Numerical experiments on urban heat island intensity

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SUMMARY

Numerical experiments with a two-dimensional model have been performed to study diurnal urban circulation and heat islands in calm conditions. Vertical structures of rural and urban planetary boundary layers, heat island intensities and circulations are examined in different conditions of stability, surface heat fluxes and city width. A simple expression to predict diurnal evolution of the urban—rural temperature difference is proposed.

1. INTRODUCTION

For a long time, studies on urban climate have shown that cities are warmer than adjacent rural areas, especially during the night (see Garstang et al. (1975), Landsberg (1981) and Oke (1982) for general reviews). Aircraft measurements of Spangler and Dirks (1974), Shea and Auer (1978), Hildebrand and Ackermann (1984) have recently drawn attention to diurnal, convective conditions, when the urban thermal anomaly is smaller in amplitude but covers a deeper layer of atmosphere.

Convective boundary layers are common during calm, summer conditions, when horizontal inhomogeneities in surface sensible heat fluxes prevail over friction variations as the driving mechanism of urban circulation (Wong and Dirks 1978). Estimates for the ratio, $\beta$, between urban and rural sensible heat fluxes range from 1.2 in the Columbia experiment (Landsberg 1981) to 2 or more (Hildebrand and Ackermann 1984). Oke (1982, Table 1) estimates that the ratio between sensible heat flux and net all-wave radiation typically ranges from an urban value of 0.44 to a rural value of 0.28. Assuming that differences of net radiation from city to country are negligible (probably less than 5%) a value of $\beta = 1.6$ can be derived from his study.

Stability plays a key role in determining both convective boundary layer growth and strength of circulation (Shreffler 1978, 1979; Vukovich and Dunn 1978) and thus influences the difference between rural and urban temperatures (heat island intensity). Heat island intensity is further affected by city size (Landsberg 1981).

This paper investigates the influence of these various parameters, using a simple, two-dimensional model of the circulation.

2. THE MODEL

A two-dimensional mesoscale numerical model as described in Pearson (1973, 1974) and Bacci et al. (1982) has been used to study diurnal urban circulation in calm conditions. The equations are
\[ \frac{du}{dt} - fv = -\frac{\partial p}{\partial x} + K_x(\partial^2 u / \partial x^2) + K_x(\partial^2 u / \partial z^2) \]  
\[ \frac{dv}{dt} + fu = K_x(\partial^2 v / \partial x^2) + K_z(\partial^2 v / \partial z^2) \]  
\[ \frac{\partial p}{\partial z} = b \]  
\[ \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \]  
\[ \frac{db}{dt} + N^2 w = -\frac{\partial B^e}{\partial z} \]

where \( u, v, w \) are components of velocity in the \( x, y, z \) directions;

\[ b(x, z, t) = g(\theta(x, z, t) - \theta(x, z, 0))/\theta(x, 0, 0) \]

is the buoyancy; \( p \) is the perturbation from the original hydrostatic pressure divided by density, and \( f \) is the Coriolis parameter. Constant diffusion coefficients \( K_x, K_z \) are used, and in its initial state the atmosphere is assumed to have a constant Brunt–Väisälä frequency \( N = [(g/\theta(x, z, 0))\partial \theta(x, z, 0)/\partial z]^{1/2} \) all over the grid.

Integration was performed using a time step \( \Delta t = 40 \) s on a staggered grid with 101 points in the horizontal and 21 in the vertical. Horizontal grid spacing varied from \( \Delta x = 1000 \) m to \( \Delta x = 5000 \) m in different runs. Vertical grid spacing was \( \Delta z = 200 \) m in each run.

Forcing is introduced in the model by means of a buoyancy flux \( B^*(x, z, t) \) related to the sensible heat flux \( H(x, z, t) \) by \( B^*(x, z, t) = g(\theta_x\rho c_p)^{-1}H(x, z, t) \).

Sensible heat flux is assumed, as in Bacci et al. (1982), to be separable into the form \( H(x, z, t) = \gamma A(t)B(x)C(z, t) \), where \( \gamma \) is the diurnal maximum of rural sensible heat flux at the ground. Temporal, horizontal and vertical weights \( A, B, C \), are non-dimensional and \( C(z, t) \) decreases from the value 1 at ground level to zero at the top. \( A(t) \) and \( B(x) \) are prescribed (see Figs. 1, 2); \( C(z, t) \) is derived at each time step and grid point in the following way.

The amount of sensible heat, \( H(x, 0, t)\Delta t = \gamma A(t)B(x)\Delta t \), released at the ground during a time step \( \Delta t \) is calculated at time \( t \) at each horizontal grid point. If advection is temporarily neglected, the area between the \( \theta(t) \) and \( \theta(t + \Delta t) \) curves in the \((\theta, z)\) plane,
\[ \Sigma_{j=1}^{n} \Delta \theta_j \Delta z, \] can be calculated as \((\rho c_p)^{-1} H(x, 0, t) \Delta t,\) where \(\Delta \theta_j = \theta_j(t + \Delta t) - \theta_j(t)\) is the potential temperature increase at the jth vertical grid point during the step, and n is the number of vertical grid points.

From the knowledge of \(\theta(t)\) and area size, a provisional temperature profile at time \(t + \Delta t\) is first computed in a way that forces constant potential temperature in the layer near the ground (Richiardone et al. 1984). The vertical dependence of the heat flux \(C((k - 1)\Delta z, t) = \Sigma_{j=1}^{n-k} \Delta \theta_j (\Sigma_{j=1}^{n} \Delta \theta_j)^{-1}\) is then derived from the fraction of area above height \(z\). Finally, the buoyancy flux at each grid point is calculated and inserted in Eq. (5), where it contributes to buoyancy increase.

In summary, heat transfer from the ground to the mixed layer is introduced by means of vertical forcing without incorporating a surface layer and variable vertical diffusion coefficients. In addition, vertical grid spacing is uniform throughout, preventing the resolution of the lowest part of the PBL. The use of this algorithm in the sea breeze case (Richiardone et al. 1984) resulted in a very good reproduction of measured temperature profiles above the surface layer. The algorithm allowed for excellent definition of the growth of the inland ground-based adiabatic layer caused by free convection in the stable sea-breeze layer. Ground-based adiabatic layers are also found in both urban and rural observations of temperature profiles (Spangler and Dirks 1974).

Two types of temporal dependence have been used in our numerical experiments: an experimental curve (Alto Adriatico experiment (Bacci et al. 1982); time starts at time when the Brunt–Väisälä frequency is constant with height); and a sine function (Fig. 1).

Horizontal variation of sensible heat flux is introduced in the model by means of the ratio \(\beta\) between urban and rural sensible heat fluxes and by the urban half-width \(D\) (Fig. 2).

3. NUMERICAL RESULTS

Numerical experiments with different values of \(K_s, \beta, N, D, A(t)\) and \(\gamma\) (Table 1) have been performed to study urban circulation and the heat island in simplified situations. Variation of \(K_s\) from 5 to 50 m\(^2\)s\(^{-1}\) showed only a minor influence on the heat island's intensity and shape even if circulation was reduced. Therefore \(K_s = 20\) m\(^2\)s\(^{-1}\) was used for most of the runs of Table 1. A value of \(K_s = 100\) m\(^2\)s\(^{-1}\) was used throughout.
TABLE 1. PARAMETER VALUES USED IN EACH RUN

<table>
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<tr>
<th>Run</th>
<th>$K_x$ (m$^2$s$^{-1}$)</th>
<th>$N$ (s$^{-1}$)</th>
<th>$\beta$</th>
<th>$\gamma$ (W m$^{-2}$)</th>
<th>$D$ (km)</th>
<th>$A(t)$ Type</th>
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(a) Vertical structure

A typical example of urban circulation with its two closed cells is shown in Fig. 3. If the horizontal dimension of the urban area increases, more time is required for the two cells to reach the centre, and this affects the shape of the cells near the front, whereas the shape of the cell's top is primarily determined by vertical stability.

The influence of stability on vertical structure is shown in Fig. 4, where the wind profiles at the urban–rural interface appear to be mainly affected in the upper part of the cell. A similar result was shown in nocturnal conditions by Delage and Taylor (1970).

Field measurements in many rural sites of northern Italy (Bacci et al. 1980) showed good agreement with the convective boundary layer formulations of Carson (1973) and

![Figure 3](image-url)  
Figure 3. Contours of streamfunction (m$^3$s$^{-1}$) in run E at 8 hours. City, suburbs and country are indicated by black, dashed and white areas at bottom.
Manins and Turner (1978), using an entrainment factor equal to zero. In these models (Richiardone and Pearson 1983) the height of the layer at time \( t \) can be expressed as

\[
h(x, t) = \{2(1 + 2k)TB(x, 0, t)\}^{1/2}/N
\]

and the increase of potential temperature from the initial state in the mixed layer as

\[
\theta'(x, z, t) = (\theta_o/g)[TB(x, 0, t)/h(x, t)][1 + (2k + 1)(1 + 2z/h(x, t))]
\]

where \( \theta_o \) is the initial potential temperature at ground level, \( k \) is the entrainment factor, and \( TB(x, 0, t) \) is the value of the integrated buoyancy flux at ground level, \( TB(x, z, t) = \int_0^z B^*(x, z, \eta) d\eta \).

Numerical results (Fig. 5) also show the height of the rural mixed layer increasing as in Eq. (6) with a rural entrainment factor \( k_r = 0 \). In the urban area, upward vertical motions contribute to the deepening of the mixed layer and cause a temperature decrease (Fig. 6) at its top. The evolution of the urban mixed layer still shows good agreement with Eq. (6) using an urban entrainment factor, \( k_u = 0.1 \) (Fig. 5). These features are observed in all the runs. In the suburbs the warming action of subsidence reduces the height of the mixed layer.

(b) Energies

If stability is decreased or \( \beta \) is increased, circulation becomes stronger and wider. The influence of \( N \) and \( \beta \) on kinetic energy, \( KE \), can be inferred from an estimate of available energy input. Potential energy, \( PE \), of the mesoscale circulation in the model is equal to \( \int b^2/(2N^2) \) \( dx \) \( dz \) (Richiardone and Pearson 1983). All the energies, here divided by density, are referred to a domain with unit width in the \( y \) direction and have units \( m^4 s^{-2} \). If the integration is performed in an idealized case, where convective boundary
Figure 5. Temporal evolution of urban (continuous bars) and rural (dashed bars) mixed layers in run E. Mixed layer height \( h = (j - 1)\Delta z \pm 0.5\Delta z \) is estimated from the first grid point \( j \) in the vertical whose temperature did not change from \( t = 0 \). \( \theta \) grid is staggered, starting at \( z = \Delta z/2 \). Lines show the predictions (Eq. (6)) of Carson's (1973) model.
layer profiles are given by (6) and (7) with \(k_z = 0\) and no circulation (the model and urban surface widths are \(2L\) and \(2D\) respectively), an estimate of total potential energy input, \(\text{PEI}\), up to time \(t\) can be derived:

\[
\text{PEI}(t) = (4/3)(L - D)U_{0T} + (4/3)D U_{0T}^2 \beta^{3/2} (1 + k_u + k_n^2)/(1 + 2k_u)^{1/2}.
\]

(8)

Here the two terms are the rural and urban contributions; \(U_{0T} = 2^{-1/2}N^{-1}\text{TIB}_r^{1/2}(0, \tau)\) is the rural value of total potential energy per unit length generated in a convective process with no entrainment (Richardone and Pearson 1983), because \(\text{TIB}_r(0, \tau)\) is the rural value of the integrated buoyancy flux at the ground. A comparison of this expression with the sum of \(\text{PE}, \text{KE}\) and their fluxes \(\text{FL}\) at the boundaries of the model, showed that Eq. (8) is a good approximation, because \(\text{PE} + \text{KE} + \text{FL}\) is always greater than 90% of \(\text{PEI}\).

The final state toward which the model evolves can be estimated in the same way using a temperature profile throughout the grid which is derived from a horizontal weighted mean of rural and urban temperatures. Final potential energy becomes

\[
\text{PEF}(t) = (4/3)LU_{0T}(1 + 3(D/L)\beta + (D/L)^2(3\alpha^2 + 3\alpha^2 \nu - 3\alpha \nu^2 + \nu^3))
\]

(9)

where \(\alpha = \beta^{1/2}(1 + k_u)(1 + 2k_u)^{-1/2} - 1\) and \(\nu = \beta^{1/2}(1 + 2k_u)^{1/2} - 1\). As \(k_u = 0.1\) the urban entrainment factor can be neglected and \(\alpha = \nu = \beta^{1/2} - 1\) becomes a good approximation. Subtracting (9) from (8) an expression for the total available energy input up to time \(t\)

\[
\text{APEI}(t) = (4/3)(D/L)(L - D)U_{0T}(\beta^{1/2} - 1)^2(\beta^{1/2} + 2)
\]

(10)
can be derived.

As \(U_{0T}\) is proportional to \(N^{-1}\), the same kind of dependence on stability would be expected in kinetic energy, if a constant efficiency in the conversion of \(\text{APEI}\) is independent of stability. Figure 7 indicates, however, that the conversion efficiency \(\text{KE}/\text{APEI}\) is proportional to \(N\) because in all cases differing only in \(N\) (runs E, J, K), the behaviour is the same; this indicates that \(\text{KE}\) is proportional to \(N^{-2}\) at any time. \(\text{KE}\)'s dependence on \(\beta\) is more complicated, because proportionality with \((\beta^{1/2} - 1)^2(\beta^{1/2} + 2)\) holds only in the early stages, when the condition of no circulation used in deriving (10) is more acceptable.

As time increases, circulation influences the production of kinetic energy; from Fig. 7 a proportionality of \(\text{KE}\) with \((\beta^{1/2} - 1)^2(\beta^{1/2} + 2)\beta^{-1}\) seems more correct when \(t/\tau > 15\) (i.e. \(t > 3-4\) hours, depending on \(\beta\); \(\tau = D(\beta \text{TIB}_r(0, \tau))^{-1/2}\) is the time scale described in the next section).
In the sea breeze case, the same model showed a production of kinetic energy proportional to $N^{-1}$ (Richiardone and Pearson 1983) with a conversion efficiency independent of stability. The different geometry of the urban circulation with 2 cells converging and horizontal flow turning to a vertical direction at the urban centre, is probably the cause of the stronger influence of stability on KE production. The influence of $N$ and $\beta$ on the streamfunction maximum, $\psi_{\text{MAX}}$, can be estimated remembering that $\psi_{\text{MAX}} = \bar{u}h_M$, where $\bar{u}$ is the mean velocity in the layer between the ground and the height, $h_M$, where circulation changes sign. This height is proportional to $N^{-1/2}$ (see Fig. 4) and is not influenced by $\beta$. Estimating $\bar{u}$ from the square root of kinetic energy, a relationship of proportionality between $\psi_{\text{MAX}}$ and $(\beta^{1/2} - 1)(\beta^{1/2} + 2)^{1/2}N^{-3/2}$ is expected. The good agreement (Fig. 8) in the first stage and a reduced increase of $\psi_{\text{MAX}}$ in cases when circulation is stronger, show that $\psi_{\text{MAX}}$ behaviour derives from that of kinetic energy.
Figure 9. Temporal evolution of urban–rural potential temperature difference of the mixed layer scaled by $N(\beta^{1/2} - 1)$ in different runs (see Table 1). Bold line indicates theoretical estimate $\Delta \theta_{\text{MAX}}$ in case of no circulation (Eq. (12)).

(c) Heat island intensity

A crude estimate of the urban–rural potential temperature difference in the mixed layer (heat island intensity) can be derived from Eqs. (6) and (7), obtaining

$$\Delta \theta_{u-r}(t) = (\theta_o/g)N\alpha[2\Pi f(0, t)]^{1/2}. \quad (11)$$

Substituting $\alpha = (\beta^{1/2} - 1)$, Eq. (11) becomes

$$\Delta \theta_{\text{MAX}}(t) = (\theta_o/g)N(\beta^{1/2} - 1)[2\Pi f(0, t)]^{1/2} \quad (12)$$

where subscript MAX has been introduced to indicate that Eq. (12) estimates urban–rural temperature differences with no circulation, i.e. at its maximum.

In Fig. 9 the temporal evolution of the urban–rural potential temperature difference in the mixed layer, $\Delta \theta_{u-r}$, is compared with the theoretical estimate with no circulation, $\Delta \theta_{\text{MAX}}$. The city half-width $D$ is the distinguishing feature in the results shown; stability appears to be correctly scaled (runs E, J, K group together) but $\beta$ scaling (runs E, D, H) is correct only in the first hours. As a matter of fact there is good agreement until circulation affects the thermal structure at the city’s centre. The time at which the model data depart from Eq. (12) depends on the city width. The narrower the width the earlier
the departure. Introducing a time scale \( \tau = D(\beta \text{TIB}_c(t))^{-1/2} \), a new graph (Fig. 10) can be drawn. All the points from the different runs are grouped together showing that heat island intensity can be expressed at time \( t \) as

\[
\Delta \theta_u - r(t) = \Delta \theta_{\text{MAX}}(t) f(t/\tau)
\]

where

\[
f(t/\tau) = e^{-0.0186t/\tau}
\]

is the best fit.

Scaling with \( D(\beta \text{TIB})^{-1/2} \) shows that the speed at which the urban circulation cell approaches the city centre is proportional to \( \text{TIB}^{1/2} \), as with the sea breeze front speed (Richiardone and Pearson 1983).

From Eq. (13) the diurnal heat island intensity can be quickly estimated from atmospheric stability, city width, horizontal distribution and intensity of heat flux.

4. COMPARISON WITH OBSERVATIONS

Many papers on urban climate show experimental data on heat island intensity; unfortunately these are very often taken in the surface layer and so cannot be used to check the validity of Eq. (13), which predicts a thermal anomaly related to the whole mixed layer in diurnal, calm conditions. Upper air summertime afternoon data collected
in St Louis by different authors during the METROMEX experiment are shown in Shea and Auer (1978) and Hildebrand and Ackerman (1984) (Fig. 11). Measurements were taken in moderate to strong wind conditions and show great variability, which is probably a consequence of the variety of meteorological situations during which they were measured. Shea and Auer derived a linear dependence of heat island intensity on wind speed, predicting a potential temperature excess of 1.44 K in calm conditions. This value can be compared with the present model's prediction (Eq. (13)) using data of summer monthly average diurnal evolution of urban and rural sensible heat fluxes in St Louis (Ching et al. 1983). A fit of sensible heat fluxes (Fig. 8 of Ching et al.) with a sine function of the type \( H = F \sin(\pi(t - a)/b) \) gives \( a = 0600 \) CST, \( b = 12 \) hours, \( F_u = 300 \) W m\(^{-2}\), \( F_r = 120 \) W m\(^{-2}\), i.e. \( \beta = 2.5 \). Equation (13) predictions at 1500 CST, using \( \theta_0 = 300 \) K, \( D = 10 \) km (reasonable values for St Louis) and with different values of stability, are plotted in Fig. 11. They show good agreement with the METROMEX observations in a wide range of stabilities.

Heat island intensity in nocturnal, calm conditions has often been empirically related (Landsberg 1981) to the logarithm of population, i.e. to \( \log D^2 \). Figure 12 shows that in diurnal conditions also this relationship is a good approximation for the influence of city size, provided that \( D \) is small. As a matter of fact, an upper limit (Eq. (12)) to heat island intensity is predicted from Eq. (13), implying that for a particular urban type (i.e. \( \beta \) value) there is a critical value of city width above which its increase does not significantly affect heat island intensity.
5. CONCLUSIONS

Numerical experiments on diurnal urban circulation in calm conditions have shown that atmospheric stability and the ratio, $\beta$, between urban and rural sensible heat fluxes at the ground are the main factors influencing urban circulation, kinetic energy production and heat island intensity.

Temporal evolution of the urban–rural temperature difference in the mixed layer can be predicted from urban and rural sensible heat fluxes at the ground, atmospheric stability and city width by means of a simple analytical expression (Eq. (13)).

The role of circulation in decreasing heat island intensity is shown by the exponential term (Eq. (14)), whose time scale is proportional to the time taken for the urban circulation cells to reach the centre. There appears to exist a critical value of city width, dependent on $\beta$, above which an increase in dimension does not affect significantly the intensity of the heat island.

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