial or large commercial centres. The warmest area is located in South Norwalk (C), other major centres are Commerce-Maywood (D), east Whittier (E), Bellflower (F), Anaheim (G), Santa Ana (H), Torrance (I), Compton (J), Burbank (K), Industry (L) and Walnut (M). There
Figure 3. (a), (b) and (c) the same as figures 1 (a), (b) and (c) except for Seattle and (c) at 13.46 (LST) on 24 September 1985.

Figure 4. (a), (b) and (c) the same as figures 1 (a), (b) and (c) except for Los Angeles and (c) at 14.01 (LST) on 11 October 1985.
are a number of small warm spots related to freeway interchanges and town centres. On the other hand, well-vegetated residential districts such as Pasadena (N), Westwood (O) and Hollywood (P) are several degrees cooler. Many of these same features were also noted by Carlson and Boland (1978) and Carlson et al. (1981). Again, it is difficult to assign an overall heat island intensity due to the topographic complexity and lack of a simple rural environs. It is probably at least 5·5°C.

In general the survey yielded $\Delta T_{u-r}$ values between 5·5 and 7·5°C for all warm season day-time cases, despite winds of up to 5 m s$^{-1}$ (table 2). Cold season values were considerably smaller (1·0 to 2·7°C) even with winds as light as 1·0 m s$^{-1}$.

4.2. Night-time

Irrespective of season, the water of the Georgia Strait is always warmer than the land at night (figures 5(b) and (c)). The Fraser River is also usually relatively warm, and the coolness of the open agricultural land is very marked, especially in the summer (figure 5(b)). Within the urban area the correspondence between temperature and land use is less distinct than by day. The industrial effects are almost absent and the smaller settlements have virtually no signature. Indeed in the cold season image there is almost no thermal differentiation between the urban and rural land uses (figure 5(c)). Proximity to a water body seems to be the prime control. If pixels near the coast are omitted $\Delta T_{u-r}$ values are less than 3·5°C despite very weak winds and clear skies.

5. Surface and atmospheric heat islands

Unfortunately it is not possible to compare these satellite-sensed surface radiance temperatures with in situ air temperatures because concurrent observations were not conducted. Nevertheless we can make some comparative statements based on extensive heat island surveys of near surface ($\sim$1·5 m height) air temperatures undertaken in Vancouver and the well-established characteristics forming the consensus outlined in §2. Our group has conducted mobile heat island surveys on 92 occasions, 18 of which involved multiple units traversing the city to yield almost 400 data points in Vancouver and Burnaby (a sampling density of $\sim$2 thermal points km$^{-2}$). The resulting maps (e.g. Hay and Oke 1976, Oke 1976) reveal a general consistency in the distribution of warm and cool features. As a result of such comparisons the following conclusions are readily apparent.

1. The location of the warmest surface areas sensed by the satellite during the day-time is in industrial-commercial zones, especially those with large flat-topped buildings or extensive open areas of pavement (airport, shopping malls, major highway intersections). The highest surface temperatures are not usually found in the central business district where buildings are tall.

2. These zones are also the sites of relatively warm near-surface air temperatures by day.

3. The correlation between surface temperature and land use is much stronger than for air temperature in the day-time.

4. The day-time urban-rural surface temperature differences are considerably larger than those in the near-surface air. (In Vancouver warm season air differences are usually not greater than 2°C.)

5. Day-time urban-rural differences and intra-urban variability of surface temperature, are largest in the warm season.

6. Nocturnal urban-rural differences and intra-urban variability in surface temperatures are much smaller than in the day-time. This is the reverse of the case for
near-surface air temperatures. (In Vancouver warm season air differences of 10·2°C have been recorded (Oke 1981)).

(7) These results are in agreement with almost all other satellite-based studies (e.g. Carlson et al. 1981, Price 1979, Vukovich 1983, Lombardo 1985, Kidder and Wu 1987).

6. Discussion

The availability of satellite-derived thermal imagery raises a series of important questions regarding its interpretation and applicability to the study of urban climate. At first glance these data provide a veritable bonanza of relatively easily acquired, spatially-resolvable thermal information on the urban heat island which, in combination with energy balance models, provide a means of calculating surface energy fluxes and the magnitude of critical surface properties such as thermal admittance (inertia) and moisture availability (e.g. Carlson 1986). However, uncritical acceptance of these data can lead to erroneous conclusions which can confuse the search for physical understanding. Here, we mention four of the questions that require attention, viz,

(1) what is the nature of the surface ‘seen’ by the imagery?
(2) how do the observed radiant temperatures relate to the true temperatures of the full urban – air interface?
(3) what is the relationship between satellite-derived surface heat islands and those measured in the air? and
(4) how appropriate are these data as input to urban boundary-layer models?

6.1. The nature of the surface ‘seen’

The answer to question (1) is simple for the case when the city is directly under the track of the satellite (i.e. elevation angles $\approx 90^\circ$). The satellite-viewed surface is then a bird’s-eye or plan view. In a city this ‘surface’ consists of roof-tops, tree-tops, roads and open flat areas (parking lots, parks, gardens). This is only a subset of the facets of the three-dimensional urban surface with which the atmosphere is in contact—the active surface. For densely built-up sites the active area is very much larger than the plan area. (For example, cubic buildings separated by a distance equal to their characteristic length (i.e., at a plan density of 0·25) have an active area to plan area ratio of 2. A low density suburban area with scattered trees may have a ratio of about 1·5 while in a downtown core values may be $\geq 3$.) Missing are all the vertical surfaces, especially building walls and those areas underneath tree canopies. The surface viewed also consists of facets existing at different elevations in the urban system: ground, canopy and roof. This places them in very different turbulent environments.

For other tracks of the satellite relative to the target city, angles of elevation can become as small as $\approx 30^\circ$. Therefore, the amount of the vertical surface viewed is increased. For a given viewing angle this effect depends upon measures such as the active:plan area ratio of the target. The impact of this viewing geometry influence upon the satellite-sensed surface radiance temperature will also be affected by the configuration of the Sun, the satellite and the city, especially in relation to the solar irradiation of the three-dimensional urban structures. Most other urban heat island studies using satellite data neglect to mention this variable geometric effect. In this study, discussion is restricted to cases with relatively large elevation angles ($\geq 60^\circ$)
since most of our data are confined to this case (table 2). The importance of this effect over rough surfaces deserves detailed investigation beyond the scope of the present study.

6.2. *Observed versus true temperatures*

Putting aside the obvious sources of measurement error involving sensor limitations, atmospheric attenuation and variation of surface emissivity, the answer to question (2) is again closely tied to the influence of surface geometry. First there is the problem of under-sampling of the active surface as noted in §6.1. This becomes a significant source of error if the materials (and therefore often the temperature) of the viewed surfaces is very different from those obscured, thereby leading to an inaccurate average of the true active surface temperature. There is good evidence to suggest that this is often the case. The effect of viewing geometry is to have the thermal characteristics of buildings mainly represented by their roof. Roofs usually have a low albedo (Arnfield 1982) and are constructed to minimize conductive heat transfer. Hence they are good absorbers of solar radiation but have a low thermal inertia, a
Figure 5. (a) Vancouver land use and surface radiant temperature distribution for the same area (b) at 02.58 (LST) on 17 June 1985 and (c) at 03.32 (LST) on 14 February 1985.
combination leading to an anomalously large diurnal range of surface temperature (Goward 1981) in comparison with their walls.

The importance of this in a light industrial area is illustrated by figure 6. It shows colour enhanced infrared images of an area of south Vancouver obtained from an aircraft survey on a summer afternoon and at the end of the succeeding night. The thermal rainbows have the same colour sequence for the two occasions but both the absolute temperatures and the range of values is different. The objective is therefore to demonstrate which surfaces are warmer (yellow and red) or colder (blue and black) compared to the approximate image mean (green). The area is composed of a light industrial area (mainly warehousing and light engineering) on the right and residential (one- and two-storey houses with gardens and trees along the side streets) on the left. There is a school and a park in the bottom left-hand corner. The most striking aspect of the images is the fact that the roofs of both large industrial and small residential buildings are the hottest surface in the afternoon and the coldest at the end of the night. The parking lots and storage yards around the industrial buildings are also warm in the day. The parts of these yards that are close to the large buildings are also relatively warm at night. This is probably because of their reduced sky view factor (Oke 1987, pp. 351–355) due to the presence of warm walls.

It therefore seems that the observed day-time warmth of industrial areas in the three cities studied here and elsewhere, is probably due to the combined influence of the large roof and storage yard areas in such districts together with the lack of vegetation and moisture. The industrial area in figure 6 is part of that identified as the North Arm of the Fraser River (K) in figure 1 (b). Undoubtedly the warmth of some industrial areas is also due to heat release from combustion activity, but it does not seem to be a necessary condition.

The error introduced by the fact that satellite-viewing geometry effectively treats buildings as if they only had roofs is likely to be accentuated near midday, in the warm season and at low latitudes. Under these conditions high solar zenith angles favour energy receipt by horizontal rather than vertical surfaces and will lead to relatively large roof-wall temperature differences and therefore sampling errors compared with the true active surface value. At low zenith angles the differences may be reversed.

We might also note that, like the roofs, the low thermal inertia of tree tops also tends to over accentuate the diurnal temperature range of an area viewed from above compared with that actually found within and below the canopy where shade and longwave trapping tend to keep conditions more thermally stable, and of course masks the presence of the higher inertia materials of the substrate.

There is obviously no simple answer to question (2) but significant systematic errors probably exist and field studies to assess their magnitude are warranted.

6.3. Satellite surface temperature versus air temperature

Several studies have been undertaken to answer question (3) by seeking correlations between remotely-sensed heat islands and those observed in the UCL using standard or mobile stations. As demonstrated in the present study the relationship is found to be weak and, in one sense, reversed (i.e. the magnitude of $\Delta T_{air}$ is larger in the day-time when using pixel-averaged surface temperatures but larger at night using conventional near-surface air temperatures). Given that near-surface climates are known to be intimately coupled to that of the active surface this presents an apparent
dilemma. Here we suggest that a significant part of this apparent contradiction is due to the following:

(a) Lack of simple coupling between the surface and the air in the urban system. Even in simple environments the surface and air temperatures are not perfectly correlated. Unlike the surface temperature which is controlled by the surface energy balance, the air temperature is dependent upon the flux divergence in an air volume, including that due to horizontal transport (advection). Micro-advection is the norm in the UCL and greatly complicates questions of cause and effect in urban energetics. In the simplest example it is well known that heat island warm cores advect downwind from their source area (e.g. Chandler 1965).

(b) Biased spatial sampling of surface temperature by remote sensors. As already noted in relation to questions (1) and (2), satellite-sensed ground temperatures do not register the full active surface of urban terrain, tending to over-emphasize the role of roofs and tree tops. Further, they mix the values from ground surfaces with those from roof and tree tops, providing spatial averaging of the viewed surfaces into a single pixel value. Depending upon the urban geometry (active: plan area ratio) and materials, the pixel value may be disproportionately weighted in favour of one surface type. For example, a few very hot roofs or a large source of combustion heat may cause the pixel value to be relatively warm in an area where most of the active surface is much cooler. In addition the anomalous influence may be located where it has little effect on the UCL climate (e.g. a roof top or cooling tower). This over representation of the role of roofs and tree-tops makes the urban area appear to be more thermally
responsive than probably is true. If so it could help to explain the apparent reversal of the day/night heat islands determined by remote techniques compared with UCL air temperatures, i.e. by day (night) the satellite-viewed urban surface is anomalously warm (cold) thereby over- (under-) indicating the heat island compared to that of the true active area. It could also account for the curiously low values of apparent thermal inertia predicted by some models (e.g. Carlson et al. 1981).

(c) Failure to recognize the different scales of climatic phenomena in the urban atmosphere. Oke (1976, 1984) has stressed the need to define the relevant space scales when seeking explanation and understanding of urban climate phenomena and in the design of appropriate theoretical frameworks and observational arrays. In that context attempts to correlate pixel-average data of surface temperatures from horizontal surfaces at different elevations between ground and roof level with air temperatures at a few points within the near-surface air of the UCL must be seen as a methodological mismatch. In studies where the scales match there is reasonable agreement between remotely-sensed surface temperature and that in the near-surface air (e.g. Bärring et al. 1985, Goldreich 1985).

Many kinds of urban heat islands can and should be defined. They include those defined according to the medium sensed (air, surface or sub-surface), the location (surface nature and height of measurement) and, as shown here, the sensing technique. Great care and precise definition is necessary to avoid contributing to confusion and unscientific methodology. A heat island based only on 2 m level air temperature observations made at fixed stations in parks, should not be expected to coincide with that from automobile surveys over roads at the same height. They could, however, be combined to form a more representative UCL 2 m level survey. None of them may be anticipated to agree closely with results from thermometers on 10 m towers or from aircraft. The point is simple but does not seem to have been widely appreciated. Satellite-derived surface heat islands are in a separate class and it is not clear that they will match others measured by more conventional means in the UCL or the UBL.

6.4. Utility of satellite data in urban climate models

All the terms in the surface energy balance (except solar radiation) can be written as a function of the surface temperature. Solar radiation can readily be calculated. Therefore the availability of remotely-sensed, areally-averaged surface temperature raises the possibility of using a boundary-layer model with a surface energy budget to calculate areal values of surface admittance and moisture availability. For a review of such models see Carlson (1986).

By extension from more simple systems these models conceptually treat the surface as a warm, rough, moist plate of uniform surface properties and possessing no other geometry. When applied to canopy systems the effective surface involved in exchange, and to which the input and output properties apply, is considered by analogy with momentum exchange to lie at some zero-plane displacement height between the ground and the height of the roughness elements. Given the heterogeneity of the urban system, definition of this surface is very difficult, if not impossible, and its relevance to the surface viewed by a satellite is therefore similarly obscure. In many ways the areal averaging provided by a pixel is ideal but, as outlined in relation to questions (1) and (2), the bias introduced by not sensing the complete active surface and smoothing of signals within a pixel combine to create the temperature of a totally
different surface from that utilized in the models. The extent to which this mismatch is serious may not be immediately testable because the problem of defining the surface not only hinders our ability to model but also to observe. The latter makes it difficult to assign realistic model input properties and to gather field results with which to test model output. Hence the availability of satellite data presents us with a special case of a central conundrum facing urban climatology.

7. Conclusion

This study demonstrates that satellite-derived thermal imagery provides a fascinating and potentially valuable source of temperature data for cities. However it is argued that it is essential for investigators to appreciate the special nature of this information before making interpretations or comparisons with other types of heat island data. Satellite-derived data are surface radiant temperatures of only those surfaces seen by the radiometer and after it has been averaged across the area of a pixel. This defines a temperature characteristic of cities which is very specific to the observation system and which has a climatology of its own which should not be simply equated with that from other systems. The relevance of such information to models of UCL and UBL climate is not immediately obvious and deserves closer scrutiny.

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