A Simulation Model for Thermal Climate in City Canyons

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Abstract This paper presents an approach to the numerical modelling of the wind and thermal climates, as well as the energy budgets of city canyons. The model involves the coupling of three sub-models: (a) a surface energy budget model, (b) a windfield model, based on the $k-\epsilon$ turbulence model, and (c) a scalar dispersion model. In its current formulation, the model is two-dimensional, for clear sky conditions, for dry surfaces, and is most appropriate for conditions in which forced convection dominates over buoyancy effects. The model is capable of simulating spatial patterns of canyon energy budget components; subsurface and air temperature; the components of the wind, as controlled by location, date (i.e. solar path), weather conditions in the overlying air mass; canyon geometry and orientation; surface radiative and aerodynamic properties; substrate thermal properties; and, building interior climate.

1. INTRODUCTION

It is estimated (Sievers and Zdunkowski, 1986) that by the year 2000, approximately 60 percent of the world population will reside in cities with populations above 5000. It is the quality of life for these urban dwellers which needs careful planning. For this reason, it is imperative that town planning must consider environmental costs of development and try to reduce the on-going resource usage. The costs to be considered should include damage which the buildings cause, such as exacerbating rain-water run-off, creating urban heat islands, and damaging the ozone layer. Trying to reduce the on-going resource usage should include minimising water and fuel usage, and trying the make the buildings as energy-efficient as possible.

Urban planners are beginning to consider as important city planning criteria, the climatic impacts of the erection of new inner-city buildings or modifications to existing inner-city buildings. Sydney City Council, for example, attempts to protect major inner-city parklands from the development of new buildings that will overshadow large areas of this park-land for long time-periods.

In some areas of Argentina (Evans and de Schiller, 1996) a planning code has been developed to use building design to try and maximise the number of properties that are able to benefit from the warm summer breezes near the river front without blocking other residents from the same breezes. Also in Argentina (Evans and de Schiller, 1996) a planning code has been developed to minimise the use of air-conditioning and the threat of wind-damage by selecting appropriate design alternatives and site locations for new major government buildings.

So at the present time, shading is beginning to be considered, as is building-shape related to wind flow, but the problems of reflections and heat creation are not yet on the agenda. Reflections can damage gardens, dazzle drivers and pedestrians, possibly causing a dangerous situation to occur.

When data is needed to justify some planning decision, it is often needed at short notice. Studies to collect data are time-consuming and costly, and usually not available in the short term. Modelling is the best answer available at this time.

The aim of this paper is to describe the mathematical model which has been developed to simulate the temperature distribution in and around a simple urban canyon, to describe the two-dimensional computer model implementation, and to present some results.

2. AN URBAN CANYON HEAT FLOW MODEL

The simulation of heat-flow within the urban canyon implements a mathematical model for this flow. Urban canyons in reality are complex structures formed by buildings, roads and the general city landscape. Further, the architecture of individual buildings differs greatly. When wind regimes and heat sources and sinks are added, a very complex system is produced, and the problem of heat flows within such canyons becomes difficult. To adapt this problem to be suitable for solving on a computer within a reasonable timeframe, this model makes a number of simplifying assumptions about urban canyons, wind and heat.

An urban canyon is a canyon where the walls of the canyon are the walls of the surrounding buildings and the floor of the canyon is the street between these buildings. An urban canyon, typically, is much longer than it is wide, has tall buildings on either side and occurs in the Central Business District of a large city. This model makes the simplifying assumption that the buildings on each side of the urban canyon are of equal height, and that the buildings are rectangular in shape with no protrusions at all.

One simplifying assumption is that the details of heat-flow through the urban canyon can be determined by a representative slice through the canyon. Using a representative slice allows the model to be constructed in two dimensions. This substantially reduces the computation involved in simulating the model. This reduced computational effort makes it easier to examine other important components, such as the time of the year, canyon geometry and building materials used. The representative slice used is a cross-section taken through the middle of the canyon. Figure 1 shows the cross section taken.

This model aims to simulate the distribution of heat and temperature within and around such urban canyons and to allow the examination of how heat flows within a city canyon depend upon the time of day, the time of year, the wind regime, the geographic location of the city, the canyon orientation, the construction materials of the canyon, and the heat generated by the buildings.

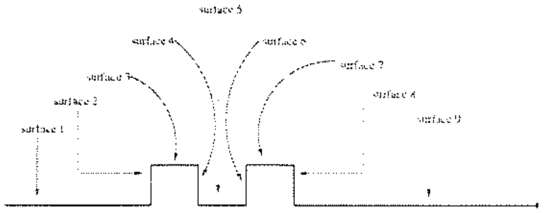

Figure 1. The Nine Surfaces Close to an Urban Canyon as used in the Energy Budget Sub-Model

It is assumed that the wind field has achieved steady state conditions prior to the commencement of the simulation, and remains constant throughout.

This model treats the temperature in a given volume of air as a passive scalar. A passive scalar is an object that can be blown around in the air volumes by the wind, and which will not affect the wind flow. This model makes the simplifying assumption that buoyancy created by the heat is negligible when compared to the temperature dispersion by the wind.

To aid in the construction of the model, existing sub-components were used. The sub-components of the model are the generation of wind, the temperature dispersion and the energy budget. Each of these sub-model components has been used as a starting point for this combined model. Where necessary, changes to the original component models have been made.

For more details on how the component models were combined and the complexities overcome, see Herbert *et al.* (1997).

The combining of these three component submodels into a computer implementable model that would allow for heat flow within a city canyon to be simulated and visualised and an application of the model are the focuses of this paper.

2.1 The Wind Model Component

The component model used to calculate the wind regime for the canyon was originally developed by Paterson (1986) and used by Paterson and Apelt (1989), and is an implementation of the $k - \epsilon$ equations.

The purpose of the wind model is to predict the wind environment around buildings, pressures on building claddings and loads on building frames. The wind model is a fully three-dimensional model, working in the x, y and z directions on the Cartesian plane. For the composite city canyon model developed here, the wind environment around the buildings is the most important component.

For the development of the k-ϵ equations, the wind model considers air to be a fluid moving around the buildings. For a derivation of these equations see Fletcher (1988). These equations are derived from the Navier-Stokes equations, and include differential equations for turbulent kinetic energy (k), and for the rate of dissipation of turbulent energy (ϵ). Paterson and Apelt (1989, p40) present these equations (in Einstein's summation notation) as:

$$U_j\frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}[\frac{v_t}{\sigma_k}\frac{\partial k}{\partial x_j}] + v_t[\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}]\frac{\partial U_i}{\partial x_j} - \epsilon, \tag{1}$$

$$U_j\frac{\partial \epsilon}{\partial x_j} = \frac{\partial}{\partial x_j}[\frac{v_t}{\sigma_\epsilon}\frac{\partial \epsilon}{\partial x_j}] + c_1 c_\mu k[\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}]\frac{\partial U_i}{\partial x_j} - c_2\frac{\epsilon^2}{k} \tag{2}$$

$$U_j\frac{\partial U_i}{\partial x_j} = \frac{\partial}{\partial x_j}[v_t\frac{\partial U_i}{\partial x_j}] - \frac{\partial P}{\partial x_i} \qquad i = 1...3 \tag{3}$$

$$\frac{\partial U_j}{\partial x_j} = 0 \tag{4}$$

$$v_t = c_\mu\frac{k^2}{\epsilon} \tag{5}$$

where $P = \frac{\bar{P}}{\varrho} + \frac{2}{3}k$ is the augmented pressure, $U_i \quad i = 1, 2, 3$ is the fluid velocity in each of the x, y and z directions, and (v_t) is turbulent (or dynamic) viscosity; $k = \frac{\overline{U_j U_j}}{2}$ is the turbulent kinetic energy, $\epsilon = v\overline{(\frac{\partial U_i}{\partial x_j})^2}$ is the turbulent energy dissipation, $c_{v_t}, c_\mu, c_1, c_2, \sigma_k, \sigma_\epsilon$ are constants as recommended by Launder and Spalding (1974, p257).

Equations 1 represent the transportation of turbulent kinetic energy and are derived from the Navier-Stokes equations. Equations 2 represent the transportation and dissipation of turbulent kinetic energy. Equations 3 represent the Momentum Equation, and Equation 4 is the Continuity Equation.

For each grid point, the wind model calculates the steady state air velocity, (U,V,W) in each of the x, y and z directions; the turbulent kinetic energy; and the dissipation of the turbulent kinetic energy.

Only the steady state air velocities and the turbulent viscosity are required by the composite model.

2.2 The Dispersion Model Component

The dispersion sub-model is used to transport the temperatures around the simulated canyon. This dispersion component uses both convection and advection. The dispersion component was originally developed by Hunter (1992) to be used in conjunction with a wind model. The dispersion model and the Paterson (1986) wind model have been used by Johnson *et al.* (1996) for comparisons with dispersion of gases in a small-scale urban canyon.

The original dispersion model is three-dimensional in its implementation, and it disperses a passive scalar through and out of an the urban canyon using the velocity vectors and turbulent diffusivities supplied by a wind model (provided that the wind data is in an acceptable format).

Assuming that the upwind profile has reached steady state, Hunter (1992) expresses the 3-dimensional atmospheric diffusion equation as the sum of a convection term (C_1 which also includes the source term), and a diffusion term (C_2) and these can be separated. The separate convection and diffusion equations are thus:

$$\begin{aligned}
\frac{\partial C}{\partial t} &= \frac{\partial C_1}{\partial t} + \frac{\partial C_2}{\partial t} \\
\frac{\partial C_1}{\partial t} &= -U\frac{\partial C}{\partial x} - V\frac{\partial C}{\partial y} - W\frac{\partial C}{\partial z} + S \\
\frac{\partial C_2}{\partial t} &= \frac{\partial}{\partial x}[K\frac{\partial C}{\partial x}] + \frac{\partial}{\partial y}[K\frac{\partial C}{\partial y}] + \frac{\partial}{\partial z}[K\frac{\partial C}{\partial z}]
\end{aligned} \tag{6}$$

where: $C(x, y, z, t)$ is the scalar concentration at the point (x, y, z) at time t, $K(x, y, z)$ is the eddy diffusivity, $U(x, y, z)$, $V(x, y, z)$ and $W(x, y, z)$ are the air velocity components in the x y and z directions at the point (x, y, z), $S(x, y, z, t)$ is the source term at the point (x, y, z).

Values for U, V, W and K are supplied by the wind model. Values for C are calculated by the dispersion model. Values for S, the source term, are provided to the dispersion model as a time-varying constant.

2.3 The Energy Budget Model Component

The energy budget sub-model is used to calculate the heat flux on the surfaces. When calculating the heat fluxes on the surfaces of the urban canyon, this model takes into consideration the canyon geometry, orientation, internal building and subsoil conditions, the materials which the surfaces are composed of, and the site location, time and weather conditions of the simulation. The energy budget component has not been used with a wind and/or dispersion component to this date.

The 2-dimensional surface energy budget model used here was devised by Arnfield and Grimmond (forthcoming) to calculate overall energy budgets in urban environments. This model calculates the turbulent sensible heat flux at all given points on the surface of any chosen urban canyon. It allows for a variety of canyon shapes (by varying the height, width and length of the canyon); it allows for any site location for the canyon (which includes latitude and allowing the canyon to face in any given direction); varying temperature conditions within the buildings, and under the ground; and, varying weather conditions. There is currently a limitation on this sub-model that the buildings on opposite sides of the canyon must be of equal height.

The energy budget model considers the nine surfaces (or facets) close to the urban canyon. These are the surfaces obtained by taking a cross-section at mid-canyon, and can bee seen in Figure 1.

The energy budget model breaks each of the nine surfaces up into a number of elements (or given points). On any individual surface the elements are spaced an equal distance apart.

Each of the elements is considered separately, with the energy budget sub-model determining the energy budget of each element on the basis of:

$$K^* + L\downarrow_S + L\downarrow_T = Q^* = Q_H + Q_G \qquad (7)$$

where K^* is the absorbed solar radiation, $L\downarrow_S$ is the absorbed long-wave irradiance from the sky, $L\downarrow_T$ is the absorbed long-wave irradiance from the contributing canyon facets, Q^* is net radiation, Q_H is the sensible heat exchange between the facet and the within-canyon air, Q_G is conductive heat exchange between the facet surface and the interior walls or deep soil beneath the canyon floor.

The model calculates the heat flows, taking into account the canyon geometry, location and orientation, the material properties of the surfaces, the time of day and year, and allows for multiple reflections between canyon facets.

Temperature data is transferred between the different grids used in the sub-models by using a spline function.

The Energy Budget Sub-Model provides a heat flux value (measured on the surface in $Jm^{-2}s^{-1}$) for each point on each of the nine surfaces. A positive value of heat flux indicates that energy is being transferred from the air to the surface. A negative heat flux value indicates that heat is being emitted from the surface into the air.

The dispersion model, allows for a temperature in each control volume, plus a time-varying constant source term to be produced. In the calculation of the source term heat coming from the building is considered to produce a constant supply of temperature change (constant until the energy budget sub-model is used again and new values are calculated). The building may sometimes actually be a sink producing a negative temperature change.

For each air grid point nearest the surface of the canyon, the temperature change is calculated as:

$$S = -\Sigma \frac{QH * A}{H_c * v} \qquad (8)$$

where QH is the splined value of heat flux for an air cell adjacent to the surface, A is the surface area of the air cell surface closest to the canyon surface, H_c is the heat capacity of air, v is the volume of the air cell closest to the canyon surface, and S is the source term representing the temperature change that will occur in the selected cell over the duration of one time step, and is summed over any adjacent surfaces.

3. APPLICATION OF THIS MODEL

This section will describe how the model reacts to different times of day, and also changing the properties attributed to the materials that the canyon is constructed of.

3.1 Columbus Ohio Simulation

The model has been run using two different locations. The locations used have been a latitude of 40N (to represent Columbus Ohio) and 34N (to represent the Los Angeles basin).

The model has been used to simulate a 2-day period, with the first 24 hours results being ignored (to overcome any unrealistic original conditions). The surface temperatures of the buildings heat and cool as would be expected, with the east-facing walls heating most during the morning hours (since the sun rises in the East), the horizontal surfaces heating most around the middle of the day, and the west-facing walls heating most during the afternoon period. Figure 2 shows the temperature change generated by the heating of the eastern walls of the buildings in the early morning. Figure 3 shows the heat plume generated by heat within the canyon. Figure 4 shows the temperature change generated by the heating of the western walls of the buildings in the mid afternoon.

Where surfaces are expected to be shadowed by buildings, at certain times of the day, these surface temperatures show the expected results.

For the simulation period, the air temperatures within the canyon remain higher than those in the surrounding level areas, thus showing the urban heat island effect as expected. Figure 5 shows the

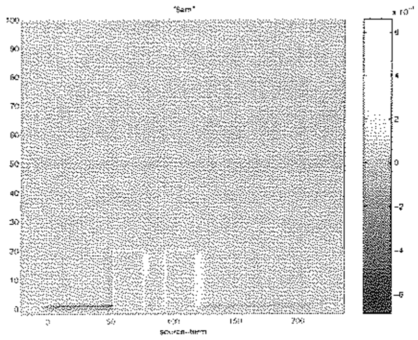

Figure 2. Source Term plot showing the heating on the Eastern walls in the early morning

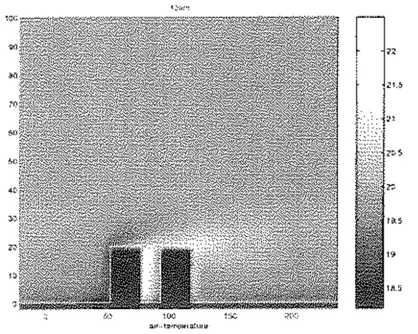

Figure 3. air temperature plot showing the heat plume emerging from the canyon mid-morning

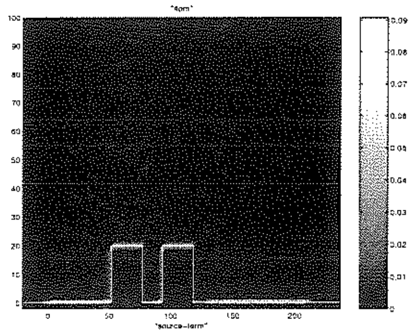

Figure 4. Source Term plot showing the heating on the western walls in the afternoon

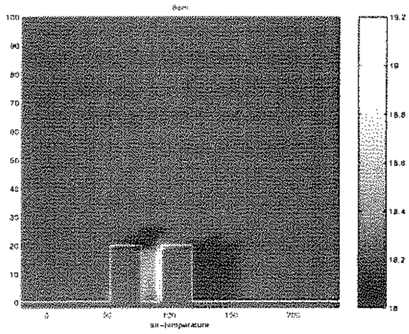

Figure 5. The temperature showing the heat island effect occurring in the canyon in the evening

temperatures of the air during the evening, when the heat island is evident.

For different times of the year, the model shows appropriate sunrise, angle, and day length for the location chosen.

3.2 Painting the Town White

Two recent studies reported in the United States by Mestel (1995) and Taha (1997) discuss two different models (one created by Tapa and the other by Taha (1997)) to determine the results of changing the urban environment. Prior to urbanisation, the Los Angeles area was a fruit growing area, with a summer average maximum temperature of 36C. After clearing and urbanisation, the summer average maximum temperature has risen to 39C.

Given that this city exists, what benefits can be gained if future buildings are more environmentally friendly, and can this urban heat island effect be minimised?

The Tapa model predicts that by realistically changing building materials and colours and planting a large number of extra trees, then these maxima temperatures can be lowered by as much as 4C.

The Taha (1997) study examines the impacts of large changes in the albedo of building materials on the ozone air quality (which depends on temperature) in a similar region of North America (California's South Coast Air Basin).

Can the model presented here also predict such climatic variations?

For the Los Angeles simulations, it was decided to try and simulate the Summer-time cooling effects of "painting the town white" compared to the usual building materials. This was done by using an imaginary canyon, with an above-canyon wind speed of 3m/s, and firstly using building materials of two layers of brick for the walls, steel reinforced gypsum roof deck for the building roofs, and dry soil with a layer of asphalt for the ground surfaces; then secondly, using the same materials, and painting all surfaces white. The changes necessary for the model to simulate painting the town white are appropriate changes in albedo and emissivity.

For both Los Angeles simulations, temperatures were observed both within the canyon, and in the overall air space.

For the full 24-hour simulation, the "white" city showed lower overall air temperatures and within-canyon air temperatures. During the heat of the day, the canyon air temperatures and the overall air temperatures were both approximately 1C cooler than the previous unpainted simulation.

4. CONCLUSION

This paper has discussed the development of a model which may be useful in town planning.

The model has been applied to a canyon in Columbus Ohio to check that the results are reasonable.

The model has been used to experiment with reducing temperatures in built-up areas where the urban heat island is a problem. This has been done using Los Angeles as an example.

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