SIMULATION OF SURFACE URBAN HEAT ISLANDS UNDER 'IDEAL' CONDITIONS AT NIGHT PART 2: DIAGNOSIS OF CAUSATION

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Abstract. A simple energy balance model which simulates the thermal regime of urban and rural surfaces under calm, cloudless conditions at night is used to assess the relative importance of the commonly stated causes of urban heat islands. Results show that the effects of street canyon geometry on radiation and of thermal properties on heat storage release, are the primary and almost equal causes on most occasions. In very cold conditions, space heating of buildings can become a dominant cause but this depends on wall insulation. The effects of the urban 'greenhouse' and surface emissivity are relatively minor. The model confirms the importance of local control especially the relation between street geometry and the heat island and highlights the importance of rural thermal properties and their ability to produce seasonal variation in the heat island. A possible explanation for the small heat islands observed in some tropical and Asian settlements is proposed.

1. Introduction

While the most important phenomenon of urban climatology and meteorology has been the near-surface urban heat island, the most active debate has been about the identification and especially ranking of its causative factors. Right from the first study of the heat island in London by Howard (1833), we have known the candidate causes considered responsible for the relative warmth of the air of cities (e.g., Oke, 1982):

1. Canyon Radiative Geometry – decreased long-wave radiation loss from within street canyons due to the complex exchange between buildings and the screening of the skyline.
2. Thermal Properties – increased storage of sensible heat in the fabric of the city.
3. Anthropogenic Heat – heat released from combustion of fuels and animal metabolism.
4. Urban 'Greenhouse' – increased incoming long-wave radiation from the polluted and warmer urban atmosphere.
5. Canyon Radiative Geometry – multiple reflection of short-wave radiation between the canyon surfaces, decreasing the effective albedo of the system.
6. Evapotranspiration – reduction of evaporating surfaces in the city putting more energy into sensible, and less into latent, heat.

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7. Shelter – reduced turbulent transfer of heat from within streets.

What has not been known is the relative role played by each of these causes and the linkage between the surface and air temperature regimes.

Part of the problem has been due to a failure to insist on scientific rigour in the definition of urban climate systems (including heat islands) and the fact that the study of urban energetics is very young. In the absence of heat balance information, some have tried to use measurements of temperature alone to infer the relative contribution of physical mechanisms, but this is not satisfactory, especially when the observations are confused by the changing influence of weather or when results from the surface and the air, and from different cities, seasons or climates are compared. Equally, the use of numerical models which are not tuned to the appropriate scale or have not been validated with field data tends to confuse matters further.

Here we attempt to reduce the question to its most basic level in order to provide a firm basis for later extension closer to the complexities of the real world. A model developed and validated in a companion paper (Johnson *et al.*, 1991) is used to study the interplay of the first four causes in the list at times when the other three are not directly active. We investigate the surface heat island on calm, cloudless nights when it is known to be most pronounced. The model provides an experimental framework within which individual controls may be varied and thus the sensitivity of the heat island to each may be assessed. Following this, we consider the influence of less than ideal weather, limitations to the model and the task of relating the simulation results to those from air temperature observations in real cities.

2. The Model

The model used is the force-restore version of the surface heat island model (SHIM) of Johnson *et al.* (1991). It is a simple energy balance model which simulates the radiative exchange, substrate heat conduction and thermal status of surfaces in near calm conditions at night when turbulent exchange can be neglected and radiative transfer is restricted to the long-wave portion of the spectrum. The model can be used to calculate the surface radiation budget and temperature of both horizontal and vertical surfaces typical of rural and urban street-canyon environments. In the canyon case it allows for a single reflection of long-wave radiation between canyon facets. The effect of space heating or cooling of buildings is accommodated by the use of a prescribed deep-wall temperature.

The input necessary to run SHIM consists of initial values of the surface, deep soil and deep-wall temperatures (T, T_G and T_B, respectively) at sunset, the thermal admittance of the surface [$\mu = (kC)^{1/2}$, where k is the thermal conductivity and C the heat capacity], the sky view factor of surfaces whose horizon is obstructed (ψ_s), the surface emissivity (ϵ) and the incoming long-wave radiation ($L\downarrow$). For a full urban heat island run, one rural and three urban-canyon (floor and two wall) surfaces need to be specified. Fuller details of the model and the results of comparisons between modelled and measured radiative fluxes and surface temperatures for several rural and urban canyon field sites are given in Johnson *et al.* (1991).

For the purposes of the numerical experimentation, one or more of the input variables are altered from a 'base' set. Unless otherwise specified the following base values typical of a temperate area are used: $T = T_G = T_B = 17°C$ for all rural and urban surfaces, $\mu = 1400\ \mathrm{J\ m^{-2}\ s^{-1/2}}\ K^{-1}$ for all surfaces, $\psi_s = 1.0$ (unobstructed) for the rural surface, $\epsilon = 0.95$ for all surfaces and $L\downarrow = 300\ \mathrm{W\ m^{-2}}$ for both environments. In the numerical experiments which follow, the urban surfaces modelled are chosen to be the mid-width of the floor and the mid-height of the walls of a street canyon with symmetric cross-section. The following subscripts are used: for systems r – rural, u – urban; for surfaces r – rural, f – floor, w – wall. For urban-rural comparisons of T and L^*, the urban value is chosen to be that of the canyon floor.

3. Evaluation of Causes

In this section, we assess the effects of radiation geometry, thermal properties, anthropogenic heat and the urban 'greenhouse' effect in generating the surface urban heat island at night. The model is also used to investigate the effects of urban-rural differences of surface emissivity.

3.1. The effect of radiation geometry (ψ_s) on long-wave radiation

A first numerical experiment is to isolate and assess the influence of the radiative geometry of urban streets, i.e., all other factors which influence urban-rural temperature differences are held constant at their 'base' values but the canyon sky view factor (ψ_s) is varied.

The view factors selected for the canyon floor are 0.2, 0.4, 0.6 and 0.8, corresponding approximately to height : width (H/W) ratios of 2.45, 1.15, 0.67 and 0.38, respectively. These span the range from the deepest city canyons in the centre of large North American cities to those in the centre of small towns (Oke, 1981, Table 3).

Altering the canyon cross-sectional geometry has the important effect of changing the exchange of infrared radiation between the sky and the walls and floor of the canyon. For a point on the canyon floor, it replaces a fraction of the cold sky hemisphere with much warmer surfaces which both intercept a portion of the long-wave output from the floor and radiate back a greater amount. The resulting decrease in net long-wave loss is therefore directly related to ψ_s. In fact, the relationship between the two for a canyon with walls and floor at similar temperatures is close to linear, as can be inferred from the spacing of the curves in Figure 1(a).

Since the net long-wave radiation determines the energy drain and therefore the rate of cooling by the system, it follows *ceteris paribus* that the surface temperature associated with each canyon geometry, and the difference between each of these and the rural surface (the heat island intensity), is governed by ψ_s (Figures 1(b and c)). It emerges that under the base conditions canyon, geometry alone can produce a heat island of at least 5 deg following sunset (1.1, 2.3, 3.6 and 5.2°C at $\psi_s = 0.8$, 0.6, 0.4 and 0.2, respectively). As will be shown later, the effect of the geometry can be larger (smaller) than this depending especially on whether μ_r is lower (higher) than the base value. Realistically, the maximum effect of geometry alone appears to be of the order of 7 deg (see Figure 3 later).

When the points located at the mid-canyon width and mid-wall height are compared, the radiation budget of the walls is always slightly less negative and they are therefore always slightly warmer. It should however be noted that these points do not fully characterize each facet. The floor mid-width has the highest ψ_s for the floor whereas the wall mid-height is intermediate between high ψ_s at the top and low values near the base of the wall.

3.2. The effect of thermal properties (μ)

In this experiment, the thermal admittance of the surface is altered whilst all other variables are held at their base values. We choose to compare flat environments (i.e., $\psi_s = 1.0$) so that the effects of geometry are eliminated. It is unrealistic to have a city without canyons but this strategy serves the aim of demonstrating the effect of thermal properties alone. We could have had both urban and rural areas with canyons but the effects would be more muted. The more realistic combined effects of geometry and thermal properties are outlined in Section 3.3.

The thermal admittances chosen in addition to the base value are 600, 1000, 1800 and 2200 J m^{-2} s$^{-1/2}$ K^{-1}. At the low end of this range, the values are typical of dry soils, deserts and old snow, at the high end, surfaces such as saturated clay and stone (Oke, 1987). Low values are associated with surfaces which do not readily release heat from storage to offset the surface radiative loss and therefore experience a relatively large temperature drop at night. Thermally conservative surfaces have high μ values. It is often assumed that a prime reason for the nocturnal heat island is that because of the different thermal properties of their constituent surfaces, urban systems are better storers and releasers of heat and cool down less rapidly at night than rural areas.

The effect of μ alone is similar to, but not as linear as, that of geometry (Figure 2). Using the base value of $\mu_r = 1400$ J m^{-2} s$^{-1/2}$ K^{-1}, a heat island of about 2 deg develops if the urban value is 800 units larger but a cool island of over 4 deg may form if the urban value is the same amount smaller (Table I). Obviously the largest heat island, due to thermal properties alone, occurs when $\Delta\mu_{u-r}$ has its largest positive value, at which time a difference of over 6 deg can be generated

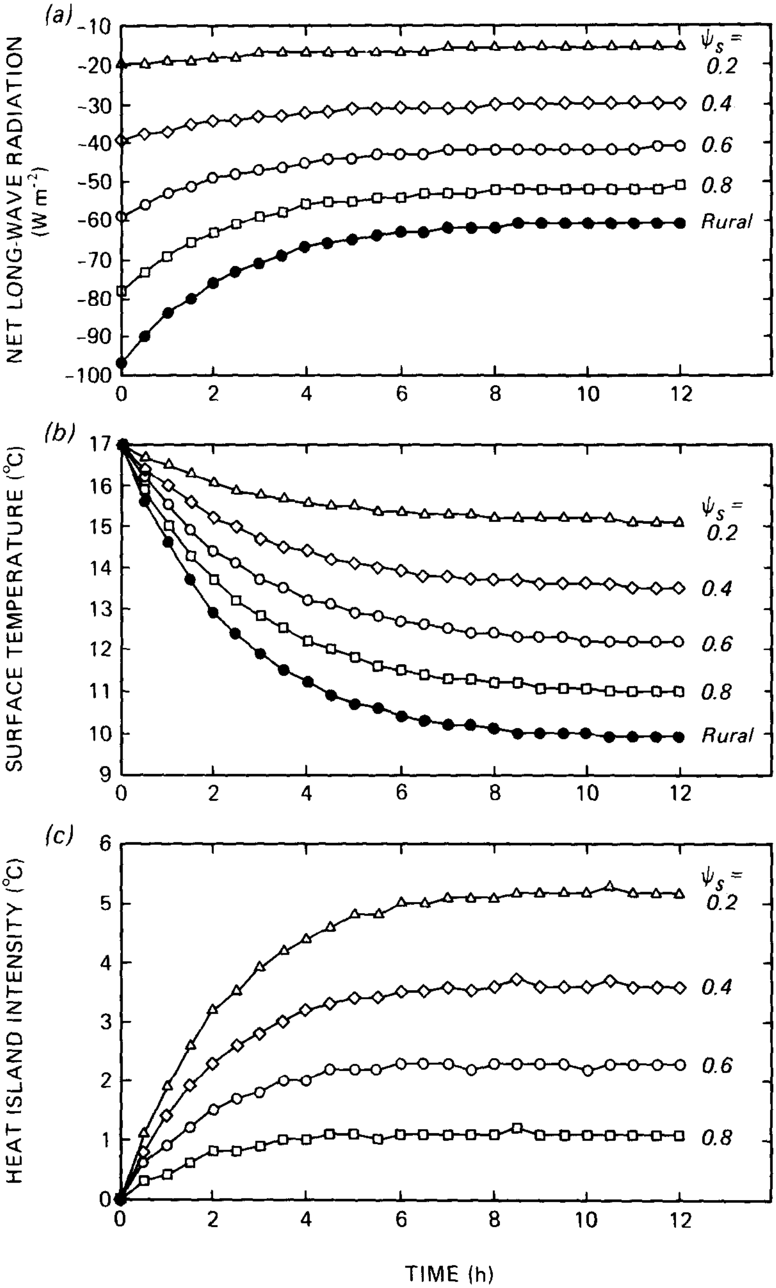

Fig. 1. The variation of (a) net long-wave radiation, (b) surface temperature, and (c) heat island intensity following sunset for different urban canyon geometries (sky view factors) using the base data set.

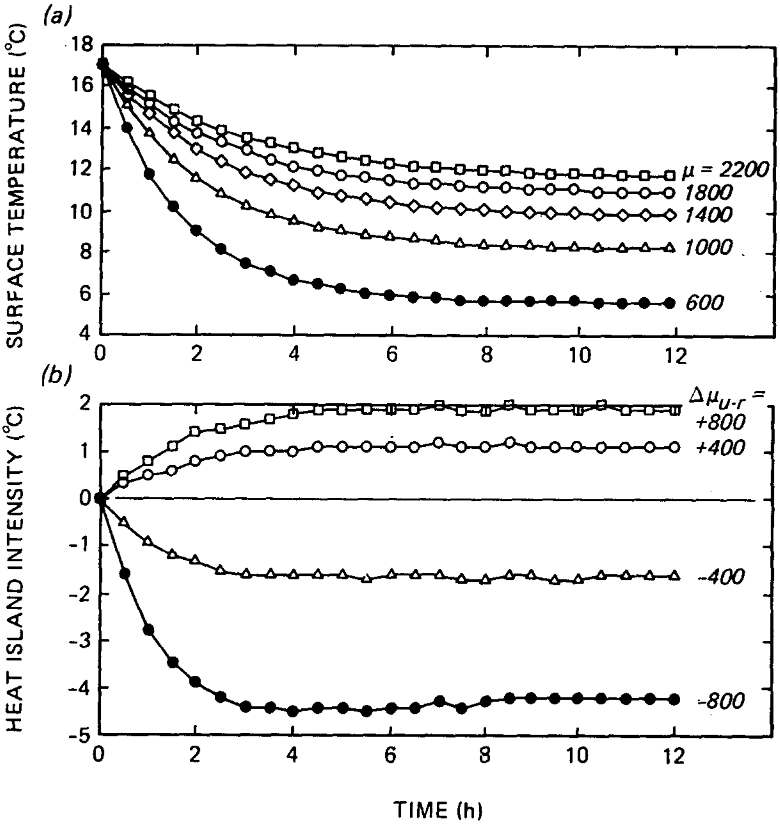

Fig. 2. The variation of (a) surface temperature and (b) heat island intensity following sunset using the base rural data set with different 'urban' thermal admittances and both environments flat (i.e., $\psi_s = 1.0$).

(Table I). It should be noted that this is only possible where the rural admittance is low (dry soils, desert sand, snow-covered). Cities whose environs are characterized by high admittances (wetlands, irrigated soils, paddy fields or rock) can only support small heat islands.

Thus Figure 2a demonstrates the apparently little appreciated fact that the nocturnal growth of the urban heat island is ultimately limited by the ability of the rural surroundings to cool. Even in the unlikely circumstance that the city does not cool at all, if $\mu_r = 2200\,\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$, the increase of the urban-rural difference cannot exceed 4.3 deg over a 12 h night whereas with $\mu_r = 600\,\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$, it can be as large as 11.3 deg (Figure 2a). Also, and unlike ψ_s, the role of μ varies seasonally with the moisture state of the ground and the extent of any insulating snow or plant cover.

3.3. The combined effects of geometry and thermal properties

In reality, the effects of geometry and thermal properties act together over a wide range of combinations. In fact their values are linked by the need to use different

TABLE I

The effect of surface thermal admittance differences ($\Delta\mu$) upon surface temperature differences (ΔT) at the end of a 12 hr cooling period. One surface is designated 'rural', the other 'urban' even though the latter has no canyon geometry. Units of all thermal admittances in $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$ and all temperatures in Celsius

$\mu_r = 600$		$\mu_r = 1400$		$\mu_r = 2200$	
$\Delta\mu_{u-r}$	ΔT_{u-r}	$\Delta\mu_{u-r}$	ΔT_{u-r}	$\Delta\mu_{u-r}$	ΔT_{u-r}
+1600	6.1	+800	1.9	−400	−0.8
+1200	5.3	+400	1.1	−800	−1.9
+800	4.2	−400	−1.6	−1200	−3.5
+400	2.6	−800	−4.2	−1600	−6.1

Positive $\Delta\mu_{u-r}$ indicates that the urban is larger than the rural value.

materials to construct buildings of different size, and their roles are linked since the geometry sets the relative influences of the walls versus the floor. These facts introduce the likelihood that preferred combinations of these two factors will create underlying intra-urban and inter-urban thermal relationships. As will emerge, these two are the dominant factors in other than extreme conditions. Therefore an appreciation of their interaction does much to elucidate the primary controls on the nocturnal heat island.

Figure 3 contains the maximum value of ΔT_{u-r} after sunset (almost always at the end of the 12 hour-long night). This is calculated as the difference between T_r simulated using one of three values of μ_r (600, 1400 and 2200 $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$) and T_u using all the possible combinations of five ψ_s (0.2, 0.4, 0.6, 0.8, and 1.0) and five μ_u (600, 1000, 1400, 1800 and 2200 $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$). The middle set of five curves, using the rural base input values, shows the two cases already discussed. The effect of ψ_s alone is given by the values in the middle of the four $\psi_s < 1.0$ curves, aligned vertically at $\Delta\mu_{u-r} = 0$. The effect of the thermal properties alone is given by the points along the $\psi_s = 1.0$ curve at $\Delta\mu_{u-r} = \pm 400$ and ± 800 (compare with the central columns of Table I).

In general terms, the following features emerge from Figure 3:

(a) a decrease of canyon ψ_s always leads to an increase in ΔT_{u-r};
(b) the ψ_s-related increase is non-linear becoming larger for narrower canyons;
(c) *ceteris paribus*, heat island magnitude increases as μ_r decreases;
(d) with large μ_r, it is not unusual to produce small or negative (cool) islands;
(e) the most favourable combination of geometry and thermal properties can produce up to 10 deg of heat island development after sunset;
(f) the sensitivity of the heat island to these two controls is approximately equal.

This figure can be used to gauge the approximate magnitude of the maximum heat-island intensity to be expected in a city once the value at sunset is known or estimated. Similarly if the relation between μ_r and soil moisture is known (e.g., Sellers, 1965, Figure 40), it shows the potential for seasonal variation of ΔT_{u-r}. Perhaps the most striking interpretation to be drawn from Figure 3 is the impor-

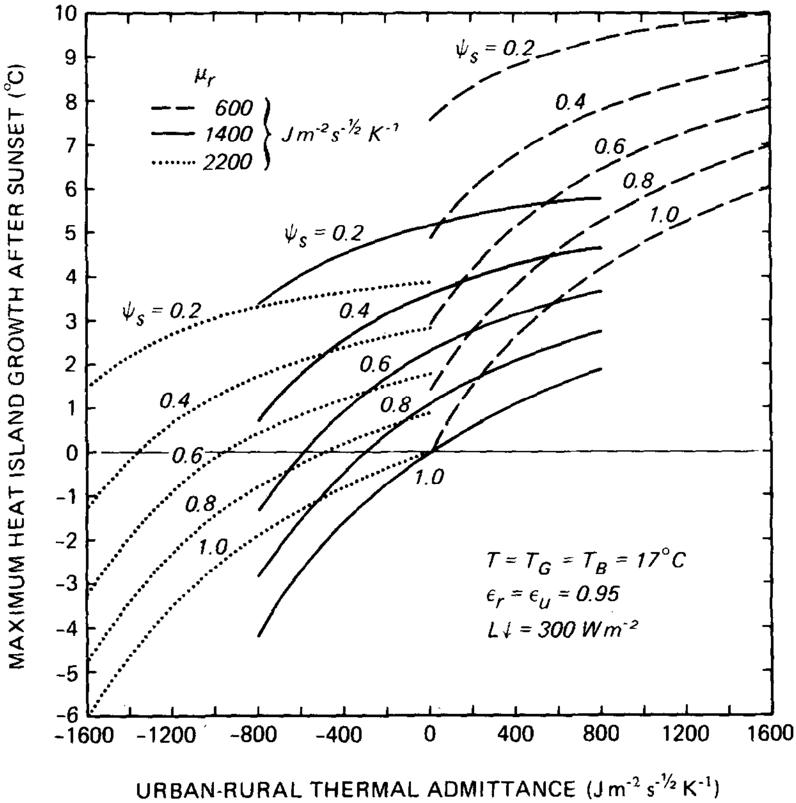

Fig. 3. The maximum intensity of the nocturnal surface heat island in relation to the sky view factor (ψ_s) of urban canyons and the difference between the thermal admittance of the urban and rural environments ($\Delta\mu_{u-r}$). Three sets of curves, each for a different absolute value of the rural thermal admittance. All other properties are set to their base values.

tance of the rural thermal admittance to the magnitude of the nocturnal surface heat island. Given this, it is a sobering fact that almost none of the heat island studies of the past have provided data on this crucial control.

The model allows the thermal admittance of the canyon walls to be set at a different value from that of the floor so we can see the effect of canyon materials. In order to keep some basis for comparison, we choose to alter μ_w whilst keeping μ_f and μ_r at the base value of $1400\,\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$ (Table II). Decreasing μ_w reduces the ability of the walls to draw upon the deep-wall heat source as the surface cools; therefore T_w drops below that in the base simulation. The effect on ΔT_{w-f} is largest in the most open canyon but because the heat-island intensity is small with open canyons, its impact on ΔT_{u-r} is only slight. Increasing μ_w facilitates heat flow from the building interior, retards cooling of the wall exterior and allows the walls to be warmer than the floor; however, the increase in ΔT_{u-r} as a result of feedback to the canyon floor is minimal (Table II). The size of ΔT_{w-f} and ΔT_{u-r} can be larger than depicted here if more extreme combinations of μ_w and

TABLE II

Effect of changing wall thermal admittance (μ_w) on wall-floor and urban-rural temperature differences. All values except μ_w kept at base values

μ_w ($J\ m^{-2}\ s^{-1/2}\ K^{-1}$)	$\psi_s = 0.2$	0.4	0.6	0.8
Wall-floor differences from base case				
600	−1.0	−1.7	−2.2	−2.5
1000	−0.4	−0.6	−0.8	−0.9
1800	0.1	0.4	0.5	0.6
2200	0.2	0.7	0.9	1.1
Urban-rural differences from base case				
600	−0.4	−0.5	−0.4	−0.2
1000	−0.1	−0.2	−0.2	−0.1
1800	0.1	0.1	0.1	0.0
2200	0.2	0.2	0.1	0.1

μ_f are used but the effect on the heat island is still not very strong. Of course if the wall exterior temperature is significantly different than the deep-wall value, the impact of wall thermal properties increases (Section 3.4).

3.4. The Effect of Anthropogenic Heat

Heat released as a by-product of fuel combustion can enter into the surface energy balance of an urban canyon. The primary source is the heat released to accomplish space heating of building interiors in cold climates. If there is a temperature difference between the building interior and its exterior, heat will flow between them due to conduction and air leakage. In the present model, we approximate this flow by keeping T_B constant at 17°C whilst varying the initial surface values of T_w, T_f and T_r and the deep temperatures of all surfaces together (i.e., maintaining isothermal conditions at sunset). We also vary $L\downarrow$ so as to preserve the same initial rural L^* forcing. The combinations used are: $T_w = T_r = T_G = T_f = -3$, 7, 17 and 27°C with $L\downarrow = 200$, 247, 300 and 358 W m^{-2}, respectively. The further these temperatures are below (above) 17°C the greater the heat flow out (in) and therefore the greater must be the anthropogenic heat production for space heating (withdrawal for air-conditioning) to maintain constant T_B.

The result (Figure 4) indicates the potential for a very significant role for anthropogenic heat if the exterior temperature forces building climate control. A 20 deg drop in temperature doubles the base case heat island intensity for all canyon shapes. When any effects of $\Delta\mu_{u-r}$ are added very large heat islands seem possible. The largest air temperature heat islands (of 14 deg) have indeed been recorded in cold cities with snow-covered rural surroundings: Fairbanks, Alaska (Bowling and Benson, 1978) and Moscow, USSR (Rastorgueva, 1979). On the other hand, if the exterior temperature exceeds T_B, the heat island is decreased as heat is absorbed by the building structure.

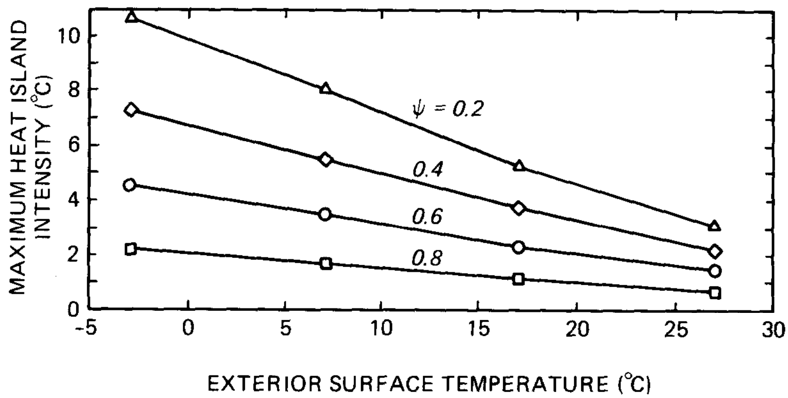

Fig. 4. The effect of anthropogenic heat control on the surface heat island intensity for the case of four street-canyon geometries. The deep building temperature is maintained at 17°C and the sunset value of L_r^* is kept at $-97\ \mathrm{W\,m^{-2}}$ while the exterior temperature is varied.

Lest these results be regarded uncritically, two points should be mentioned. First, since the extent of this effect is governed by μ_w, the appropriate value should apply to the bulk characteristics of the full depth of the wall, not just its outer cladding. In cold climates, insulation will reduce μ_w (in fact the value used here may be too large) so the effect will be reduced. Second, in the case of high exterior temperatures, active cooling systems may not be employed and T_B may be allowed to climb, ameliorated only by passive cooling techniques. Moreover, if air conditioning is used, some systems vent hot air to the exterior where it will warm the atmosphere. This model does not account for heat release from such vented sources or by vehicles in the street. Their impact on the temperature of the surface is much less than upon the air.

3.5. The Effect of the Urban 'Greenhouse'

The urban atmosphere is warmer, usually is more polluted and often has a different humidity from that of the rural environs. Whilst the relative roles of these characteristics are not agreed upon, there is observational evidence to show that their combined effects increase sky long-wave radiance over the city. In a large city, these differences can be up to $40\ \mathrm{W\,m^{-2}}$ but are typically about $15\ \mathrm{W\,m^{-2}}$ (Oke and Fuggle, 1972; Kobayashi, 1982; Estournel *et al.*, 1983). This extra radiative input to the urban canyon will reduce the net radiative drain. To simulate this, we compare the base results with those obtained when $L\downarrow_u$ is increased from the base value of 300 to $340\ \mathrm{W\,m^{-2}}$ whilst keeping $L\downarrow_r$ constant at the base value.

The impact of increasing $L\downarrow_u$ on the heat island is straightforward (Figure 5). There is an almost linear increase in ΔT_{u-r} with $L\downarrow_u$. Further, the effect increases with ψ_s. For the deepest canyon, the increase in ΔT_{u-r} is typically only about 0.3 deg with a maximum of 0.7 deg. In the most open case, the respective increases are 0.9 and 2.4 deg. The wall-floor temperature difference (not shown) becomes smaller with increased $L\downarrow$, because the floor has the largest sky view of all facets.

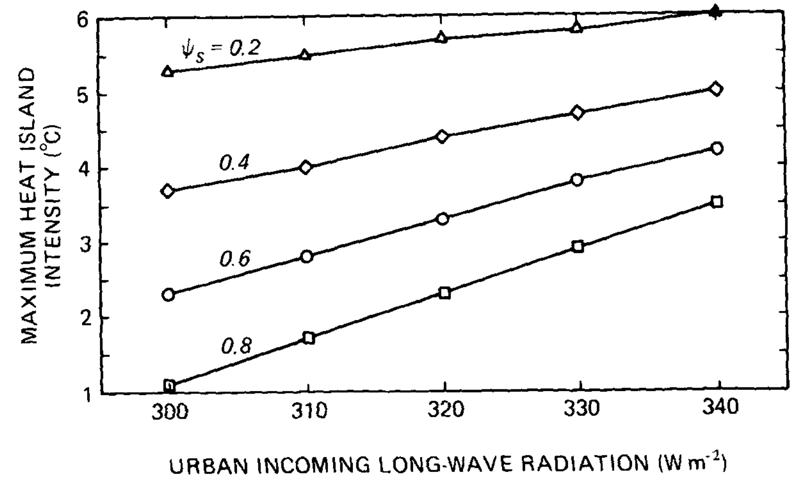

Fig. 5. The effect of increasing the incoming long-wave radiation from the urban 'greenhouse' upon the surface heat-island intensity for four canyons with different geometry.

It is important to realize that the potentially relatively large effects produced for open canyons are unlikely to be realized. The greatest 'greenhouse' effect is likely to be found in the largest cities which have the deepest canyons (Oke, 1981).

3.6. The effect of surface emissivity (ϵ)

Although it is hardly ever mentioned, systematic urban-rural differences of surface emissivity hold the potential to cause a portion of the heat island (Yap, 1975). In most natural environments, this property does not give rise to significant spatial variation of temperature because most surfaces have similar values, but in urban areas, some building materials have rather low emissivities (Arnfield, 1982). This is simulated by running the urban and rural base cases with the emissivity of the canyon walls and floor changed to values of 0.85, 0.90 and 1.0.

Under the base conditions, the role of emissivity is minor. As ϵ_u is increased from 0.85 to 1.0, there is a slight increase of 0.4 deg in ΔT_{u-r} for the $\psi_s = 0.2$ canyon, almost no change for the $\psi_s = 0.4$ case and a maximum decrease of 0.5 deg for the $\psi_s = 0.8$ canyon. SHIM only allows single reflection of radiation in the canyon; inclusion of multiple reflection would increase the effects of emissivity.

4. Extension of SHIM

This paper focusses upon the special case of the heat island in cloudless and calm conditions. It is relatively easy to extend the model to investigate the control exerted by nocturnal cloud.

The effect of cloud type (cloud base temperature) on $L\downarrow$ can be simulated using the Bolz coefficients (e.g., Sellers, 1965; Oke, 1987). Since the cloudless sky base

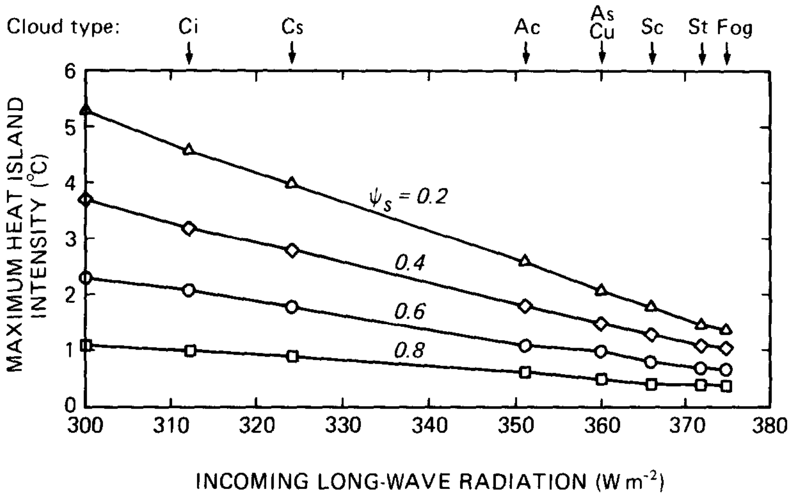

Fig. 6. The effect of seven different cloud types, upon the surface heat-island intensity assuming an overcast sky.

value of $L\downarrow$ is 300 W m^{-2}, under overcast skies with Cirrus (Ci), Cirrostratus (Cs), Altocumulus (Ac), Altostratus or Cumulus (As or Cu), Stratocumulus (Sc), Stratus (St) and Fog (F), the values will be 312, 324, 351, 360, 366, 372 and 375 W m^{-2}, respectively. The effect on the heat island is then calculated in the same manner as the effect of the urban 'greenhouse' with the important difference that the increase now applies to both the rural and urban environments.

The result (Figure 6) shows that the increase in $L\downarrow$ produced by cloud causes a decrease in ΔT_{u-r} from the base values on the left-hand side. The reason is that the crucial rural radiation budget and surface cooling are affected most because the surface is fully open to the sky there. The rate of decrease is greatest for the deepest canyons because they benefit least from the increase in $L\downarrow$. If a partial cloud cover is involved, the effect increases up to the maxima given here in proportion to the square of the fractional cover.

An interesting and not uncommon case occurs when the rural area is blanketed by fog but the city is fog free. Using the base values but with $L\downarrow_r = 375$ W m^{-2}, the rural surface only cools 1.5 deg over the night. This results in no heat island for the $\psi_s = 0.2$ canyon and cool islands of -1.6, -2.9 and -4.1 deg for the 0.4, 0.6 and 0.8 canyons because cooling to the cloudless urban sky is permitted.

The role of wind speed on turbulence and advection cannot be incorporated into the model in a simple fashion. As a first approximation, note that ΔT_{u-r} in the air decreases as the inverse square root of the speed (e.g., Oke, 1973; Uno *et al.*, 1988).

SHIM could be used to predict intra-urban spatial patterns of the heat island. The building density and land-use across a city are accompanied by preferred mixes of radiation geometry, thermal properties and anthropogenic heat flux density. In general they reinforce each other so that intra-urban spatial variability is increased but since SHIM only applies to calm conditions, the accompanying effects of advective exchange between different thermal climates within a city would not be included.

5. Limitations of SHIM

The form of the cooling curves produced by SHIM does not lend itself easily to the establishment of the time when the maximum heat island occurs. In most cases, ΔT_{u-r} grows throughout the night so that the maximum occurs at sunrise. This matches the pattern of growth in some cities, especially in the tropics (e.g., Jauregui, 1986b) and in a scale model study (Voogt, 1989). But this is not the case in another scale-model study (Oke, 1981) or in most cities where the maximum occurs at some intermediate time (e.g., Hage, 1972; Oke and Maxwell, 1975; Lee, 1979; Taesler, 1980; Helbig, 1987). Typically, the maximum occurs several hours after sunset and then remains almost constant or the intensity gradually declines through the rest of the night. SHIM is unable to mimic the latter pattern. This failing was noted in Johnson *et al.* (1991).

It is not totally clear how SHIM estimates relate to the large body of heat island observations using air rather than surface temperatures because the coupling between the two, which involves flux divergence, is not included. Under ideal cooling conditions the rural surface is cooler than screen-level by several degrees, while in urban canyons, the difference is less and commonly the surface is the warmer (Barring *et al.*, 1985; Nakamura and Oke, 1988). This suggests that surface heat islands are larger than those in the air at night. In the section which follows, we shall assume that the two are linked but no exact relationship is inferred. The urban surface temperatures used here (T_f and T_w) must not be confused with integrated effective surface temperatures of cities measured from aircraft or satellites which are dominated by roof-top influences (Roth *et al.*, 1989).

SHIM only predicts the development of surface heat islands after sunset. This urban-rural difference therefore has to be added to that existing at sunset and there is no simple method to estimate the latter. Usually the sunset heat island is positive (e.g., the cases in Johnson *et al.*, 1991) but negative values are also possible (e.g., Jauregui, 1986b). Therefore, the growth of the nocturnal heat island can start from a very different base set by daytime conditions in both the city and its environs.

6. SHIM Results and Heat Island Studies

The simulations indicate that in the absence of large anthropogenic heat control, the nocturnal surface urban heat island is primarily due to the radiative effects associated with canyon geometry and the storage effects associated with the thermal properties of the canyon materials. They thus confirm the importance of local surface morphology in urban canopy heat island development.

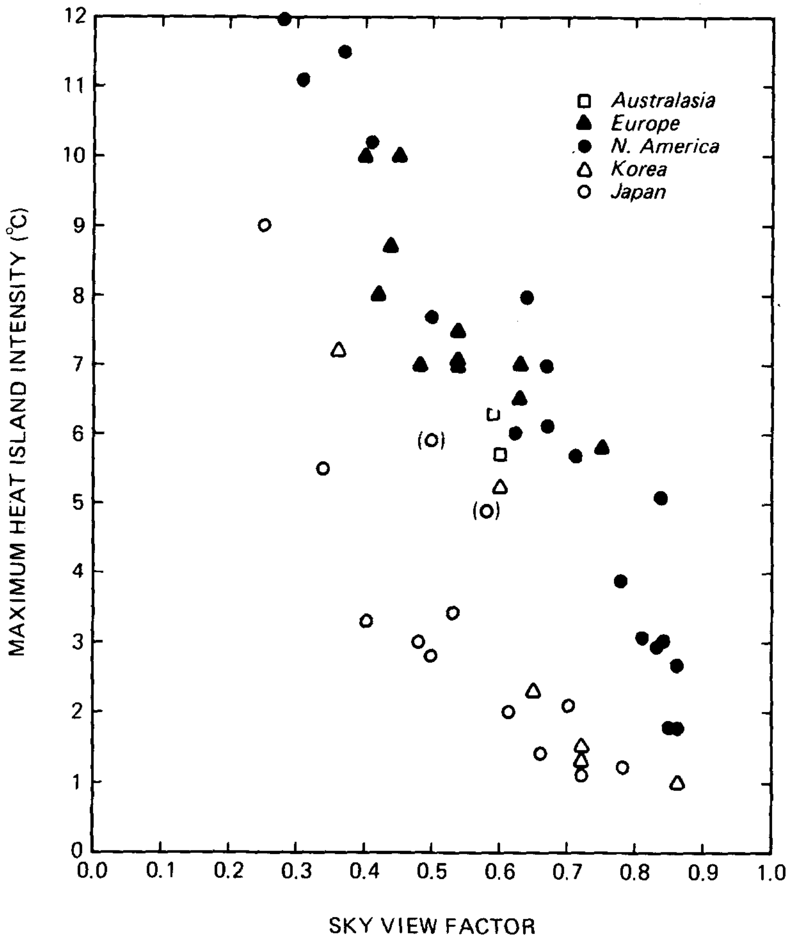

Fig. 7. The relation between the maximum heat island observed in a settlement and the canyon sky view factor of its central area. The European/North American/Australasian data are for calm, cloudless nights in summer gathered using automobile traverses through the city centre and into the surrounding rural area. Data from Oke (1981) with minor amendment to ensure summer only. The Japanese and Korean data are from Park (1987). Japanese data in brackets are from Hokkaido.

Based on an analysis of the results of a scale model, Oke (1981) suggested a relation between the maximum heat island observed in a city and the sky view factor:

$$\Delta T_{u-r(\max)} = a - b \cdot \psi_s \,. \tag{1}$$

He stressed that ψ_s is a surrogate for more than the effects of canyon shape on radiation because other morphological factors are automatically tied to geometry, including the thermal properties of the building materials, the density of anthropogenic heat release and the removal of greenspace. The form of Equation (1) was found to be a fair representation of summer air temperature heat island data from 31 settlements in Europe, North America and Australasia (Figure 7).

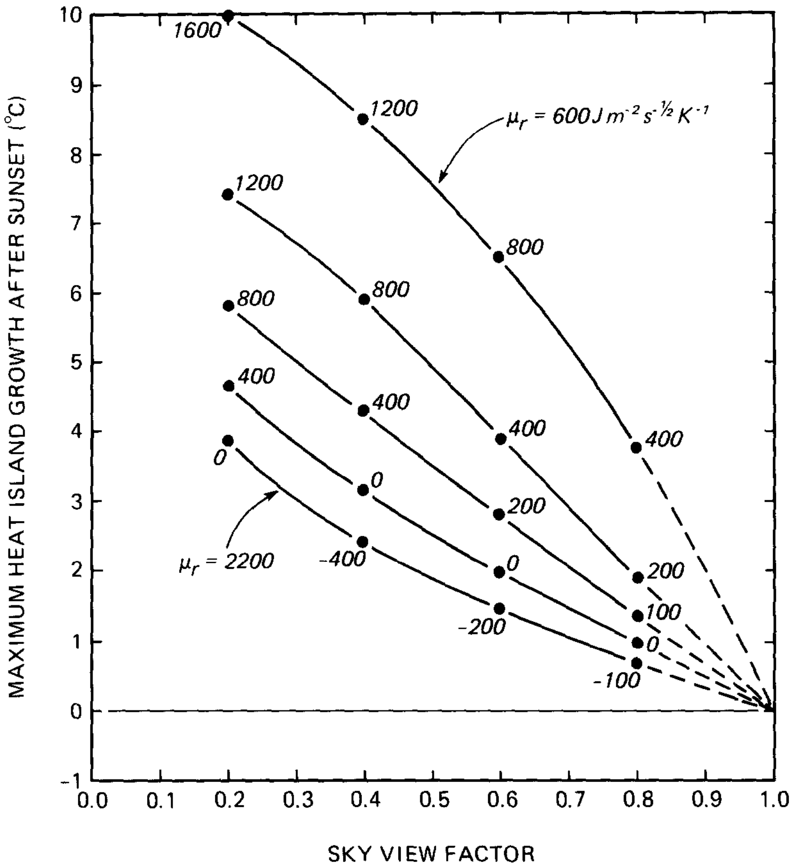

Fig. 8. Simulated relationships between the maximum heat island intensity and the urban street geometry. For details of construction see the text. The curves are for five values of rural thermal admittance at increments of 400 units from 600 (upper) to 2200 J m^{-2} s$^{-1/2}$ K^{-1} (lower). The figures on the curves refer to the values of $\Delta\mu_{u-r}$.

Subsequent studies confirm the general nature of this relation (Barring *et al.*, 1985; Yamashita *et al.*, 1986; Park 1987). SHIM can confirm the reason for the form of this relation and explain the cause of some of the scatter.

If it is assumed that in Equation (1), ψ_s represents only radiative effects, then SHIM estimates of $\Delta T_{u-r(\max)}$ at the surface (e.g., Figure 1c) are far too small to match those observed in the air. If the effects of $\Delta\mu_{u-r}$ are included as a constant difference at all ψ_s, SHIM estimates become large enough but describe straight lines which cut across the graph with no possibility of converging towards the reasonable expectation of small heat islands as $\psi_s \to 1.0$. A satisfactory solution is found when μ_u is allowed to vary with city size as in Figure 8. This graph is constructed from runs of the surface heat island model using the base conditions and various combinations of μ_r, μ_u and ψ_s. Most of the values necessary to create this graph are found in Figure 3. We arbitrarily set μ_u to the values 2200 and

$1800\,\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$ for $\psi_s = 0.2$ and 0.4, respectively, on the expectation that such deep canyons are often constructed of dense materials with high thermal admittance. (However, it should be recognised that many modern buildings are constructed with light cladding rather than having solid walls.) At larger ψ_s, the value of μ_u is graded towards μ_r (see numbers on the curves) on the premise that as the canyon geometry becomes more open (and often the community smaller) the construction materials become less dense and the role of the underlying ground (assumed to be the same as the rural ground) increasingly asserts itself.

Figure 8 shows that estimates of surface $\Delta T_{u-r(\max)}$ involving the effects of ψ_s and $\Delta\mu_{u-r}$ are of the same order as those observed in the air of real cities and follow a similar relation to street geometry. It also demonstrates the remarkably important role of μ_r and the sensitivity of the heat-island increases as μ_r decreases.

The nature of Figure 8 may help to explain some of the confusion over the seasonality of ΔT_{u-r}. Some cities apparently exhibit their largest heat island in the summer, others in the winter. In a city where anthropogenic heat effects are not important, a significant portion of the seasonal effects must be related to changes of thermal admittance, especially in the rural area, due to changes of soil moisture, snow cover or vegetation canopy. The largest value may then be expected in the summer if that is when soils are dry, vegetative insulation is in place and daytime solar absorption by the urban fabric is large. This means that in tropical cities with little anthropogenic heat use, *ceteris paribus* the largest heat islands may be expected in the dry season, if there is one. This agrees with observation (Tyson *et al.*, 1972; Philip *et al.*, 1973; Bahl and Padmanabhamurty, 1979; Jauregui, 1986a). The seasonal timing of the maximum heat island for the case of a city with a cold climate and a large space heating demand is less easy to predict. It may be largest in winter when its energetics are dominated by anthropogenic heat and enhanced by the presence of a rural snow cover and/or a polluted atmosphere or it may occur in summer for the reasons already elaborated.

The sensitivity to μ_r seen in Figure 8 may also help to explain the difference in the relation between ΔT_{u-r} and ψ_s found for European/North American/Australasian cities by Oke (1981) compared with that for Japanese/Korean cities reported by Park (1987). The results for the Asian cities follow the form of Equation (1) but the ΔT_{u-r} values, especially for the smaller more open settlements, are consistently smaller (Figure 7). At least three possibilities exist: first, the test data are inappropriate, second, Asian cities are unlike others or third, the rural surroundings of these cities are different. On the first two points, there are reasons to query the appropriateness of some of the Asian data because of the use of winter surveys and the adequacy of rural sampling, and there is the fact that many smaller Asian cities are constructed of rather light materials (especially wood), but here we suggest that it may be most fruitful to pursue the third possibility.

Most Japanese settlements, and especially the smaller ones, are surrounded by paddy fields which greatly increase μ_r in the growing season and keep soil moisture high throughout the year thereby reducing rural cooling. For example, Park (1987) shows total rural cooling of only 4.6 deg from sunset to sunrise near Gifu City (35° N) on a calm, cloudless summer night. Such conditions put an absolute limit upon heat island development no matter how favourable the urban characteristics. A difference of only about 800 J m^{-2} $s^{-1/2}$ K^{-1} in μ_r between the Asian and other data sets is sufficient to explain the lower heat island intensities (Figure 8). Such a difference is well within the expected range, given that the non-Asian data are from the summer when soil moisture and therefore μ_r are usually at their seasonal low. Since the paddy fields are engineered, their properties are not likely to be similar to the ground of the urban areas they surround. This could explain the fact that the Asian data appear to extrapolate to cool islands at large ψ_s (Figure 7). It is also interesting to note that two of the Japanese points (bracketed) in Figure 7 lie well above the rest and almost join the European/North American/-Australasian group. Both points are from Hokkaido, above latitude 43° N, where the area of paddy fields is relatively small, seedbeds are dry not inundated (Trewartha, 1965), annual rainfall is 500–1000 mm and the summer is the driest season. All the other data are from sub-tropical Honshu between 35 and 37° N where wet paddy acreage is large, annual rainfall is 1000–2000 mm and the early summer is the wettest period. Also note that in winter with a rural snow cover the maximum for one of these two points (Sapporo, $\psi_s = 0.50$) increases from its summer value of 5.9 to 8.0 deg (Ishikawa *et al.*, 1978).

Carrying these considerations further, it seems likely that relatively high μ_r could explain another enigma; the common observation that many tropical heat islands are smaller than their temperate counterparts (Jauregui, 1986a; Oguntoyinbo, 1986; Oke 1986). The great majority of the examples with relatively small ΔT_{u-r} are from cities in wet climates or are surrounded by wetlands, rain forest or paddy fields (e.g., in addition to the Japanese settlements, Kuala Lumpur, Lagos, Visakhapatnam, Bogota) and again the effect seems most marked for the smaller communities (see Jauregui, 1986a, Figure 4) where one may anticipate less urban sprawl into the rural areas. Equally the tropical cities with heat island intensities that approach the magnitude of those in temperate areas are those with a distinct dry season (e.g., Mexico City, Delhi, Poona, Ibadan) and $\Delta T_{u-r(\max)}$ is always in that season.

Other factors can be involved in the explanation of small heat islands in tropical cities. For example, as city canyons become deeper (a traditional design in hot, dry cities in the tropics) there comes a point where daytime shade becomes sufficient to reduce absorption of solar radiation and produce a canopy-layer cool island. The light colour of many tropical building exteriors may also reduce absorption due to a higher albedo. Both characteristics will reduce the amount of heat storage in the fabric and therefore affect the heat island on the succeeding night. A city in an arid region may also start the night with a negative heat island due to either or both the irrigation-driven oasis effect and higher thermal admittance of the city.

The scatter in relationships such as Equation (1) due to variations of μ_r and

$\Delta\mu_{u-r}$ could be accounted for if the b coefficient were a function of these properties. Other sources of scatter in Figure 7 are contributed by urban 'greenhouse' and anthropogenic heat effects, and different built:greenspace mixes together with topographic effects (Goldreich, 1984). The form of Figure 8 and other results of SHIM can help suggest some of the needed modifications but it must be remembered that the model gives predictions of surface, not air temperature. It also only addresses the growth of the heat island from sunset, not its full intensity.

All of this argues for the need to document all the relevant physical properties in future heat island studies. Johnson *et al.* (1991) note their difficulty in obtaining the appropriate data for validation puposes. It is also clear that the characteristics of the rural area (especially those related to μ) are at least as important as those of the city. Further, there is much to recommend integrated studies involving observation and modelling in tandem.

7. Conclusions

The surface energy balance model of Johnson *et al.* (1991), which has been validated with field data, has been used to explore the roles of hypothesized causes of the nocturnal urban heat island. It is shown that:

1. The effects of street canyon geometry on long-wave radiation alone are sufficient to generate a heat island.
2. Urban-rural thermal admittance differences alone can produce a heat (or cool) island, and that the absolute magnitude of the rural admittance is very important in setting the maximum heat island and its seasonal variation.
3. In other than extreme thermal climates these two causes are usually dominant, and the heat island is almost equally sensitive to each.
4. The release of anthropogenic heat from buildings in cold weather has at least the potential to match the role of the geometry and thermal admittance as a cause of the heat island but its effect is likely to be mitigated by wall insulation practice.
5. The influences of the urban 'greenhouse' effect and urban-rural emissivity differences are relatively minor.
6. As expected, the simulated effect of cloud over both environments is to reduce the heat island. Fog over the rural, but not the urban, area can eliminate the heat island or cause a cool island.
7. The simulations confirm the form of the relation between street geometry and the maximum heat island suggested by Oke (1981). They also reveal a strong dependence of this value upon the rural and urban-rural thermal properties. The rural moisture conditions may explain the scatter between data from different parts of the world and the existence of relatively small heat islands in many tropical cities.
8. The work points to the need for better documentation of the physical properties

of urban, and especially rural, sites during heat island surveys. It also signals the need for heat island research which combines observation of both thermal and energetic characteristics together with modelling as a unified endeavour.

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