Using a simulation model for thermal climate in city canyons to illustrate the effects of canyon geometry

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Abstract This paper presents some results from a numerical model of the wind and thermal climates, and the energy budgets, of city canyons. The model is capable of simulating spatial patterns of canyon energy budget components, subsurface and air temperature, and the components of the wind, as these are 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. Some model results are presented to illustrate the effects of changing canyon geometries on the model output. Geometries considered important in the literature are the ratio of the height of buildings to the width of the canyon and the ratio of the length of the canyon to height of the buildings. The variables considered here are building height, canyon width and canyon length. The effects of changing canyon geometry are demonstrated by changing the canyon length whilst keeping the the other two variables constant; using a different width canyon whilst keeping the other two variables constant; and, using a different building height whilst keeping the other two variables constant.

1. INTRODUCTION

The model used in this paper simulates the diurnal temperature distribution in and around a dry urban canyon. The model is made up of three interlinked sub-models: – the wind field (Paterson and Apelt, 1989), dispersion (Johnson *et al.*, 1997), and energy budget (Arnfield and Grimmond, 1998) sub-models. The mathematical basis of these models and their controller has been described in a previous paper (Herbert *et al.*, 1997).

The model allows the canyon to be located at any position on the earth's land mass. Further, it allows for the user to specify the thermal properties of the objects or surfaces comprising the canyon; and, the general meteorological conditions for the canyon locale. This makes the model a powerful tool in cityscape planning and for urban canyon research generally. The model is limited to dry canyons and cloudless skies.

This paper presents the results of model simulation experiments on canyon geometry. Researchers such as Oke (1988) have found that canyon geometry has an important influence on wind regimes in the urban canyon. The measures of geometry considered important are the height to width ratio (H/W) and the length to height (L/H) ratio of the canyons.

In the present study we are interested to see if differing canyon dimensions affect the temperature distribution of the two-dimensional cross-section taken at the centre point of the canyon. The modifications are to the length of canyon, to the canyon width, and to the building height. Each experiment in this section changes one canyon measurement, keeping all other values constant and compares the result with that obtained for the 'control' canyon.

The use of the complete information system is illustrated with respect to a 'control' canyon, in a time and a location, for which there exists a good knowledge of the diurnal thermal climate.

2. DESCRIBING A SIMULATION

ENVIRONMENT

A full description of a simulation, involves a description of the chosen canyon geometry and location, the physical properties of the surfaces which the canyon and surrounds are built from, the wind environments and the initial temperature conditions.

2.1 Canyon Geometry and Identification

The model is designed for modelling a single canyon. The general requirements for the canyon are that it must be symmetric; have no other buildings nearby; and, be long enough so that at mid-canyon, orthogonal to the wind-flow, the along-canyon flow is insignificant compared to the within canyon flow. Usually, the canyon is assumed to be one of a suite of such canyons, and this determines the initial conditions.

To describe a chosen canyon, it is necessary to specify the canyon dimensions. These include the height of the buildings, the length of the canyon, the width of the canyon, and the width of the two buildings.

In order for the model to compute appropriate sunrise and sunset times and when shadings will occur, the location of the canyon must be specified by providing the canyon orientation angle (measured clockwise from North), and the latitude of the location.

To allow for seasonal variation, it is necessary for the model to know the month and day of the simulation.

Average climate data for the selected season is also required, including the mean daily station pressure (Kilo Pascals), the mean daily air temperature (degrees Celsius), and the mean daily dew-point temperature (degrees Celsius). Also required is the surface substrate depth and the surface substrate temperature for each of the surfaces.

2.2 Physical Properties of Surfaces

For each of the surfaces used in the model, the physical properties of the surface must be described by providing values for the albedo, emissivity, thermal conductivity, volumetric heat capacity, and roughness length.

2.3 Upwind Profile

To generate a wind regime, the wind sub-model requires data specifying the roughness lengths and an upwind roughness length which reflects the upwind (external to the modelling domain) environment. The upwind profile, which is used as a boundary condition for the wind field sub-

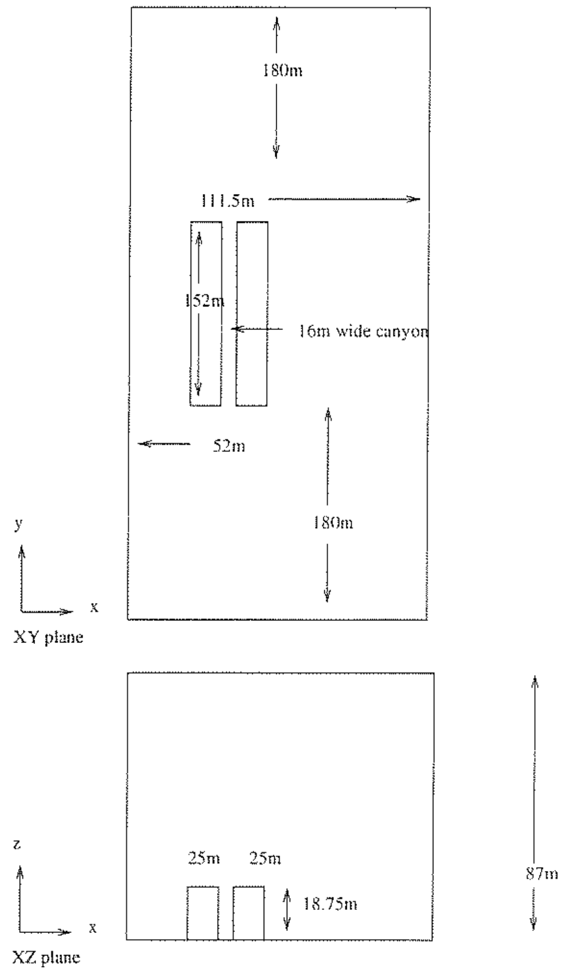

Figure 1. Geometry of the 'Control' Canyon

model, is provided on the basis of a wind speed at a given reference height and the assumption of a logarithmic profile. The wind direction is specified as degrees North of West.

2.4 Initial Conditions

The initial conditions used in the model include the starting time of day, the initial temperature change distribution (which will normally be zero), the initial surface temperatures, and the initial air temperatures.

3. THE 'CONTROL' CANYON

The 'control' canyon selected is a realistic canyon located in Columbus, Ohio, U.S.A. The latitude is 40 degrees North. The canyon runs due North-South giving a canyon orientation angle of 0 degrees. The buildings have two layers of brick for each wall, have steel reinforced gypsum roofs, are surrounded by asphalt car parks, and are divided by an asphalt roadway.

The day modelled is the 15th of March, which

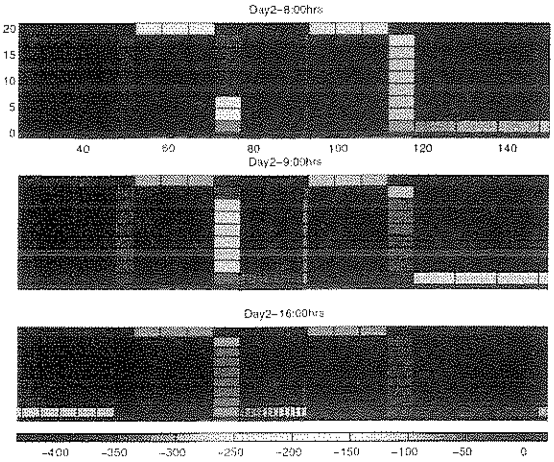

Figure 2. Sensible Heat Fluxes at 8am, 9am and 4pm for the 'control' canyon

represents early Spring. At this time of year in Columbus, the weather conditions are usually stable and not extreme, and typically includes dry, clear skies, with a constant wind speed and direction.

A starting time of 5am was chosen since at that time there is a negligibly small amount of heat transfer occurring between the buildings, ground and the external air; thus the temperature changes can be set to zero. There would also be very little variation in air temperature and surface temperature at this time, and thus constant temperatures have been chosen. The simulation commences with a uniform air temperature of 5 degrees Celsius and the canyon surface start-up temperatures are set to 4.4 degrees Celsius for all surfaces. For March, a soil substrate temperature of 5 degrees Celsius is used, and a building substrate temperature of 21 degrees Celsius is used to represent air conditioning within the building.

Roughness lengths of 0.04 are used for all building surfaces (walls and roofs). The wall surfaces are each representing two layers of brick, while the roof surfaces are representing steel reinforced gypsum roof deck. Roughness lengths of 0.08 are used for all ground surfaces (both inside the canyon and outside the canyon areas). The ground surfaces are all representing dry soil with a layer of asphalt.

A wind-field with a logarithmic profile using a $3ms^{-1}$ wind at 20 metres height with an upwind roughness length of 1.5 has been used. This upwind roughness length represents a high density urban or suburban area (Oke, 1992, page 298).

The dimensions of the 'control' canyon can be seen in Figure 1.

3.1 'Control' Output

The control simulation extended over a 2-day period, with the first 24 hours results being used to provide realistic initial conditions for the second 24 hours. The predicted surface temperatures of the buildings heat and cool as would be expected. In the morning, the east-facing walls are at their hottest. Horizontal surfaces are at their hottest around the middle of the day, compared to the cooler surface temperatures at 7am. By 1pm the west-facing walls are beginning to heat up. Figure 2 shows the sensible heat flux (Wm^{-2}) generated on solid surfaces by the simulated heating of the eastern walls of the buildings in the early morning, and later in the afternoon. Note that in the early morning, the East-facing wall external to the canyon is predicted to generate the most heat as it is not shaded by any of the buildings. Some sensible heat flux is also predicted to be generated by the roof surfaces and the area of the downwind ground surface that has not been shaded. In the afternoon the west-facing walls have the highest heat flux values; and at 4pm, the most heat flux is on the external western wall, followed by the internal canyon west-facing wall, and finally by the non-shaded horizontal surfaces.

A small heat plume is predicted for the air and generated by heat within the canyon during mid-morning, with the warmer air rising from the heated walls and being blown in an Easterly direction by the wind. The 10am air temperature has a within-canyon areal average[1] air temperature of 9.1 degrees Celsius compared to an overall air areal average temperature of 6.7 degrees Celsius. At noon the warmer canyon has an areal average air temperature of 9.9 degrees Celsius, and for 2pm the canyon is beginning to cool and has an areal average air temperature of 9.1 degrees Celsius, and at 3pm the Western side of the canyon is the warmest (Figure 3), and at 5pm when the canyon areal average air temperature has cooled to 6.8 degrees Celsius.

Where surfaces are expected to be shadowed by buildings, at certain times of the day, these predicted surface temperatures show the expected results. As an example, at 11am the canyon floor shows much less heat in the east-most element, whereas at 1pm the east-most element is heating up, as it would now be irradiated, whilst the (now shaded) west-most floor element is cooling down.

For the whole simulation period, the air temperatures within the canyon remain higher than those in the surrounding level areas.

[1] An areal average is an average over the whole cross-sectional area taking into account the differing volumes of the cells.

4. DIFFERENT GEOMETRIES

4.1 A Longer Canyon

The first experiment considers the effect on the wind and heat distributions of lengthening the canyon. The longer canyon is 256 metres long, with the other measurements and the modelling domain remaining the same as the 'control' canyon.

The length/height ratio of the lengthened canyon is 13.7 whereas the 'control' is 8.1. For both the 'control' and lengthened canyon geometries, the expected flow regimes would be skimming flow (Oke, 1988). The model predicts the wind flow external to the canyon to be very similar for both canyons, and the within-canyon wind flow, shows that whilst both geometries do have skimming flow, the longer canyon has a stronger vortex. The vortex for both geometries is located in the upper eastern quarter of the canyon. The areal average wind speed within the 'control' canyon is $0.13ms^{-1}$ and for the lengthened canyon this average increases to $0.29ms^{-1}$. There is no difference in the areal average wind speed along-canyon nor the areal average diffusivities within the canyon.

With no change in predicted winds external to the canyon, it would be expected that the temperatures external to the canyon would be similar for both geometries. The prediction of a stronger vortex, and stronger overall wind within the experimental canyon, would lead one to the conclusion that expected temperatures within the experimental canyon would be more evenly distributed (and thus less extreme) than in the 'control' canyon. This is indeed the case. It can be seen, by examining a typical model output such as the 3pm air temperatures, that the lengthened canyon has more evenly distributed temperatures within the canyon (Figure 3 and Figure 4). The overall maximum temperature is lower, being 10.3 degrees Celsius compared to 11.2 degrees Celsius for the 'control'.

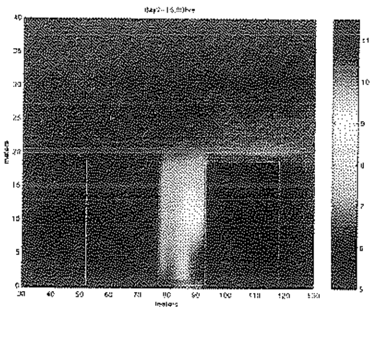

Figure 3. Predicted Air Temperatures in the 'Control' Canyon at 3pm

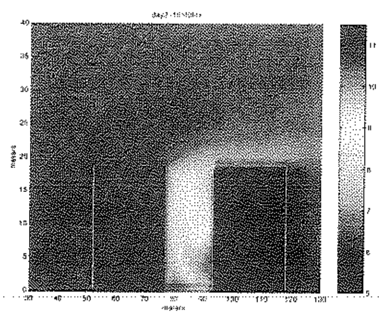

Figure 4. Predicted Air Temperatures in the Lengthened Canyon at 3pm

4.2 A Wider Canyon

The next modification to the geometry allows for a different canyon width, with a wider canyon (of 25 metres width) being tested. This wider canyon can either represent a wider road, or a larger pavement for pedestrians. This wider canyon gives a smaller height/width ratio than the 'control' canyon. The wider canyon height/width ratio is 0.75, whilst the 'control' canyon height/width ratio is 1.17.

The wider canyon changes the height/width geometry enough such that extrapolating from Oke (1988) leads to a prediction bordering between

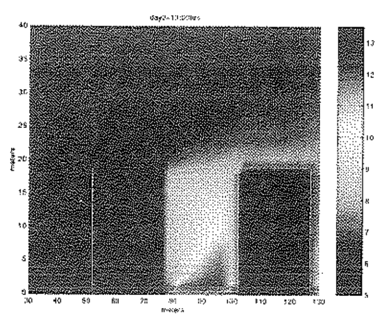

Figure 5. Predicted Air Temperatures in the Wider Canyon at 1pm

skimming and wake interference flow. Wake interference flow is typically stronger than skimming, with a less emphasised vortex. This model predicts a flow without an obvious vortex. The areal average wind speed within the 'control' canyon is $0.13ms^{-1}$ and for the wider canyon this areal average is $0.16ms^{-1}$. The areal average within-canyon diffusivity for the 'control' canyon was $0.07m^2s^{-1}$, whilst for the experimental canyon it was $0.04m^2s^{-1}$.

Lower diffusivities within the wider canyon should lead to less dispersion, whilst the stronger winds should lead to more dispersion. It would be expected that more heat would be generated in the wider canyon, as the centre of the wider canyon floor area would be less shaded than that of the 'control' canyon. The distinctly different flow pattern within the canyon should provide a rather different air temperature distribution.

The wider canyon, although having a larger area, has an areal average temperature equal to the 'control', and a lower maximum temperature (12.7 compared to 13.6 degrees Celsius). But the temperature distribution is quite different (Figure 5 and Figure 6), responding to the different flow patterns experienced.

4.3 A Shorter Building

The next modification to the geometry allows for the use of a different building height. The shorter buildings give a height/width ratio of 0.6, and a length/height ratio of 15.2, which can be compared with the 'control' height/width ratio of 1.17 and length/height ratio of 8.1. The predicted wind flow from the model external to the canyon is very similar for both of these geometries, whilst the predicted within-canyon wind flow, shows that the experimental canyon has substantially stronger winds at the top and bottom of the canyon, especially near the west-facing canyon wall, and a stronger vortex. In fact the areal average wind speed for the 'control' canyon is $0.13ms^{-1}$ and for the lower buildings this areal average rises to $0.22ms^{-1}$. The within-canyon areal average along-canyon wind speed is the same for both experiment and 'control'. The areal average within-canyon diffusivity for the 'control' is $0.07m^2s^{-1}$ and for the shorter building is $0.04m^2s^{-1}$ and we thus would expect less mixing.

Interestingly, the canyon areal average air temperatures for the shorter buildings are lower than those of the 'control' during the daylight hours, and slightly higher during the evening. Taking 10am as a typical daytime example, the 'control' canyon has an areal average air temperature of 9.1 degrees Celsius and the experimental canyon has a lower average of 7.7 degrees Celsius; using 9pm as a typical evening example, the 'control' canyon has an areal average air temperature of 5.1 degrees Celsius and the experimental canyon has a slightly higher average of 5.3 degrees Celsius. Perhaps the most heat loss in the evenings is through the building walls, and thus the shorter buildings lose less heat at this time. The experimental geometry (which has a less pronounced canyon) predicts the generation of a more pronounced plume, and this can be seen by looking at the 3pm predictions. (see Figure 3 for the 'control' 3pm prediction and Figure 7 for the experimental prediction) During the morning when radiation is occurring, air near the east-facing wall in the 'control' canyon is hotter than with the shorter buildings. At 9am, the areal average temperature within the control canyon is 7.9 degrees Celsius compared to 6.9 degrees Celsius for the experimental canyon. The maximum value in any one cell for the 'control' canyon at this time is 13.4 degrees Celsius compared to 10.3 degrees Celsius for the experimental canyon. During the evening the experimental canyon retains more heat in the air near the west- facing canyon wall. At 9pm, the areal average temperature within the control canyon is 5.1 degrees Celsius compared to 5.3 degrees Celsius for the experimental canyon. The maximum value in any one cell for the 'control' canyon at this time is 5.4 degrees Celsius compared to 6.4 degrees Celsius for the experimental canyon. The hottest cells are near the west-facing wall of the experimental canyon.

5. CONCLUSION

This paper has undertaken some experiments with changing canyon geometry with a simulation model. This model has been found to produce reasonable temperature distribution results for a 'control' canyon. Lengthening the canyon gave more evenly distributed temperatures. Widening the canyon gave a similar overall average temperature, but with an altered within-canyon distribution. Shortening the height of the buildings gave lower day-time temperatures and slightly higher night-time temperatures within the canyon. Each of these experiments altered the basic characteristics of the L/H (length to height ratio) and H/W (height to width ratio), and confirmed the literature that these characteristics are important in urban climatology.

These simple experiments illustrate the way in which the model can be used to answer questions as to changes in temperature distribution within urban canyons dependent on changes to the geometry and fabric of the canyon. The concept of running the model for one diurnal cycle before the simulation of a 24 hour period seems to allow the various physical processes to strike a balance with each other.

This model is thus a significant tool for use in urban canyon research and for the practical design of city landscapes.

6. REFERENCES

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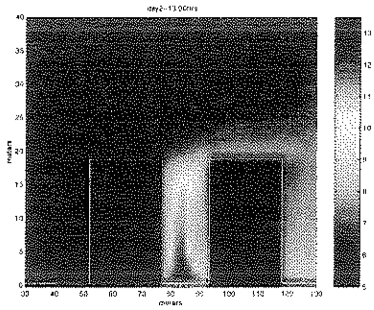

Figure 6. Predicted Air Temperatures in the 'Control' Canyon at 1pm

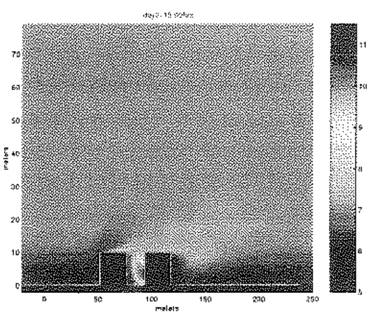

Figure 7. Predicted Air Temperatures with Shorter Buildings at 3pm