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A simple model for estimating the maximum intensity of nocturnal urban heat island

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ABSTRACT: Several studies have tried to determine the empirical relationships between the maximum urban heat island (UHI) intensity and factors such as the city size taking the number of inhabitants as indicator, the geometry of the city (i.e. the H/W ratio), meteorological factors, etc. On the other hand, numerical models have also been formulated to understand the main factors contributing to the formation of UHI.

In this work, a set of empirical equations for determining the maximum of the UHI is presented. The equations have been fitted to the output results of a set of experiments performed by a canyon model (Montávez *et al*., 2000a), investigating the main factors contributing to the nocturnal UHI. The input parameters are the thermal inertia of rural and urban materials, the H/W ratio and the increase in long-wave sky radiation due in part to pollution over cities. The results obtained are able to reproduce most of UHI intensity maxima around the world. Copyright © 2007 Royal Meteorological Society

KEY WORDS urban heat Island; urban climate; urban canyon

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1. Introduction

Urbanization produces radical changes on the morphology and air composition of built-up areas, resulting in perturbation of the radiation, energy, humidity and wind balances, and leading to a modification of the local climate (Wanner and Hertig, 1984). The best known phenomenon resulting from this modification is the so-called urban heat island (UHI) (Landsberg, 1981; Oke, 1987; Montávez *et al*., 2000b), which can be defined as the temperature difference between the urban area and its rural surroundings, always assuming that the records should be similar if there were no urbanization. Usually these differences show that cities are warmer than the surrounding rural areas, particularly during the night, and in the presence of clear skies and low wind speeds (Oke, 1987).

Some of the main factors related with UHI formation are the canyon radiative geometry, the thermal properties of the materials, anthropogenic heat release and the urban greenhouse effect (Oke *et al*., 1991). The canyon geometry leads to a decrease in the long-wave radiation loss due to the complex exchange between buildings and the screened skyline. The thermal properties usually lead to an increase of the sensible heat stored in the fabric of the city. Air composition changes because of the emission of pollutants and occasional low ventilation, while temperature and humidity modifications lead to changes in the long-wave radiation balance. Direct anthropogenic heat from buildings constitutes another factor, which modifies the energy balance of an urban area.

The above-mentioned mechanisms have been shown to contribute to the formation of the UHI (Oke *et al*., 1991). Among them, the canyon structure of the city and the difference between urban and rural thermal properties have been identified as the main factors affecting the intensity of the UHI. However, It should be mentioned that this is just the general rule since the behaviour of any UHI is to a great extent dependent on the morphological, geographical and dynamic properties of the site. For instance, the release of anthropogenic heat becomes more important in the case of cold climates where the difference between indoor and outdoor temperatures is greater (Oke *et al*., 1991). Differences in emissivity and the urban greenhouse effect generally play a minor role (Oke *et al*., 1991).

The relative role of those mechanisms has been studied by modeling the UHI phenomenon (Oke *et al*., 1991; Arnfield, 1990). There are, however, many statistical studies that have contributed to our understanding of the UHI and its intensity. For example, Oke (1981) investigated the relationship of UHI intensity with the H/W ratio (height and width of the canyon). Other studies have demonstrated the dependence of the UHI on meteorological conditions and the season of the year (Landsberg, 1981; Montávez *et al*., 2000b). Oke (1973) related the UHI intensity with population and wind speed, while Moreno (1994) observed multiple relationship between pressure, cloud cover and UHI intensity. In other studies (Eliasson, 1996a; Montávez *et al*., 2000b), the

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results have shown that in fine weather the city size and the urban structure (H/W) play an important role in the intensification of UHI.

Although the results of these studies are of undoubted value, they often suffer to some extent from the local characteristics of the site under consideration, and it is difficult to generalize the conclusions to cover other cities. For instance, regression coefficients usually depend on the geographical situation of the city, and Oke (1981) and Oke (1987) have demonstrated that coefficients can be grouped by continents. In cases where the relationship to the meteorological conditions is being assessed, it is often difficult to generalize the results to other locations and their different dynamics.

The variety of factors contributing to UHI formation makes it difficult to establish general relationships to explain UHI intensities in different locations that may have different morphology. In this respect the set of simple equations proposed in this work attempts to help evaluate the expected UHI intensities for different locations in fine weather conditions. For this purpose, we use a Monte Carlo canyon model (Montávez *et al.*, 2000a) that takes into account the main UHI-contributing factors mentioned above and that can be used to derive intensities of the nocturnal UHI. The specification of a wide set of materials and geometry combinations has allowed us to derive a simple set of equations for evaluating the intensities of UHI during night, assuming that the values of some basic parameters from the city and its outskirts are known.

A note of caution is necessary concerning the definition of UHI intensity. It is defined above as the temperature difference between the urban areas and the rural environs. The practical application of this definition varies through the literature depending on the characteristics of the case under study. Ideally, UHI intensity in one location should be provided by the difference between the temperature in this built-up location and the temperature for the same location if no urbanization had taken place. In experimental studies it becomes clear that this definition is not feasible in most of cases. However, in modeling studies it is possible to make simulations in which the urban environment is arbitrarily imposed, allowing the local temperature to be assessed for a site under rural or urban conditions, as desired. Thus, the intensity of the UHI in a given site will be defined here as the temperature difference between two simulations. In one, the site is embedded in an urban environment, and in the other, rural conditions are imposed.

In Section 2 a brief description of the model used and the experiments is presented. Section 3 shows the assumptions made and the set of equations obtained. Section 4 verifies of the equations obtained in Section 3 for some specific cases. In the last section the conclusions are presented and some comments on the limitations of the model discussed.

2. Model and Experiment Description

The experiments were conducted with the canopy layer numerical model of Montávez *et al.*, (2000a). This is a canyon model (Arnfield, 1990; Arnfield and Mills, 1994a; Arnfield and Mills, 1994b; Johnson *et al.*, 1991; Mills, 1993) that simulates the main energy transfer processes involved in the energy budget of an urban canyon during night time. Thermal conduction, radiation and convection are simulated by means of Monte Carlo methods. Latent heat is not taken into account. The model has been successfully tested (Montávez *et al.*, 2000a) and seems to be slightly better than the Force-Restore method used by several authors in this type of study (Johnson *et al.*, 1991; Swaid, 1995).

The form of the canyons is described by the width W and height H, while it is the H/W ratio that really takes into account the geometry of the canyon. The width of walls w is also an input parameter of relevance, as discussed in Montávez *et al.*, (2000a). The thermal properties of walls and ground are given by the thermal conductivity k, and the heat capacity C. These two parameters are related to the thermal inertia $\mu = \sqrt{kC}$. The radiative behaviour of a material is given by the emissivity, ϵ, while the downward sky radiation $L\downarrow$ can be chosen as a constant during the integration time or be given by the Idso formula (Idso and Jackson, 1969) as a function of air temperature. The initial conditions of the model are the indoor and outdoor surface temperature of the walls and ground, the inner temperature profile, the air temperature and wind speed. The length of the integration period is another input parameter.

Although the model allows different radiative and thermal properties to be taken for both walls and floor as well as for the initial conditions, identical values for all components are used in the experiments performed in this work. The inner temperature profile is taken as a linear gradient between the indoor and outdoor temperatures for a wall at the initial time. In all the experiments performed, the integration time is 12 h, the initial air temperature equals that of the exterior surfaces and wind speed is taken to be nil. Although in some cases the steady state was not reached by the end of the integration time, the differences in estimating UHI using different integration periods (10 and 14 h) were at most 0.3 °C.

The experiments selected to quantify the respective role of each factor involved in UHI intensity were performed in a way similar to those performed by Oke *et al.*, (1991). The different set-ups for the experiments described were designed to study the variations of the causal mechanisms contributing to the nocturnal UHI formation.

2.1. Geometry and thermal properties

In this section we present the maximum UHI intensity obtained using the model output results for a wide range of materials and geometry combinations. All the experiments were performed with initial temperature

$T_0 = 17\,^\circ\mathrm{C}$ $\epsilon = 0.95$ for all surfaces and $L\downarrow$ fixed at 300 $\mathrm{Wm^{-2}}$ during the integration period.

The set of experiments performed consists in running the model for many combinations of H/W and μ. Then the maximum differences between urban and rural ($H/W = 0$) are calculated for a wide range of cases, which gives the UHI intensity. In most cases the maximum UHI was found at the end of the integration period.

In Figure 1 the temperature differences between urban and rural as a function of thermal inertia variations from the urban to rural area ($\Delta\mu_{\mathrm{u-r}}$) are represented. Results are shown for a variety of values of μ and H/W. Model runs were carried out for values of μ between 600 and 2200 at intervals of 400 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$. A range that covers the usual values of rural and urban thermal admittances (Oke, 1987). For the sake of clarity, Figure 1 shows the results only for the cases of μ equal to 600, 1400 and 2200 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$. Results for μ equal to 1000 and 1800 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$ show intermediate behaviour.

In agreement with those of other authors (Oke *et al.*, 1991), the results shown in Figure 1 suggest that geometry and thermal properties are able to generate intense UHI by themselves. In general, it can be stated that the higher the value of $\Delta\mu_{\mathrm{u-r}}$ and H/W, the larger the UHI intensity will be. Thus, as the H/W ratio increases, more radiation is trapped in the urban canopy layer and greater will be the local impact on temperature. The influence of H/W and its relation to the emissivity will be revisited in the next section. Additionally, it should be noted that for the same value of $\Delta\mu_{\mathrm{u-r}}$ and H/W, $\Delta T_{\mathrm{u-r}}$ is greater when μ_r is lower. This result suggests that the surroundings of the city and the season are of some relevance for the intensification of nocturnal UHI.

It should be noted here that throughout this paper, the thermal properties of the materials are specified with the value of μ, but, as mentioned above, the model uses K and C. It can be argued that the use of μ leads to uncertainties, since a single value of μ can be obtained from different combinations of C and k. In order to evaluate the potential errors in using this approach, a set of experiments (not shown here) were carried, running the model for all the cases mentioned above with several combinations of C and k that produce the same value of μ. The difference in the final results indicates that UHI intensity in the most sensitive case does not reach 1.5 °C, and is in most cases less than 0.5 °C.

2.2. Emissivity

According to some authors (Yap, 1975), emissivity may be one of the factors contributing to UHI. Its role in urban areas was assessed by studying the dependence of UHI intensity on H/W for a value of $\mu = \mu_{\mathrm{u}} = \mu_{\mathrm{r}}$. The experiment involved taking $\mu = 1400\ \mathrm{Jm^{-2}s^{-1/2}K^{-1}}$, $T_0 = 17\,^\circ\mathrm{C}$ and running the model for several values of H/W, changing the surface emissivity from 0.8 to 1 at

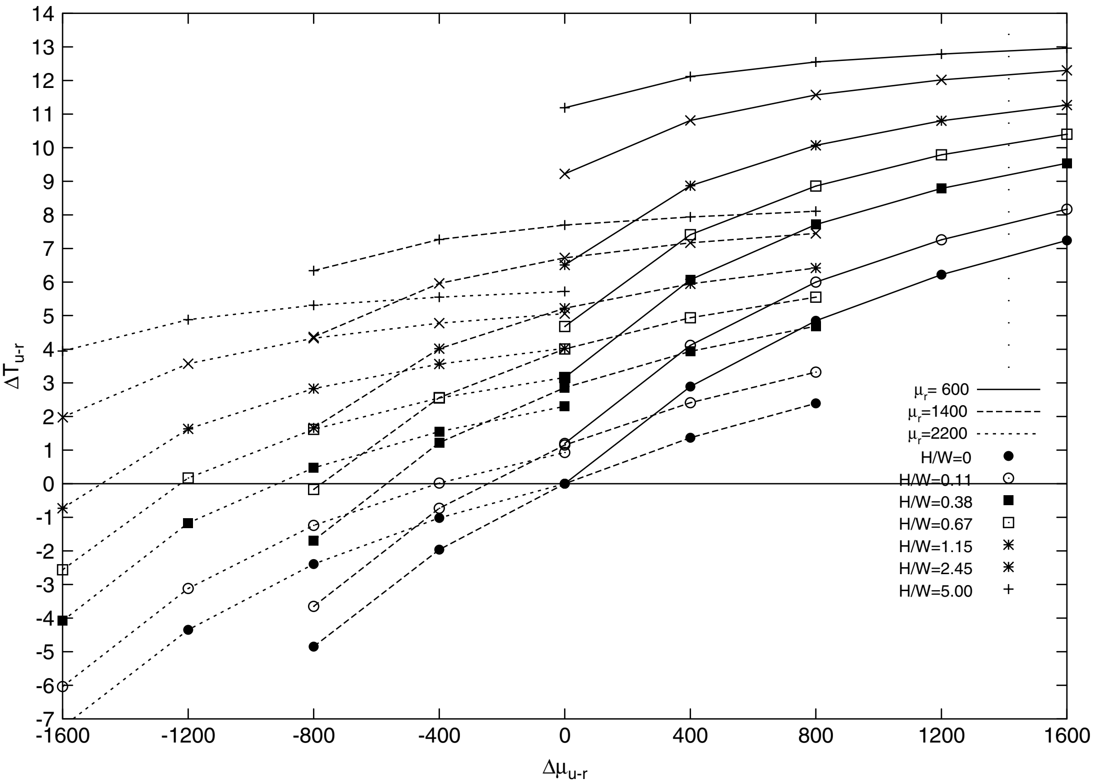

Figure 1. Intensity of UHI $\Delta T_{\mathrm{u-r}}$ as a function of the urban-rural thermal differences $\Delta\mu_{\mathrm{u-r}}$ and H/W geometry. Each line style indicate a given μ_{r} ($H/W = 0$) and each point type a H/W, as indicated in the legends. Each point on the figure indicates $\Delta T_{\mathrm{u-r}}$, calculated as the maximum difference between the temperature in the urban and rural case. For each case, μ_{u} can be obtained as $\mu r + \Delta\mu_{\mathrm{u-r}}$.

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0.05 intervals for each value of H/W. The modification in UHI intensity when the value of emissivity is incremented with $\Delta\epsilon$ with respect to a reference case of $\epsilon = 0.80$ is calculated.

The results are presented in Figure 2. Note that ΔT does not indicate the UHI intensity as defined above, but the differences in temperature by running the model in which an emissivity value of $\epsilon + \Delta\epsilon$ was considered with respect to the reference state using emissivity ϵ ($\Delta T \equiv T_{\epsilon+\Delta\epsilon} - T_{\epsilon}$). Since the rural environment was kept constant, this modification in the temperature of the city is directly related to modifications in ΔT_{u-r}.

The main conclusions that can be drawn suggest that differences due to changing the value of emissivity of urban areas are in most cases less than 1 °C, and depend on geometry. One interesting aspect is that there is a value of H/W for which ΔT is independent of ϵ. Values of H/W over (under) 1.5 lead to positive (negative) values of ΔT, i.e. UHI intensity increases (decreases) regardless of ϵ. This is due to the effect of multiple radiation reflections off the canyon surfaces.

2.3. Local greenhouse effect

Urban atmospheres usually contain higher concentrations of pollutants. Additionally, the air is warmer and the water vapour content higher. These two causes contribute to higher long-wave radiation in urban than in rural areas, as noted by several authors (Oke and Fuggle, 1972; Kobayashi, 1982).

The experiment carried out to assess the local greenhouse effect consisted of studying the effect of increasing the sky radiation from 300 to 340 Wm^{-2} (usual range of increments in sky radiation) for several values of H/W and to observe the increase in UHI compared with that in a rural area not affected by such increases ($L\downarrow = 300$ Wm^{-2}). The value of the urban and rural thermal inertia used was $\mu_u = \mu_r = 1400$ $Jm^{-2}s^{-1/2}K^{-1}$ and $T_0 = 17$ °C.

The results are shown in Figure 3. The increase of incoming long-wave radiation has only a slight effect on deep canyons but produces substantial increases in UHI ΔT_{co} in shallower canyons. As a first result, one can state that industrial areas are strongly affected by the local greenhouse effect.

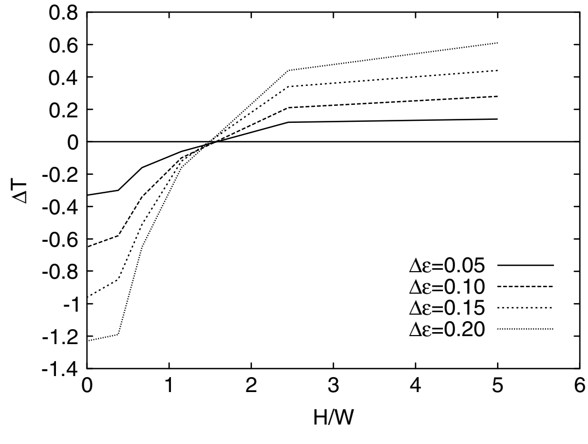

Figure 2. Modification of urban temperature ΔT as a function of H/W geometry for several values of $\Delta\epsilon$. The line styles identify $\Delta\epsilon$ for a reference case with $\epsilon = 0.80$.

2.4. Dependence of UHI on the initial temperature

The results shown above were obtained by specifying the initial temperature, which was fixed at 17 °C. This initial temperature sets the initial value both for indoor and outdoor temperatures in the canyon. Since the final aim of this work was to determine a set of equations depicting the dependence of the UHI intensity on the main factors contributing to it, the question addressed here is the impact of this initial temperature specification on ΔT_{u-r}. For this purpose, a set of runs for several values of H/W and $\mu = 1400$ $Jm^{-2}s^{-1/2}K^{-1}$ were performed, changing the values of the initial temperature in the range 7 to 27 °C. The sky radiation was calculated by means of Idso's formula (Idso and Jackson, 1969).

Figure 4 shows the results obtained from these experiments. The maximum impact did not exceed 0.1 °C, suggesting that the choice of initial temperature is of secondary importance. This statement should, however,

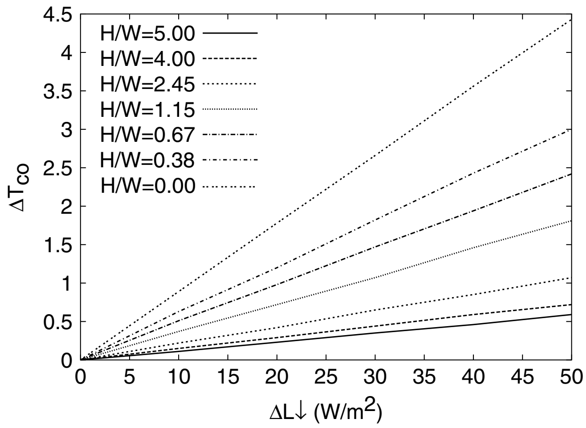

Figure 3. Increase of UHI intensity as a function of increasing downward radiation due to local greenhouse effect. Each line style represents a value of H/W.

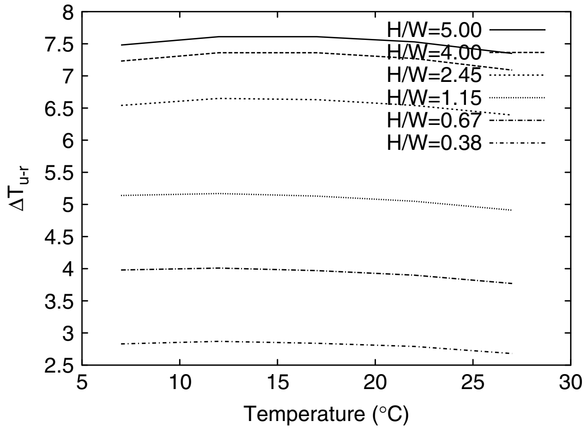

Figure 4. Intensity of UHI ΔT_{u-r} as a function of initial temperature T_0. Each line style represents a value of H/W.

be treated with caution since it can be argued that it is not realistic to set a common value of the initial temperature for the indoor and outdoor walls. This point will be addressed in the next section and in the discussion.

2.5. Anthropogenic heat release

Anthropogenic heat emissions that take into account the sensible heat release from the buildings can be simulated in the Monte Carlo model. The internal building temperature is assumed to be constant during the integration period and therefore constitutes a source of heat that is released through the walls. This means that the width of the walls plays an important role for determining the exterior surface temperature of the walls. Fuel consumption and the heat released by factories or vehicles, though of potential relevance, are not taken into account.

A set of experiments were conducted with the indoor temperature fixed at 17 °C, while outdoor temperature values varied from −3 to 27 °C. The resulting modification of UHI intensity is presented in Figure 5. The results indicate that when outdoor temperature in lower (higher) than indoor temperature, UHI intensity tends to increase (decrease) linearly with the temperature difference especially in deep canyons. However, when the indoor temperature is lower than the outside temperature, the use of air conditioning releases considerable amount of heat, which is not taken into account by the model, and therefore increases UHI intensity. Thus, we conclude that anthropogenic heat plays an important role in UHI intensification especially in cold climates, where differences between indoor and outdoor temperatures are large.

3. An Empirical Model

Oke (1987) described an empirical relationship between UHI intensity and the H/W ratio where H is the height of buildings and W the width of streets. This formula can be expressed as

$$\Delta T_{u-r} = 7.54 + 3.97 \ln(H/W) \quad (1)$$

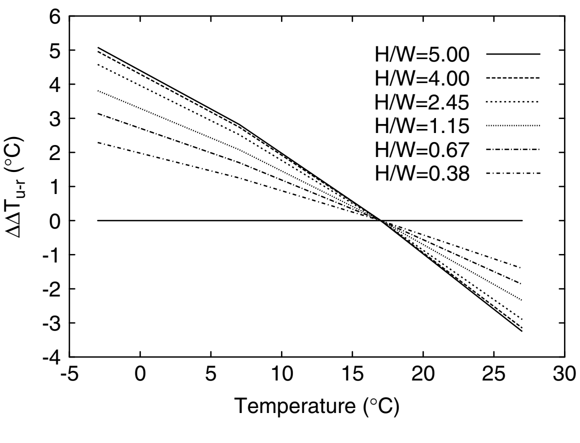

Figure 5. Modifications of UHI intensity $\Delta\Delta T_{u-r}$ when varying exterior temperature T and keeping inside temperature constant at 17 °C. Each line style, represents the results of experiments for different values of H/W.

or as a function of the sky view factor Ψ_s

$$\Delta T_{u-r} = 15.27 - 13.88\Psi_s \quad (2)$$

These formulas seem to work quite well in the case of North American and European cities (data used for fitting the model). But it seems that for other cities with different climates, such as Korean and Japanese cities, the model is not able to explain the lower values of UHI intensity. As suggested by Johnson *et al.*, (1991), the very different thermal admittances of these places are presumably the reason. This aspect of the problem will be discussed later.

On the basis of these previous works, and using the formula 2 because of its better behaviour near the origin, our proposed model is a fit as follows:

$$\Delta T_{u-r} = a + b\Psi_s \quad (3)$$

where coefficients a and b are functions of the thermal admittance of the rural μ_r and urban μ_u environments, and Ψ_s is the sky view factor for the floor center of the canyon, given by

$$\Psi = \cos(a\tan(2H/W)) \quad (4)$$

Before looking for the functions of a and b, we shall discuss the physical meaning of the coefficients. Let us compare the behaviour of this formula when comparing two plane surfaces, i.e, $H/W = 0$ for the urban case. In this case $\Delta T_{u-r} = a + b$ and so $a + b$ will provide the information about the cooling differences between the two surfaces. Note that $a = -b$ when $\mu_r = \mu_u$. If we now suppose lim $H/W \to \infty$, then $\Delta T_{u-r} = a$, i.e. the UHI intensity is only a function of rural cooling, because urban surfaces do not cool at all. Therefore, a and b provide information about the cooling of urban and rural plane surface. Additionally, Ψ_s is a function of street geometry and regulator of urban surface cooling.

After making a physical interpretation of the coefficients involved in Equation 3, we can operate in two different ways to fit the model. The first option assumes that, owing to the physical interpretation, the only data needed for fitting the model is the cooling of plane surfaces (simple fit). The second option is to run the model for many combinations and then look for the functions that minimize the differences compared with the Monte Carlo Model (better fit).

3.1. A simple fit

The simple fit of a and b is based on the idea mentioned above, that these parameters provide information about the cooling of urban and rural plane surfaces. The proposed fitting functions are

$$a = f(\mu_r) = \alpha + \beta ln(\mu_r)$$
$$b = f(\mu_u) = -\alpha - \beta ln(\mu_u) \quad (5)$$

To obtain the necessary data for calculating the relationships between μ_r, μ_u and a and b, we use the outputs

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from the canyon model (Montávez *et al.*, 2000a). The model is run for several values of μ, ranging from 600 to 2200 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$ and $H/W = 0$, for a 12-h period and then the temperature change, i.e. the cooling experienced by the surface, is calculated. The values obtained for the parameters are $\alpha = 49.74$ and $\beta = -5.63$.

3.2. A Better fit

In this case, we simply look for the best fit able to explain a large set of comparisons between rural and urban runs for Equation 3.

For this, a set of experiments were carried out. The idea was to choose a set of pairs (μ_r, μ_u) and for each pair to run the model for several values of H/W ranging from 0 to 4 and to obtain a pair of (a, b) by fitting ΔT_{u-r} to Equation 3. We performed the experiments for values of μ_r and μ_u ranging from 600 to 2200 at 200 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$ interval. Finally, a set of pairs (a, b) were directly related to the set of pairs (μ_r,μ_u). Now, the next step was to obtain a set of equations to relate these pairs. The best fit was obtained for the functions

$$a = f(\mu_r, \mu_u) = \alpha_1 + \beta_1 \ln(\mu_r) + \gamma_1 \ln(\mu_u) + \delta_1 \mu_u$$
$$b = f(\mu_r) = -\alpha_2 - \beta_2 \ln(\mu_u) \quad (6)$$

Figure 6(a) and 6(b) show the relations obtained and the fits performed. The coefficients are listed in Table 1. The

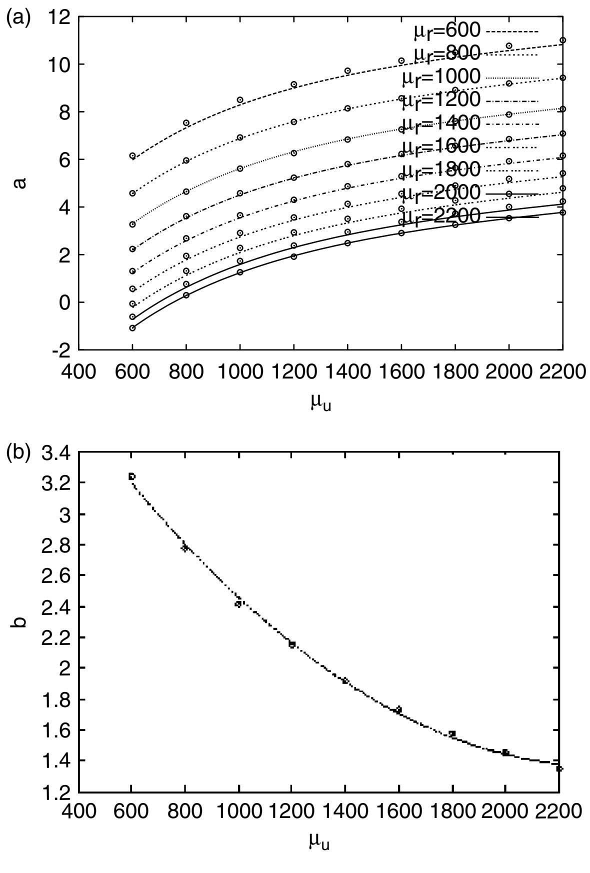

Figure 6. (a) Values of a and fit of Equation 3. (b) Values of b and fit to Equation 3.

Table I. Coefficients obtained for Equations 6 and 10.

	α	β	γ	δ
1	0.251E+02	0.363E+01	−0.169E-02	−0.563E+01
2	−0.380E+02	0.420E+01		
3	0.150E-07	−0.788E-04	0.156E+00	
4	0.951E-08	−0.372E-04	0.385E-01	

errors in obtaining ΔT_{u-r}, i.e. the difference between empirical and the Monte Carlo model, were at most 0.2 °C.

3.3. Including the effect of air pollution on sky radiation

As mentioned in Section 2.5, another factor of relative importance for UHI intensification is the increase in long-wave radiation from the sky due to air pollution. As before, we looked for an empirical relationship between the increase in sky radiation $\Delta L \downarrow$ with respect to rural areas and an increase in UHI intensity ΔT_{co}; the proposed function is

$$\Delta T_{co} = f(\mu_u, H/W)\Delta L \downarrow \quad (7)$$

where $f(\mu_u, H/W)$ gives the lapse rate and depends on the canyon geometry H/W and the urban materials μ_u. To fit the function $f(\mu_u, H/W)$, we performed a set of experiments that consisted of running the model for several values of H/W, μ and $\Delta L \downarrow$.

Analysing the results of the experiments performed, we decided to take

$$f(\mu_u, H/W) = c + d\Psi_s \quad (8)$$

where the coefficients c and d depend on μ_u. Once these coefficients had been obtained, the fits providing the best results for obtaining coefficients as a function of μ_u were

$$c(\mu_u) = \alpha_3 \mu_u^2 + \beta_3 \mu_u + \gamma_3$$
$$d(\mu_u) = \alpha_4 \mu_u^2 + \beta_4 \mu_u + \gamma_4 \quad (9)$$

The values of the coefficients are listed in Table 1. The errors were at most 0.2 °C.

Thus, the final UHI intensity ΔT_{u-r} can be obtained as a combination of Equations 3 and 7

$$\Delta T_{u-r} = a + b\Psi_s + (c + d\Psi_s)\Delta L \downarrow \quad (10)$$

4. Checking the Models

The simulations performed indicate that in the absence of large anthropogenic heat emissions, the nocturnal surface UHI is primarily due to the radiative effects associated with canyon geometry and the storage effects associated with the thermal properties of the canyon materials. These results are in close in agreement with those obtained by Oke *et al.*, (1991).

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The statistical relationships (Equations 1 and 2) obtained by Oke (1981) seem to fit very well the UHI intensity records for some European, Australian and North American cities during summer, when anthropogenic heat release is usually slow, and therefore UHI is mainly due to morphology effects. However, they do not seem to work in the case of cities with different climates. This can be seen in Figure 7(a), and 7(b), where the dots indicate values of ΔT_{u-r} for cities with different climates and where the Oke's formula (Eq. 2) is also plotted.

Thus, from the above comments it can be stated that it is not possible to obtain a single pair of coefficients (a, b) as in Oke's formula to explain all the UHI intensities found around the world. Furthermore, it is not possible to find a single combination of urban and rural materials to obtain the coefficients of Equation 2. So, to fit the data given in Figure 7, one has to proceed in a different way. The method we use is similar to the one provided by Oke *et al.*, (1991).

As we have no information about μ_r and μ_u for obtaining the UHI intensity by means of the formulas shown above, an assumption that can be made to obtain a curve similar to Oke's is as follows. Let us suppose that the environs of each group of cities are similar and therefore μ_r can be taken as constant. Additionally, let us suppose that μ_u depends linearly on H/W, given the assumption that deeper canyons will be constructed of dense materials and therefore have larger thermal admittances.

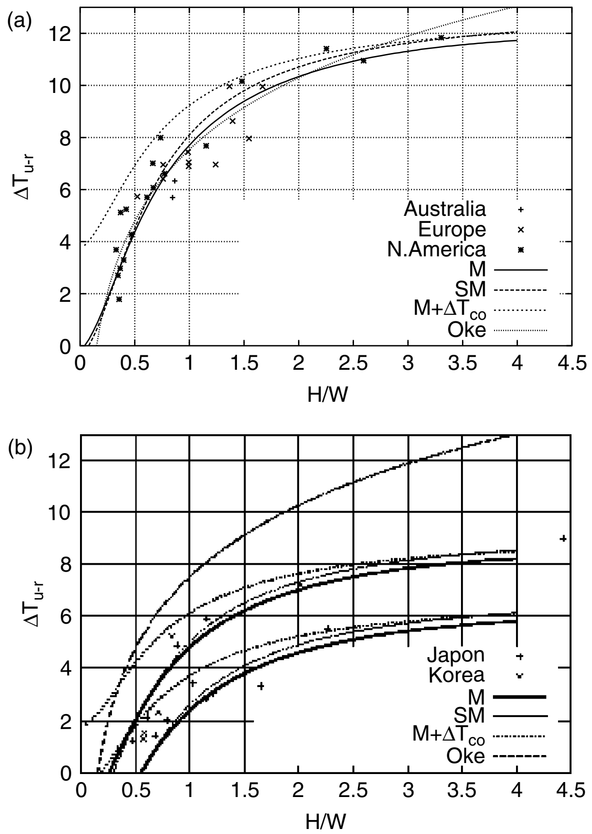

Figure 7. (a) UHI intensity for Australian, European and N. American cities. The points correspond to measured values for several cities of the mentioned continents (see legend). The lines indicate the results of the model used: SM simple model (Eq. 3), M better model (Eq. 3), $M + \Delta T_{co}$ is Equation 10 and Oke denotes Oke's formula (Eq. 1) (b) Same as (a) for Korean and Japanese cities, but in this case two rural admittances are used, the top lines are related to the lower thermal admittance (see text).

For the case of European, Australian and American cities, taking $\mu_r = 700\ \mathrm{Jm^{-2}s^{-1/2}K^{-1}}$ and varying μ_u between 700 and 2200 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$ while H/W varies between 0 and 4, the results (Figure 7(a)) obtained with this combination seem to fit the data reasonably well. One can also include some extra temperature due to increased long-wave radiation from the sky, i.e. a local greenhouse effect. In Figure 7(a), $\Delta T_{u-r} + \Delta T_{co}$ is also included, taking $\Delta L \downarrow = 30\ Wm^2$.

The intensities of ΔT_{u-r} for Japanese and Korean cities cannot be explained by taking the above values of rural and urban thermal inertia. The explanation is that usually the surroundings of these cities consist of paddy fields and so μ_r must be higher, meaning that UHI intensity is lower. On the other hand, the spread of data in this case is much bigger that in the previous case, and it is not possible to satisfactorily explain all the cases with one μ_r. Therefore, in this case we use two values of μ_r, 1300 and 1900 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$, while in both cases μ_u has been varied between 1100 and 2200 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$ when H/W varies between 0 and 4. Again, the results for $\Delta L \downarrow = 30\ \mathrm{Wm^{-2}}$ were also calculated. The curves obtained are represented in Figure 7(b).

As can be seen in Figure 7, the model is able to explain in a acceptable way the UHI intensities collected by other authors around the world, as well as the dispersion of the data which seems to increase at low H/W values. Although the methodology used may not be absolutely rigorous and other combinations may give similar results, this example explains the differences in UHI intensity due to different climates, land use and geometries as well as the dispersion of data.

5. Conclusions and Comments

A diagnosis of the causal mechanism behind UHI has been presented, using a numerical canopy model of the energy transfer in an urban canyon (Montávez *et al.*, 2000a). The results obtained are similar to those presented by Oke *et al.*, (1991). The morphology of the city seems to be the main factor. An increase in H/W is inherently associated with an increase in UHI intensity. The greater the difference between urban and rural thermal admittances, the greater the UHI intensity , especially when the rural thermal inertia is lower. Both causes can give rise to similar UHI intensities, but the temperature difference due to canyon geometry is always positive while differences in thermal inertia may sometimes lead to negative values. Anthropogenic heat release seems to become more important when the difference between indoor and outdoor temperatures is large and

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urban canyons are deep. In cold situations, anthropogenic heat release produces an intensification of UHI, the contrary being true when the outside air is hotter. The local greenhouse effect is not as important as morphology, but may increase in importance in polluted areas with low H/W. The effect of emissivity differences on UHI intensity is less important than the above-mentioned factors and depends on the canyon geometry. It is also demonstrated that UHI intensity is not dependent on initial temperatures of canyon surfaces, which is important for applying the empirical models to different climates and seasons.

The main goal of this article was to build an easy tool for estimating the UHI intensity as a function of the above-mentioned factors. A set of equations have been presented for estimating the maximum heat island intensity. The empirical models have been fitted with the outputs of the Monte Carlo model (Montávez *et al.*, 2000a), and they take into account μ_r, μ_u, H/W and the increase of sky radiation $\Delta L \downarrow$ due to a local greenhouse effect.

For estimating UHI intensity due to canyon geometry and differences in thermal properties between urban and rural environs, the equation $\Delta T_{u-r} = a + b\Psi_s$ has been proposed. Two different approximations, simple and better fit, were used to obtain a and b. Both formulations give similar results, but there are differences between them. The physics of the 'better fit' model is somewhat different from that of the simple model, for example, in the dependence of rural and urban thermal inertia for both a and b. A separate equation has been proposed for estimating the increase in UHI intensity due to the local greenhouse effect.

By means of these simple formulas, the UHI intensity can be estimated easily for multiple applications such as urban design and temperature predictions in urbanized sites. However, the empirical models have some limitations. These are due to the canopy model employed to fit the coefficients the statistical nature of the empirical model that does not take into account all the physical processes involved.

It is necessary to remark that the results apply to surface UHI, which should not be confused with surface UHI as seen from an aircraft or satellite (Roth *et al.*, 1989). Because of the advection and convection of the air mass (Montávez *et al.*, 2000b; Eliasson, 1996b), it may be claimed that the bigger the city, the greater the similarity between surface and air UHI. This is why the model is able to explain UHI around the world.

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