AN INVESTIGATION OF THREE-DIMENSIONAL CHARACTERISTICS OF FLOW REGIMES WITHIN THE URBAN CANYON

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Abstract—Canyon geometry is an important determinant of characteristic airflow regimes observed within urban canyons. Three principal flow regimes are: "skimming" flow, "wake interference" flow and "isolated roughness" flow, following the nomenclature of Oke (1987, Boundary Layer Climates, 2nd edn, Methuen, London). The transition between flows is determined by canyon geometry and can be described in terms of threshold height/width (H/W) ratios for an arbitrary length/height (L/H) ratio.

The determination of threshold H/W ratios has previously relied on repeated wind tunnel experiments or repeated runs of a numerical model, with canyon geometry altered until the observed flow regime changes. The present numerical investigation of typical three-dimensional flows within urban canyons identifies the key parameters which mark transition between flow regimes. On this basis it is possible to establish the geometric thresholds between regimes with analysis of a horizontal cross-section of a few simulated flows.

Key word index: Urban canyon, airflow regimes, numerical modelling.

INTRODUCTION

The climate of urban canyons is primarily controlled by micrometeorological effects of canyon geometry rather than the mesoscale forces controlling boundary layer climates. Much attention has been directed to the study of the various canyon flow regimes (DePaul and Sheih, 1986; Hussain and Lee, 1980; Nakamura and Oke, 1988; Oke, 1988), since air flow is responsible for the transport of properties such as pollutants, heat and moisture.

The emphasis has usually been on the supposed two-dimensional nature of the flows and the assumption made that most of the important features can be explained in those terms. For example, in numerical studies the threshold H/W ratios for the transition between flow regimes have been evaluated by investigating changes in flow patterns in vertical cross-sections at mid-canyon aligned with the undisturbed flow. This has involved repeated observations of the flow regimes with increasing canyon width, necessitating many numerical experiments each of which is computationally expensive. Part of the reason for this approach is that genuine three-dimensional numerical models have become available relatively recently and thus most existing numerical experiments are limited to two dimensions. An alternative which is explored here is to focus on a single plan view and to use readily identifiable characteristics of the flow present in that view to determine geometric canyon properties which influence flow regimes.

It is generally accepted that the relative height (H), width (W) and length (L) of a canyon are the important determining factors of flow regime. Here their values will be taken to be as shown in Fig. 1. When the above-roof flow is perpendicular to the canyon, flow may be described in terms of three basic regimes. For widely spaced buildings the flow returns to the upwind profile before the downwind building is encountered and is described as "isolated roughness" flow. If the buildings are more closely spaced the downwind building disturbs the flow before readjustment can take place, resulting in "wake interference" flow. In the case of narrow canyons the bulk of the mesoscale flow skims over the canyon producing "skimming" flow which is characterized by a vortex circulation within the canyon. Knowledge of threshold height/width (H/W)
ratios for the transition between flow regimes is important if the problems associated with urban canyon climates, such as high pollution concentrations or channelling of air flow, are to be minimized.

**PREVIOUS STUDIES**

Field studies and wind tunnel studies have established the relationship between change in flow regimes from “skimming” flow to “wake interference” flow to “isolated roughness” flow and increasing $H/W$ ratios. Wind tunnel studies of Hussain and Lee (1980) and associated empirical relationships, such as those of Hosker (1985), have established the effect of canyon length ($L$) on these threshold $H/W$ ratios for length/height ($L/H$) ratios ranging up to 4.0. The method used to obtain this information relied on repeated measurements with changing geometries. Oke (1988) summarized these results diagrammatically, as shown in Fig. 2.

Hunter et al. (1991) used a $k$–$ε$ model of air flow to confirm the wind tunnel studies and to extend the results to a wider range of canyon geometries. The model was based on that developed by Paterson and Apelt (1986, 1989) to predict pressure experienced by walls of buildings within cities. It solved the Navier–Stokes equations for momentum and the equations for the transportation and dissipation of turbulent kinetic energy. Solution of the model for pressure involved the calculation of the mean velocity components making it readily applicable to canyon flows of interest to urban climatologists.

Vertical cross-sections of simulated flows, examples of which are shown in Fig. 3, were analysed to determine which geometries represented transition points between flow regimes. No attempt was made to describe general flow characteristics which might suggest key geometries and thus many simulations were required to provide the series of vertical cross-sections which were examined. Results for the threshold values obtained from the above methods are shown in Fig. 2.

![Fig. 2. Threshold $H/W$ ratios for the transition between flow regimes. (a) Skimming $\rightarrow$ wake interference, (b) wake interference $\rightarrow$ isolated roughness.](image)

![Fig. 3. X–Z plane representations of the basic flow regimes produced by the $k$–$ε$ model (Hunter et al., 1991).](image)
As can be seen, both the wind tunnel studies (Oke, 1988) and the $k$-$\varepsilon$ model give similar results for the transition from "skimming" to "wake interference" flow but the results differ for the transition to "isolated roughness" flow when $L/H$ ratios are greater than unity. For $L/H = 4.0$ (the limit of wind tunnel observations) the threshold $H/W$ ratios for the transition from "wake interference" flow to "isolated roughness" flow observed in wind tunnels is 0.33, whereas the $k$-$\varepsilon$ model predicts 0.22. In Hunter et al. (1991) no attempt was made to argue that the transition to "isolated roughness" flow as predicted by the $k$-$\varepsilon$ model is to be preferred to that given by Oke (1988).

But there is further evidence that the model predictions are sound. Sturrock (1988) discusses the reduction in wind velocity and turbulent kinetic energy behind barriers. He notes that studies of flow behind a dense barrier show a zone of recirculation and wake zone which occurs downwind and above the recirculation zone. The recirculation zone for a dense barrier occupies a triangular zone extending from the top of the barrier to a distance $7H - 8H$ (where $H$ is the height of the barrier) downwind of the barrier. The edge of this recirculation zone is defined to be where the upwind velocity and turbulence have been re-established and is somewhat further downwind than the point where "isolated roughness" flow is evidenced. Nevertheless the corresponding $H/W$ ratio is in the range 0.14–0.125 and is quite consistent with the value of 0.22 found numerically for large $L/H$ ratios.

Encouraged by the ability of the $k$-$\varepsilon$ model to reproduce and extend existing wind tunnel work it was decided to use the model to investigate and characterize canyon flows under different geometries. The aim of this characterization is to understand better the transition between flow regimes.

\[ U_i \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu_t \left( \frac{\partial U_i}{\partial x_j} \right) \right] + \nu \left[ \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right] \frac{\partial U_i}{\partial x_j} - \varepsilon; \tag{3} \]

\[ \frac{U_i}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu_t \left( \frac{\partial U_i}{\partial x_j} \right) \right] + \nu \left[ \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right] \frac{\partial U_i}{\partial x_j} - \varepsilon \tag{4} \]

where

\[ U, i = 1, 2, 3 \] is fluid velocity,

\[ \rho \] is augmented pressure,

\[ k = \frac{1}{2} \rho k \] is turbulent kinetic energy,

\[ \varepsilon = c_{1}c_{2} k^{2} \] is dissipation of turbulent kinetic energy,

\[ \nu_t = c_{n} \frac{k^{2}}{\varepsilon} \] is turbulent viscosity, and

\[ c_{n}, c_{1}, c_{2}, \sigma_{k}, \sigma_{\varepsilon} \] are constants (Paterson and Apelt 1986, 1989).

In order to solve the set of partial differential equations it is necessary to obtain a substitute set of equations for solution by standard techniques. Paterson and Apelt's implementation (1986, 1989) employs finite differencing with hybrid upwinding. The resultant linear equations are then solved by the alternating direction implicit (ADI) method.

**Model parameters**

In this investigation the Cartesian coordinate axes are aligned so that $x_1$ and $x_2$ form a horizontal plane with $x_3$ in the vertical: $x_1$ is directed across the canyon and $x_2$ is directed along the canyon (Fig. 1). It is necessary to initialize the model with canyon dimensions, vertical wind profiles at the grid boundaries and roughness characteristics of building and ground surfaces. For the present purpose, building heights and widths are assumed to be 20 m, while the upwind wind profile is chosen to approximate flow over medium density suburban areas by using a logarithmic wind profile (suitable for neutral conditions) with a roughness length of 0.7 m (Oke, 1987). The buildings are assumed to be smooth with a roughness length of 0.004 m and the ground roughness length is set as 0.1 m. Wind speed is specified as 5 m s$^{-1}$ at a height of 20 m, ensuring that the threshold speed of 2 m s$^{-1}$ for the development of canyon vortices is comfortably exceeded. It should be noted that increasing upwind speed produces a similar relative increase in wind speed throughout the modelled region but does not alter flow patterns.
RESULTS AND DISCUSSION

In order to relate characteristics of canyon flow to previous discussions, vertical cross-sections at mid-canyon were investigated. These cross-sections provide a reasonable basis for a two-dimensional interpretation of the flow. Throughout this study, the upwind profile has been specified as logarithmic and "isolated roughness" flow has been defined as a return to a logarithmic profile down to 0.5H from the ground before the downwind building is encountered. It is not required that the resultant profile have the same velocity or gradient as the upwind profile. This formalizes Oke's definition (1987, p. 266) of "isolated roughness" flow as "the flow pattern appears almost the same as if they [the roughness elements] were isolated". Flow around an isolated building shows a return to a logarithmic profile with a steeper gradient in the lower heights, due to increased turbulence, to a distance of approximately 9H downwind (Oke, 1987). The depth of 0.5H was chosen on the basis of the results illustrated in Fig. 3c, which show that a "bolster" eddy formed on the face of the downwind building resulting in reverse flow across the canyon floor for canyons with H/W ratios greater than 0.2. Effectively there will never be a return to logarithmic profile near ground level within the canyon.

To gain insight into three-dimensional characteristics of the flow a series of plan-view (lateral) cross-sections within the canyon were analysed, looking in particular at the double-eddy circulation (Fig. 4). Simulated flows for wide canyons revealed that the horizontal extent of the double-eddy circulation on the lee side is constant with height above the ground. Figure 4a shows the extent of this circulation at a height of 1 m (0.05H) and Fig. 4b a similar extent at 9 m (0.45H). This result is in agreement with the diagrammatic flow representation of Hosker (1985) in

a) at height of 1m (0.05H)

b) at height of 9m (0.45H)

Fig. 4. Plan views showing extent of double-eddy circulation at two heights.
Fig. 5. Flow pattern near a building (Hosker, 1985, p. 1690).

It will be argued that the threshold $H/W$ ratio for the transition from skimming to wake interference flow can be determined from the extent of the double-eddy circulation which may be inferred from a plan-view at an arbitrary height within the canyon.

Beyond the double-eddy circulation the flow is characterized by a relatively strong cross-canyon velocity component (Fig. 6). The point where this cross-canyon flow is firmly established will be used to determine the threshold $H/W$ ratio for the transition from wake interference to isolated roughness flow.

Fig. 6. (a-c).
Fig. 6. Plan views at a height of 9 m (0.45H) showing extent of circulation and establishment of cross-canyon flow together with corresponding $H/W$ ratios. (N.B. diagrams are not to a common scale but an indication of wind speeds is given by the velocity vector marked $x$ in (c) with magnitude 4.8 m s$^{-1}$).

Transition from skimming flow to wake interference flow

The bulk of the incident flow on a canyon is forced by the upwind building over the top or around the ends of the canyon. As flow separates near the corners of the upwind building, areas of lower pressure are created at the sides and in the lee of the building. One of the effects of this is a horizontal double-eddy circulation with the familiar horseshoe pattern as described by Oke (1987). The along-canyon extent of
The double-eddy circulation is limited to near the corners of the buildings as illustrated in Fig. 5. It is encouraging to note that model simulations showed a similar pattern. As the relative length of the canyon is increased, the double-eddy circulation is maintained near the building corners (Fig. 6).

The reason for focusing on this circulation is our hypothesis that the transition from skimming to wake interference flow is related to the extent of the circulation. The horizontal double-eddy circulation and vertical vortex both require a counter-flow towards the lee wall of the upwind building; between the two eddies and beneath the vortex. Our suggestion is that the geometry of forces which maintain the circulation and the vortex is similar. (The vortex weakens once the canyon width exceeds the extent of the eddy circulation and wake interference flow ensues.) One of the factors may be the lack of along-canyon flow in the eddy circulation region implying that the major driving mechanisms are tangential forces imparted by above-roof and canyon-end flows.

The extent of the circulation for a canyon of given geometric proportions is determined visually from a vector flow diagram. The point, at the centre of the circulation, where no horizontal flow is observed (the eye of the circulation) is identified. The extent of the circulation is assumed to be twice the distance of the eye from the lee wall (Fig. 7).

It is marked for five geometries in Fig. 6 and the corresponding distance from the upwind building is listed in Table 1 as a fraction of building height. This distance increases as the relative length of the canyon increases until the $L/H$ ratio reaches about 5 and then remains constant at 1.5H.

As far as the transition from skimming flow to wake interference flow is concerned our hypothesis is that the transition takes place once the canyon is sufficiently wide that the double-eddy circulation is fully formed. On this basis it is possible to calculate the $H/W$ ratios at which this transition takes place for the five geometries considered by dividing $H$ by the extent of the circulation (Table 1).

A comparison of these results with those obtained from wind tunnels and derived from vertical cross-section flow analysis of the $k-\varepsilon$ model can be made by viewing Fig. 2 which portrays all three sets. The relative consistency of these results is a positive indicator of the validity of our hypothesis.

**Transition from wake interference flow to isolated roughness flow**

As the relative width of a canyon is increased in the numerical simulations then the double-eddy circulation is fully developed and a predominantly cross-canyon flow becomes established beyond the circulation (Fig. 6). This flow, on reaching the far wall, is deflected vertically upwards and along-canyon and escapes from the canyon (Fig. 3c).

Analysis of the flow patterns for different canyon geometries (Fig. 6) shows that just beyond the circulation, horizontal entrainment takes place from each side with air flowing into the canyon from the two leading edges. Subsequently the flow direction stabilizes and a point is reached within the canyon where the flow is essentially cross-canyon with negligible flow up or down the canyon. We will define this point to be that at which all horizontal velocity vectors are less than $10^\circ$ from the cross-canyon direction.

It is our hypothesis that the transition from wake interference to isolated roughness flow is related to the position of this point in the canyon. Dependent on the relative length, if the relative width of a canyon is greater than the distance of this point from the lee wall, then isolated roughness flow will be observed. That is, if the relative width exceeds this distance, then the downwind canyon wall has little effect on the

<table>
<thead>
<tr>
<th>$L/H$ ratio</th>
<th>Extent of double-eddy circulation</th>
<th>$H/W$ ratio</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>$0.8 , H$ (16 m)</td>
<td>1.25</td>
</tr>
<tr>
<td>2</td>
<td>$1.1 , H$ (22 m)</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>$1.4 , H$ (27 m)</td>
<td>0.74</td>
</tr>
<tr>
<td>5</td>
<td>$1.5 , H$ (30 m)</td>
<td>0.67</td>
</tr>
<tr>
<td>7</td>
<td>$1.5 , H$ (30 m)</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Table 2. Threshold $H/W$ ratios for the transition to isolated roughness flow

<table>
<thead>
<tr>
<th>$L/H$ ratio</th>
<th>Cross-canyon flow established</th>
<th>$H/W$ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1.8 , H$ (36 m)</td>
<td>0.55</td>
</tr>
<tr>
<td>2</td>
<td>$3.1 , H$ (62 m)</td>
<td>0.32</td>
</tr>
<tr>
<td>3</td>
<td>$4.1 , H$ (82 m)</td>
<td>0.24</td>
</tr>
<tr>
<td>5</td>
<td>$4.6 , H$ (92 m)</td>
<td>0.22</td>
</tr>
<tr>
<td>7</td>
<td>$4.6 , H$ (92 m)</td>
<td>0.22</td>
</tr>
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Fig. 7. Sketch showing calculation technique of horizontal extent of the double-eddy circulation.
general nature of the within-canyon flow. This hypothesis is tested by using it to determine threshold $H/W$ ratios for transition to isolated roughness flow for the five geometries previously considered (Table 2). The resultant $H/W$ ratios are included in Fig. 2 to enable comparison with previous methods of assessment. Using this approach the results are in good agreement with results for vertical cross-sections using the $k$-$\varepsilon$ model.

CONCLUSION

Investigation of the three-dimensional nature of flow within urban canyons suggests that the maintenance of a vortex circulation, associated with skimming flow, is dependent on the extent of the double-eddy circulation near the corners of the lee face of the canyon. The transition to wake interference flow occurs for canyons sufficiently wide that the double-eddy circulation is fully formed. It is the change from skimming to wake interference flow that is the most significant to urban climatologists since skimming flow, a feature of narrow canyons, provides minimal flushing of the canyon and is relatively ineffective in removing pollutants, heat and moisture.

This study has demonstrated the value of three-dimensional numerical models which are becoming available and whose computing resource requirements can increasingly be supplied relatively inexpensively. The model used still requires further validation but, subject to validation, the model gives flexibility in investigation of flow patterns making it competitive with field observations or wind tunnels. It should be noted that the results presented are preliminary and restricted to flow normal to the canyon.

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REFERENCES


