Coupling of a Scalar Dispersion and an Urban Canyon Energy Budget Model.

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The development of SCAM, a three-dimensional numerical model for the prediction of airflow and scalar dispersion in urban canyons, is described in two other papers (Cleugh et al., and Johnson et al., this volume). The first application of SCAM (Johnson and Hunter, 1995) was to a study of the dispersion of carbon monoxide emanating from car exhausts, but the long term aim has been to develop an urban canyon energy exchange model. In this quest, SCAM represents a facility which is capable of simulating the advection and turbulent diffusion of any scalar and hence can be applied to the convective transfer of heat, provided buoyancy is ignored.

In order to achieve the long term aim, SCAM must be coupled with an energy budget model which simulates the heating and cooling of the urban fabric under the full range of atmospheric environments experienced during any 24 hour period at any given location. A building facet energy budget model for an idealised building group already exists (Arnfield, 1995). This model is based on a radiation budget model (Arnfield 1990) which has been used by the climatological research community.

This paper reports on the work achieved thus far in linking the two models. The initial formulation is two-dimensional, for clear skies and for a dry system. The crucial linkage between the models occurs at surface boundaries and the heat fluxes there are checked with respect to physical plausibility.

1 Introduction

As populations and industries in urban centres continue to expand, the effects are being felt in the air quality, water quality, and quality of life. These effects have now become high-profile political issues. Planning is becoming much more important, especially in these larger cities, where planning decisions may effect the lives of great numbers of people in many ways. Traditionally, many planning decisions were made on an ad hoc basis, without scientific tools. Planners are now requiring new tools to assist them to more accurately and scientifically predict the possible consequences of the erection of new city buildings, or the modification of existing buildings. This project is concerned with developing a model which may be used to help provide such tools for urban planners in order to give them more information when determining the thermal climatic effects of building structures in urban areas.

A simple urban canyon, typically, is much longer than it is wide, and has tall buildings on either side of a street. The typical urban canyon occurs in the Central Business District of a large city. Modelling is important for learning about urban canyons. This is because it is extremely time-consuming and expensive to collect data in urban canyons, and modelling can replace this data collection, once a realistic model has been established. Data collection involves the setting up of sensors at various locations around the canyon over long time periods. This location of sensors often involves the interruption of traffic and pedestrian flows around busy intersections in the middle of the city. It is difficult when taking these measurements to actually get the range of weather conditions that the researcher is interested in, and this can extend the data collection time horizon.

This project aims to model the distribution of heat in a simple urban canyon. A simple urban canyon is a canyon in which the walls are vertical, the floors are horizontal, and there are no protrusions. The model aims to simulate the combined impacts on the thermal climate of solar geometry, atmospheric effects and building forms, materials and internal climate. The model then aims to simulate the transfer of this heat from place to place by the wind currents created above and within the canyon.

To achieve these aims, the model must include the capacity to calculate the radiative effects of sun and atmosphere at any given time, and at any given location within the canyon. The model must be able to predict wind flow in the canyon, and be capable of dispersing the heat in the direction of the wind movements. The model must be adaptable to the canyon having any orientation, and being at any latitude and longitude, and to making predictions at any time of the day and year.

In order to simplify the undertaking, we have looked for existing models which may be used to perform parts of the overall task. Given the authors' previous involvement in model development we have decided to use the Arnfield (1995) model for the energy budget within the canyon and SCAM (Johnson et al this volume) as the dispersion model. The aim of this paper is to discuss the coupling of these two models.

2 The Models

Two sub-models are combined to form the composite model. SCAM disperses heat around the canyon. The Arnfield energy budget model generates heat sources and sinks on the canyon and surrounding surfaces.

2.1 SCAM - airflow and scalar dispersion model.

This section will briefly describe SCAM, the dispersion model of Johnson and Hunter. SCAM is a three-dimensional numerical model for the prediction of airflow and scalar dispersion in and around urban canyons. There are two components to SCAM, a windflow model and a dispersion model, and both of these are described individually in the following sections of this paper.

2.1.1 Windflow Model

The wind model is CITY, developed by Paterson and Apelt (1989). The aim of this model is to predict the wind environment around buildings, pressures on building claddings and loads on building frames.

CITY is an implementation of the k-ε equations for turbulence. The model calculates the three components of steady state air velocity (one in each of the x, y and z directions), the augmented pressure, the turbulent kinetic energy and the dissipation of the turbulent kinetic energy.

The fundamental equations governing fluid motion are the continuity equation and the Navier-Stokes equations. By averaging the Navier-Stokes equations with respect to time, the steady-state Reynolds equations are obtained.

Solution of the Reynolds equations and the time averaged continuity equation relies on an approximation of the Reynolds stress tensor. This approximation is obtained by using the k-ε model of turbulence, producing a set of six equations in six unknowns. Paterson solved the equations by hybrid upwind differencing and integrating the equations over appropriate control volumes to obtain difference equations. The resultant algebraic equations were solved using the alternating direction implicit (ADI) method wherein, at each iteration, three sweeps of the solution domain are made (one in each co-ordinate direction).

The model thus determines the three-dimensional flow in and around the urban canyon, given the canyon geometry, the upwind vertical profile and the roughness lengths of the building and ground surfaces.

The grid used by the windflow model can be set up to give great detail in some areas, and less detail in other areas. In our implementation of the model, the grid is such that the nodes are closest together within the canyon, especially near the floor and are further apart away from the canyon floor and outside the canyon. Thus a finer grid is employed where the largest gradients are experienced.

In order to simulate a full day in an urban canyon, it must be considered that wind conditions may vary. If, during the 24-hour period, three different wind regimes occur, then it will be necessary to have three sets of wind data for the simulation. Thus three distinct runs of the wind program must be performed prior to execution of the combined model.

2.1.2 Dispersion Model

This section of the paper considers the dispersion model which is based on SCALAR, developed by Johnson and Hunter (1995). SCALAR was designed to simulate the atmospheric dispersion of a passive scalar around urban canyons. The model is three-dimensional in its implementation.

SCALAR disperses a passive scalar through and out of an the urban canyon using the velocity vectors and turbulent diffusivities supplied by CITY. SCALAR is based on the atmospheric diffusion equation

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}[K\frac{\partial C}{\partial x}]+\frac{\partial}{\partial y}[K\frac{\partial C}{\partial y}]+\frac{\partial}{\partial z}[K\frac{\partial C}{\partial z}]-u\frac{\partial C}{\partial x}-v\frac{\partial C}{\partial y}-w\frac{\partial C}{\partial z}+S \qquad (1)$$

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
$u(x,y,z)$ is the air velocity component in the x direction at the point (x,y,z)
$v(x,y,z)$ is the air velocity component in the y direction at the point (x,y,z)
$w(x,y,z)$ is the air velocity component in the z direction 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 CITY. Values for C are calculated by SCALAR. Values for S, the source term, are provided to SCALAR as a time-varying constant.

The original version of SCALAR has been modified for use in this project. Our implementation of SCALAR restricts it to two dimensions, taking a cross-section of the urban canyon at a point mid-way along the canyon.

2.2 Surface Energy Budget Model

We now consider the surface energy budget model selected for incorporation into our model. The surface energy budget model was devised by Arnfield. 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, as well as allowing for any site location for the canyon, and varying weather conditions.

The energy budget model considers the nine surfaces (or facets) close to the urban canyon. These nine surfaces which can be seen in figure 1 are:

(1) the ground surface before the wall of the first building on the outside of the canyon
(2) the outside wall of the first building of the canyon,
(3) the roof of the first building,
(4) the inside canyon wall of the first building,
(5) the roadway between the buildings of the canyon,
(6) the inside canyon wall of the second building,
(7) the roof of the second building,
(8) the outside wall of the second building,
(9) the ground surface after the second building.

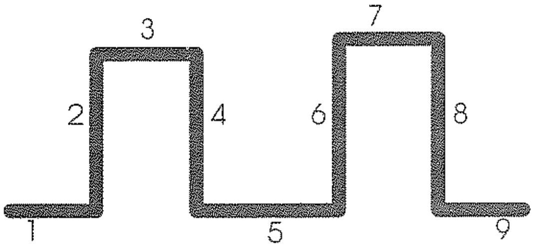

Figure 1: The Nine Surfaces close to an Urban Canyon

The energy budget model breaks each of the nine surfaces up into a number of elements (or given points) and considers each point separately, determining the energy budget of each on the basis of

$$K^{*}+L{\downarrow}_{S}+L{\downarrow}_{T}=Q^{*}=Q_{H}+Q_{G} \qquad (2)$$

where

K^{*} is the absorbed solar radiation;
$L{\downarrow}_{S}$ is the absorbed longwave irradiance from the sky;
$L{\downarrow}_{T}$ is the absorbed longwave 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 and orientation, and allows for multiple reflections between canyon facets. At present the model is being used for cloudless skies, but this can be changed in later testing.

For each surface, the energy budget model uses a constant grid size across the whole area in question. Grid points cannot be selected, just the number of points on the surface, and from this information, the energy budget model equally spaces the points across that surface.

3 Coupling the Models

In order to couple these large models together, a number of problems have been encountered, and we have attempted to overcome them. In this section we will describe the problems, and our solution methods.

There are four major problems: the alignment of the grids;, the alignment of the time steps; the boundary heat transfer; and the size of the models. Each of these will be considered in turn.

3.1 Grid Points

Each of the sub-models uses a completely different technique for forming grid points, and these grid points are not easily made to be compatible. Further, each sub-model works in different units and on different materials.

SCALAR, the dispersion model, allows the grid points to be selected independently for each dimension. A set of x-, y- and z-grid-points can be selected independently. The dispersion model, divides the solution domain into non-overlapping control volumes about each grid point, and the scalar to be dispersed by the model is considered to be contained within these volumes. The control volumes being considered in SCALAR are the small parcels of air contained within the grid lines of the three axes, and because of the different size grid positions, each volume may be of a different size.

This selection of independent grids for the three axes is to allow for an in-depth study of some areas, and a brief overview of other areas. The control volumes each contain a grid-point at their centre. Figure 2 demonstrates these concepts.

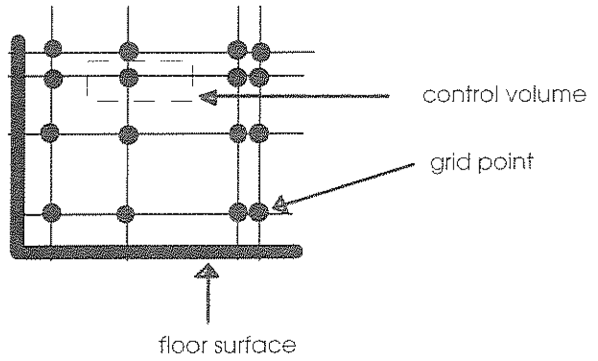

Figure 2: Grid Points and Control Volumes

The grid points used by SCALAR are never actually on the canyon surfaces, although the nearest is a very small distance away.

On the other hand, the energy budget model has grid points which are actually on the nine surfaces of the model. On each individual surface, the grid points are a constant distance apart. The user can specify how many grid points are to be on each surface, and the grid points are automatically spaced equidistance apart along the chosen surface. Figure 3 shows grid points on the surfaces.

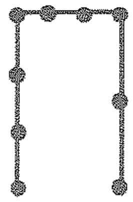

Figure 3: Equally Spaced Grid Points on Three Surfaces

Thus the two sub-models have differently spaced grid points and, theoretically, the boundary grid points cannot be the same physical location, for SCALAR has these points in the air, and the energy budget model has them on the surface.

It would be possible to use a very similar set of grid points (they can be aligned, although not on the same surface) by choosing the smallest grid spacing in each dimension. But this would be extremely computationally expensive. We prefer to let both models use their own independent grid points designed to give sufficient accuracy for the individual models to be acceptable, and yet to be economical of computer time.

Given that the two models use different grid points for their calculations, it is necessary to transfer data from one model to the other. That is, transfer heat data from the surface points used in the energy budget model to the air points used in SCALAR, or transfer the air temperature very near the surface in SCALAR to the surface points in the energy budget model. To transfer the heat data, interpolation is used to estimate the values at the grid points for the model to which data is being transferred. We have chosen to use a cubic spline interpolation which calculates an estimate of the data values at each desired point using the existing data values and positions from the alternate model. Hence for data to be transferred from say, the energy budget model to SCALAR, a cubic spline is placed through the grid points of the energy budget model and the values for the grid points of SCALAR are interpolated.

3.2 Time Steps

The sub-models have independent time steps. SCALAR does two calculations:- one for diffusion, and one for advection. Each of these calculations has a different time step. The typical time steps used by SCALAR are 0.2 seconds for advection, and 1 second for diffusion, and it seems reasonable to continue with these time steps in the current implementation.

The energy budget model has an independent time step which is used for calculating the transfer of heat through the walls of the canyon.

As a simplification, the current version of the model requires that (i) the diffusion time step be an integer multiple of the advection time step, and (ii) the energy budget model time step be an integer multiple/division of the diffusion time step. Thus the time step for looping through the composite model is the greater of the energy budget model time steps and the diffusion time steps.

SCALAR expects as input its two time steps, and runs the diffusion and the advection parts of the model accordingly. SCALAR also expects a total duration time. The composite model acts as timekeeper between the two sub-models. It first runs SCALAR for an elapsed time equal to the calculated composite time step. The data from SCALAR are converted ready for use in the energy budget model. Then the energy budget model is run for as many times as needed to encompass an elapsed time equal to the calculated composite time step. The data is converted from energy budget model format to SCALAR format. This sequence is performed as many times as are needed to encompass the desired elapsed time.

3.3 Heat Transfer

The interpolation of data gives us a data value at each point in each of the sub-models, but these sub-models work in different units, and on different materials. It is not meaningful to interpolate a heat flux value from one material to another material. A conversion must also be performed taking into account the different properties of the two materials.

Firstly consider the conversion from the surface to the air. The heat on the surface is measured in joule $m^{-2}s^{-1}$ and this must be converted to temperature change in the air parcel nearest the surface. Thus the volume size, and material properties of the air need to be included in the calculation.

The dispersion model, allows for a temperature in each control volume, plus a constant source term to be produced. Is is the calculation of the source term that is discussed here. The heat coming from the building is considered to be a source term, producing a constant supply of temperature change. Note also that the building may sometimes actually be a sink producing a negative temperature change.

In order to calculate this source term, initially all source temperatures are set to zero, then for each air grid point nearest the surface of the canyon, the temperature change is calculated as follows:

$$source = source + \frac{Q_H}{(heat\_capacity\_of\_air * volume\_of\_parcel)} \tag{3}$$

Some source terms will have components from both the x and y axis.

When converting from air temperatures to surface temperatures, interpolation can be used to give the new surface temperature on each grid point on each of the surfaces. This interpolation is necessary, as the grid points on the surface do not have any relationship to the grid points in the air. As heat is not being considered here, there is no need for a conversion of units.

3.4 Computational Resources

To aid in the development of what is a very large and complex model, initially the simplification to a two-dimensional case is used and it is this two-dimensional situation that is reported here.

This composite model and its sub-models rely on doing large numbers of calculations on many large arrays, and thus take considerable time to execute. The wind program, for example, running with an average sized grid of 39 x-values, 33 y-values and 26 z-values took 7.75 hours to execute on a Sun workstation. Because of the time taken to run the wind program, it is run as many times as is necessary to simulate the varying wind strengths and directions and each resultant data-set is saved, in readiness for use when the composite model is run.

Only preliminary tests of the combined model have been run at present. When more extensive testing begins, we plan to use the CRAY Y-MP at the Ohio Supercomputer Center from whence we have obtained a grant for this purpose.

4 Details of the Simulation

The coupling of the models involves the writing of a quite large computer program, and this is described in the next sections.

4.1 The Software

The two existing models (SCAM and the energy budget model) are both large programs requiring much computation. These models were in fact written by different people, in different styles, and in different countries. All of the actual programs are written in FORTRAN, and it was decided that the combined model would also be best written in FORTRAN. To this end, all models are being run using FORTRAN 77.

Because the programs were written independently, it was decided to try and keep the original models as separate as possible, but some modifications have been necessary. Where possible, the original developers have made the modifications to their own models. This has been particularly interesting with John Arnfield, one of the authors of this paper, being located in Columbus Ohio (USA).

4.2 Status of Project

The model for performing the linkage has been designed, and the program has been coded. It is currently being tested to check for heat loss at boundaries and 'reasonableness' of output.

For simplicity we are using a symmetric canyon which has no other buildings nearby. The canyon is long enough so that at mid-canyon, the along-canyon flow is insignificant compared to the within canyon flow.

The canyon being used at this stage of testing the model is a canyon in Columbus Ohio (40° North), during the 15th of March.

The canyon ground surfaces (1, 5 and 9) are all dry soil with a layer of asphalt. Surface 5 is a roadway, whilst surfaces 1 and 9 are parking lots. Each of these surfaces has 12 nodes equally spaced along the surface.

The wall surfaces (2, 4, 6, and 8) are each two layers of brick and each of these surfaces has 8 nodes equally spaced along the surface.

The roof surfaces (3 and 7) are both steel reinforced gypsum roof deck. Both of these surfaces have 4 nodes equally spaced along the surface.

The 15th of March has been chosen as this is early Spring and hence weather is mild. Typical March weather includes dry, clear skies, with a constant wind speed and direction, so these are the conditions being used in our initial testing.

Our testing time commences early in the morning when a uniform temperature can be assumed. We are commencing with a uniform temperature of 5° Celsius.

Johnson et al (1995) found in their testing of CITY that the model should only be used when roof-level wind speeds exceeded 1.5 - 2.0ms^{-1}. This is also the wind speed recommended by DePaul and Sheih (1986), so the wind speed adopted here will satisfy this condition.

5 Conclusions

This paper has described the creation of the composite model for linking the dispersion model SCAM to the building facet energy budget model. It has discussed the problems encountered and the chosen solutions.

Testing of the model under ideal conditions is underway, and when completed satisfactorily, the model will be used to investigate relationships between heat flow and canyon geometry.

Eventually, it is hoped to extend the model to be a full three-dimensional model.

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