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MULTISCALE MODELLING OF URBAN CLIMATE

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ABSTRACT

Climate Modelling is a complex task. One of the most important reasons is the presence of a large variety of spatio-temporal scales. There are climatic changes that take place over a time period of a few months and then there are gusts which might last only a few seconds. Similarly there can be a strong influence on the weather of a city due to the presence of a large water body like a sea or of a mountain having a dimension of a few tens or hundreds of kilometres and then there can be a local influence due to the presence of urban structures like buildings and canopies having dimensions of the order of a few meters only. It is not computationally tractable to handle all of these scales in a single climate model. However, we can solve this issue by an integration of a global, meso and micro scale model capable of handling each of the different scales of interest. In this paper we describe in detail one such approach, along with some sample results demonstrating the capabilities of this tool.

INTRODUCTION

Due to differences in radiation exchange, surface thermophysical properties, anthropogenic gains and evaporative sinks as well as reduced mean air velocity, the mean air temperature in cities tends to be higher than in the immediate rural surroundings. But due to inertial differences the magnitude of this heat island effect (which may also be negative) varies with the time of day. Accounting for this complexity requires a detailed numerical model. Another problem arises because of the diverse time and length scales involved in atmospheric flow. The length scale for example can vary from a few meters (buildings) to a few kilometers (mountains). It is almost impossible to resolve all these scales in a single model with the presently available computational power.

A way to overcome this problem is to couple different models capable of resolving different scales. As shown in Figure 1 in our approach we use a global numerical model having a resolution of a few hundred kilometers to provide boundary conditions to a mesoscale model having a resolution of a few hundred meters. The exchanges of mass, momentum and energy with the urban texture are implicitly represented by an urban canopy model. Such a model would improve the accuracy of energy predictions from both building and urban resource flow simulation software.

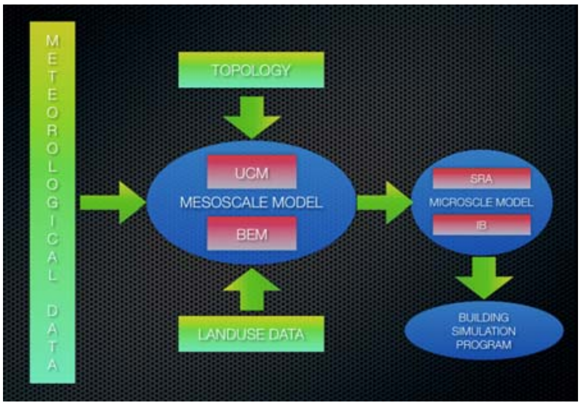


Figure 1 Multiscale Modelling approach

But when investigating natural ventilation strategies for buildings or the comfort of pedestrians in a city, it is also important to account for the local temperature and velocity field in an accurate way; which depends on local as well as on large scale phenomenon. For this we couple our mesoscale predictions with a microscale solver. With this one-directional coupling high level models may be regarded as pre-processors to the lower level ones. This opens the possibility of being able to couple microclimate models with pre-computed mesoclimate results, which could be made available from internet sites. Our modelling methodologies are presented along with some sample results in the following sections.

MODELS

Mesoscale Model

A Global Model developed by NCEP (National Center for Environmental Prediction) having a resolution of 270km x 270 km forces our Mesoscale Model (MM) having a resolution ranging from a few hundred meters to a few kilometres. The MM solves equations 1 to 6 (below) on a structured terrain following grid using a finite volume approach. Turbulence is modelled using a one equation model suggested by Bougeault and Lacarrere (1989)

Governing Equations

Mass Conservation equation: This simply states that, in any arbitrarily chosen control volume in the atmosphere, the mass of air is always conserved. Furthermore since the wind speed encountered in the atmosphere is never comparable to the speed of sound we can further make an assumption that the fluid is incompressible. Putting this mathematically we have that:

$$\frac{\partial \rho U_i}{\partial x_i} = 0 \quad \text{...(1)}$$

Momentum Conservation Equation

This simply states that, for any arbitrarily chosen control volume in the atmosphere, the rate of change of momentum of the packet of air is equal to the resultant of the total force acting on that volume. Mathematically, this can be represented as follows:

$$\frac{\partial \rho U_i}{\partial t} = -\frac{\partial p}{\partial x_i} - \frac{\partial U_i U_j}{\partial x_j} - \frac{\partial \overline{U_i' W'}}{\partial z} - \rho \frac{\theta - \theta_0}{\theta_0} g \delta_{i3} - 2\varepsilon_{ijk} \Omega_j (U - U_k^G) + D_{ui} \quad \text{… (2)}$$

In Equation 2, the term on the left hand side is the rate of change of momentum. The first term on the right hand side is the gradient of pressure. The second is the advection term, the third term arises due to turbulence, the fourth term is the result of buoyancy and the fifth term is the corialis force that results from the rotation of the earth, while the last term is the source or sink of momentum. This can be used to account for the drag or shear forces due to buildings encountered in a city.

Energy Conservation Equation

The energy conservation principle states that for a particular control volume the imbalance in energy input and output leads to a change in the internal energy of the air in that volume.

$$\frac{\partial \rho \theta}{\partial t} = -\frac{\partial \rho \theta U_i}{\partial x_i} - \frac{\partial \rho \overline{\theta' W'}}{\partial z} - -\frac{1}{C_p}\left[\frac{p_0}{p}\right]^{R/C_p} \frac{\partial R_l}{\partial z} + D_\theta \quad \text{…(3)}$$

In Equation 3, the LHS is the rate of change of the internal energy of the air packet. The first two terms on the RHS are the advection and the turbulent transportation of potential temperature respectively The third term on the RHS represents the radiative heating of the packet of air, while the last term represents the source or sink of the energy equation.

Turbulent Kinetic Energy Equation

$$\frac{\partial \rho E}{\partial t} = -\frac{\partial U_i E}{\partial x_i} - \frac{\partial \overline{E' W'}}{\partial z} + \rho K_z \left[\left(\frac{\partial U_x}{\partial z}\right)^2 + \left(\frac{\partial U_y}{\partial z}\right)^2\right] - \frac{g}{\theta_0} \rho K_z \frac{\partial \theta}{\partial z} - \rho C_\varepsilon \frac{E^{3/2}}{l_\varepsilon} + D_E \quad \text{…(4)}$$

The LHS of the Equation 4 is the rate of change of turbulent kinetic energy. The first, second, third, fourth, fifth and sixth terms on the RHS correspond to the advection, turbulent transportation, shear production, buoyancy production, dissipation and additional sources of turbulent kinetic energy.

The turbulence terms in all of the above equations are modelled as Equation 5 and 6:

$$W'A' = -K_z \frac{\partial A}{\partial z} \quad \text{…(5)}$$

$$K_z = C_k l_k E^{3/2} \quad \text{…(6)}$$

The radiation (both longwave and short wave) model of Schayes (1982) is used along with the possibility to switch to the Simplified Radiosity Algorithm described later in this paper.

Urban Canopy Model

In the previous section we described our mesoscale model which typically has a resolution of a few hundred metres. In order to resolve the scales smaller than this grid a one-dimensional Urban Canopy Model (UCM) has been developed. The governing equations (7,8,9) of the UCM for predicting the velocity, temperature and turbulent kinetic energy profiles inside the canopy is obtained by a spatial averaging of the equations which form the basis of the mesoscale model. This averaging assumes periodicity in the occurrence of urban structures. A building is represented by a block of specified width, breadth and height while the street is represented by its width and orientation (Figure 2).

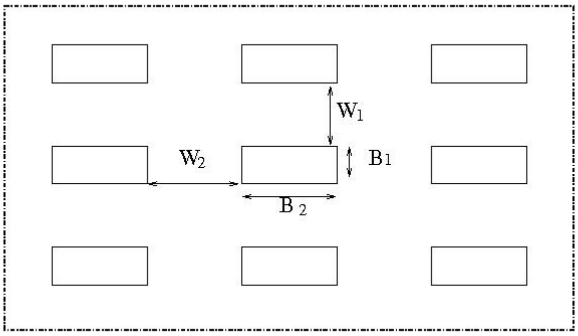


Figure 2: Geometries handled in the UCM

The drag forces offered by the rectangular cuboids have been taken to be proportional to the square of the local velocity field and the turbulent and dispersive fluxes (which arise due to the spatial averaging) have been combined (because they are similar for B/W > 1). At the lower boundary both the horizontal velocity components are taken as zero. The upper boundary condition is applied at 3.4 times the height of the cube. Constant values are applied at the upper end by the MM. For the energy equation a constant heat flux is given at the ground surface and at the top boundary the temperature is supplied by the MM.

$$\frac{\partial u}{\partial t} = \frac{1}{\Lambda}\frac{\partial}{\partial z_c}\left(K_{zu}\Lambda \frac{\partial u}{\partial z_c}\right) - a_1 C_d u \sqrt{u^2 + v^2} \quad \text{… (7)}$$

$$\frac{\partial v}{\partial t} = \frac{1}{\Lambda}\frac{\partial}{\partial z_c}\left(K_{zv}\Lambda \frac{\partial v}{\partial z_c}\right) - a_2 C_d v \sqrt{u^2 + v^2} \quad \text{…(8)}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Lambda}\frac{\partial}{\partial z_c}\left(K_{z\theta}\Lambda \frac{\partial \theta}{\partial z_c}\right) - Q_\theta \quad \text{…(9)}$$

$$a_1 = \frac{B_1 P_b(z)}{(B_1 + W_1)(B_2 + W_2) - B_1 B_2 P_b(z)} \quad ...(10)$$

$$a_2 = \frac{B_2 P_b(z)}{(B_1 + W_1)(B_2 + W_2) - B_1 B_2 P_b(z)} \quad ..(11)$$

$$\Lambda = 1 - \left(\frac{B_1 B_2}{(B_1 + W_1)(B_2 + W_2)} \right) P_b(z) \quad ...(12)$$

$$K_{zu} = K_{zv} = K_{z\theta} = L^2 \left| \sqrt{\left(\frac{\partial u}{\partial z_c}\right)^2 + \left(\frac{\partial v}{\partial z_c}\right)^2} \right| \frac{S_m^{3/2}}{\sqrt{C}} \quad ...(13)$$

A complete derivation of the expression of K_{zu} can be found in Gambo (1978). The length scale L is given by Watanabe and Kondo (1990) and was derived from considerations of a forest canopy:

$$L(z_c) = \frac{2\kappa^3}{ca}\left(1 - \exp(-\eta)\right) \quad ...(14)$$

$$\eta = \frac{caz}{2\kappa^2}; \quad ...(15)$$

and above the canopy we use an interpolation formula after Blackadar (1968):

$$L(z_c) \le \frac{\kappa z_c}{1 + \frac{\kappa z}{L_0}} \quad ...(16)$$

which interpolates between two limits $L \sim kz$, at $z = 0$ and $L = L_o$ as $L \to \infty$. In this study we have used a value of $L_o = 70m$.

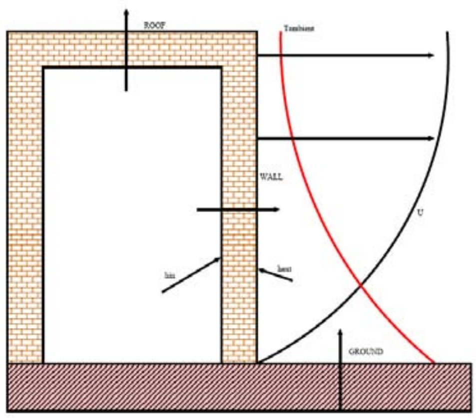
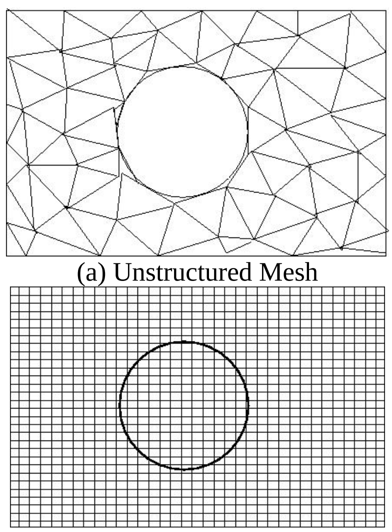


Figure 3: Modelling of the urban element

The source term appearing in the energy equation of the UCM is the amount of energy exchanged with the urban elements. To estimate this, a one dimensional conduction equation is solved for walls, roofs and ground (Figure 3) by assuming a fixed temperature inside the building and 2m below the ground. At the other surface (in contact with the air) a time dependent heat flux (due to radiation) is applied as the boundary condition. The UCM computes the vertical profiles of velocities and temperature which are then used to compute the effects of drag forces, shear forces and the convective exchange of energy between the building and its surroundings. These are called the sources of momentum and energy at the Urban Canopy scale. They can be further modified using a Building Energy Model to include the effects of air-conditioning. These UCM sources are then interpolated back to the Mesoscale grid thus providing the sources of the respective equations at the mesoscale.

Microscale Model

As stated earlier the mesoscale model gives the velocity and temperature profile at a resolution of a few hundred meters. However, one might be interested in a more detailed profile of these quantities to evaluate natural ventilation potential or pedestrian comfort. To achieve this, a high-resolution numerical computational model is used which combines fluid dynamics calculations with the thermodynamic processes taking place at the walls and roof surfaces encountered in a city. To use a purely conventional CFD approach to simulate air flow around complex geometries encountered in a city one is normally left with no option but to use an unstructured mesh (Figure 4(a)). But unstructured grid generation is a time consuming process and also the numerical methods for solving the conservation equations with unstructured meshes suffer from stability and convergence issues. In contrast a Cartesian mesh (Figure 4(b)) is very easy to generate and efficient numerical algorithms are available to significantly reduce the computational time. However, it is not straightforward to fit Cartesian grids to complex geometries and doing so invariably creates a great many redundant cells. As a compromise we use a solution which combines numerical stability with the possibility of creating grids for complex geometries, called immersed boundaries.



(a) Unstructured Mesh

(b) Structured mesh

Figure 4: Different types of mesh

In this approach the simulation around complex geometries is conducted using a non body conformal cartesian grid in which the fluid solid interface is represented by a surface grid, but the Cartesian volume is generated with no regard to this surface grid. Thus the solid boundary would cut through the Cartesian volume grid. Because the grid doesn't conform to the solid boundary, incorporating the boundary conditions requires us to modify the equations in the vicinity of the boundary. Assuming that such a modification is possible (of course it is) the modified governing equations would then be discretized using a finite difference, finite volume or a finite element technique without resorting to coordinate transformation or complex discretization operators. When compared with unstructured grid methods, the Cartesian grid-based IB method retains the advantage of being amenable to powerful line-iterative techniques and geometric multigrid methods, which can also lead to lower per-grid-point operation counts.

Immersed Boundary Approach in an Urban Context: This new algorithm as against the conventional CFD approach offers us the possibility of simulating large domains. In principle constructing urban geometry with a 3-D modeling tool is trivial and quick and such geometries can be readily converted into a STL (sterio lithography file) format which holds information about the solid-liquid interface (in our case the building-atmosphere interface). The file is parsed to find out the solid and fluid zones. The flow equation is solved only in the fluid zone, so that in the solid zone the flow equations are switched off. The air flowing over the buildings are treated as phase one and the buildings are treated as phase two. The Specific heat capacity, conductivity and density of the two phases are specified for each building and the air separately. The amount of solar radiation as well as the anthropogenic heat generated due to human activities can be looked upon as heat sources which might vary with time. The methodology to compute the solar radiation is explained in the next section. The boundary conditions of velocity and temperature are forced through the interpolation of results from mesoscale simulations on to the microscale grid, with care being taken to impose mass conservation over the full domain.

Simplified Radiosity Algorithm: In order to implement the SRA (Simplified Radiosity Algorithm) for the calculation of longwave and shortwave exchange in urban context, the view factors from each surface to a descretized sky vault, the sun to each surface and from surface to surface are required. The view factors are computed by rendering the scene from different points (sun positions or the centroids of the triangles resulting from surface tessellization). The view factors of the sky are used with the cosine of the angle of incidence between the surfaces and the sky patches to obtain the sky contribution matrix. This matrix is then simply multiplied by the radiance of each sky patch to obtain the incident energy at each surface. Similarly, the sun view factors are used to obtain the direct contribution matrix. Finally, the view factors between surfaces are combined with the relative angle between the surfaces to obtain the surface contribution matrix. This matrix allows for computation of the contribution due to reflection. Further details including results from extensive validation tests can be found in Robinson (2004)

MODEL CALIBRATION

To demonstrate the capabilities of our Multiscale Model we have chosen the city of Basel. Basel is located at the border with Germany and France, at a latitude and longitude of 47° 00' North and 8° 00' East, respectively.

To conduct a realistic simulation, input data such as the topography and land use are required. Furthermore, to force the effects of the scales larger than those handled by the mesoscale model appropriate meteorological data are required as boundary conditions. Fortunately, these data are available on the internet to be used by the scientific community. However, before using them in the simulations these data have to be processed. Below we explain briefly how the various input data are obtained and processed.

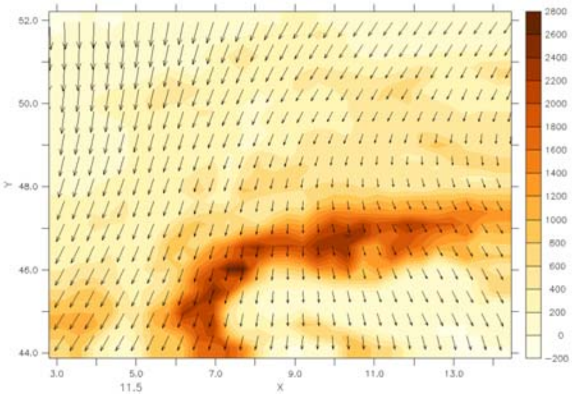
Meteorological Data

As noted earlier the scales that are comparable to the grid size are resolved by the model. However, scales that are bigger than the domain or lie outside of the domain can't be parameterized or resolved. Their effects are captured in the mesoscale model using a procedure called nesting (Figure 5(a) and 5(b)) via boundary conditions. The effects of oceans and mountains are taken into account by a Global model like NCEP (National Center for Environmental predictions). The data (velocity, humidity, temperature, pressure) from this global model is available via a web portal cdc.no.gov (2008).

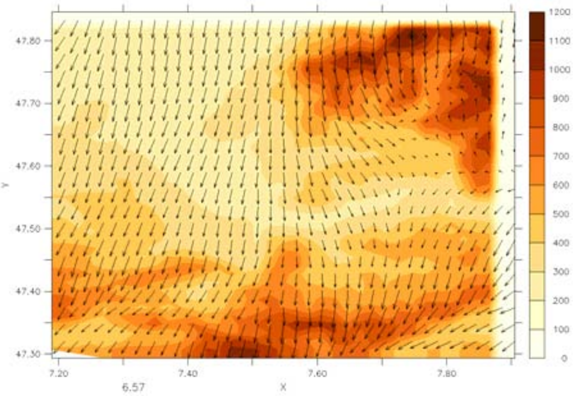
Moreover, the global model has a resolution of 270km X 270km whereas we require the velocities, temperature and humidity to be interpolated to a grid having a resolution of just 1m X 1km. For this we first construct a domain with a resolution of 15 X 15 km and assuming it to be 100% rural. We then run a simulation to generate an output file. This output file is then used to force another smaller domain with a higher resolution. We thus interpolate in a few steps from the global model to the mesoscale model domain.

Landuse

A major aim of this project is to study the interaction between the climate of a region and the urban texture. It has been well established through various field experiments and numerical simulations that the urban texture significantly affects the urban microclimate. Relevant simulations of the urban climate are therefore only possible when we input the correct landuse data into the model. This data is obtained from another web portal. The Global Vegetation Monitoring Unit of the European Commission Joint Research Centre, provides for the year 2000 a harmonized land cover database over the whole globe. From this data we can determine the fraction of artificial surfaces. In Figure 6(a) one can see the graphical representation of the data obtained from the net and in Figure 6 (b) the processed result in the format required by the mesoscale model.



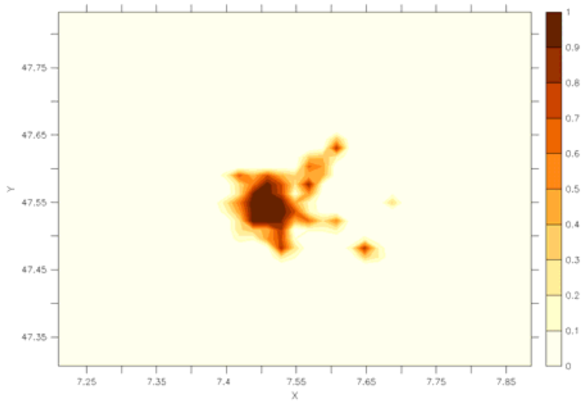
(a) Raw downloaded data



(b) Interpolated data

Figure 5: Interpolation of meteorological data

(a) Downloaded land use data



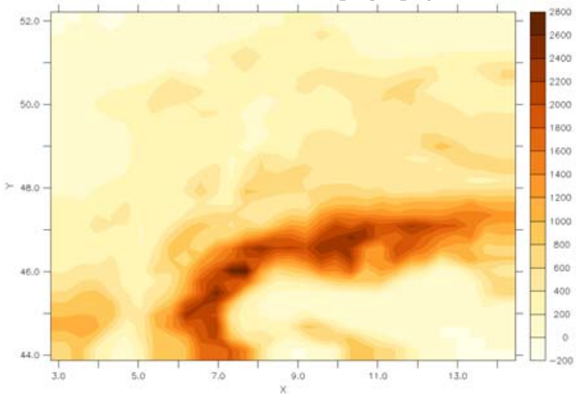
(b) Interpolated land usedata

Figure 6: Interpolation of land use data

Topography

A mesoscale domain may range from a few kilometers to a few hundred of kilometers. Over such a large expanse the topography may vary significantly. Such variations can be taken into account by downloaded topological data from the website edc.usgs.gov (2008). This data is expressed as a global digital elevation model (DEM) with a horizontal grid spacing of 30 arcs seconds (approximately 1km). In our case we have downloaded the topography of Europe. In Figure 7(a) below one can see the graphical interpretation of the raw data downloaded from the website. This data is then processed (see Figure 7(a)) to extract the topographical information for the domain we want to simulate.

(a) Downloaded topography

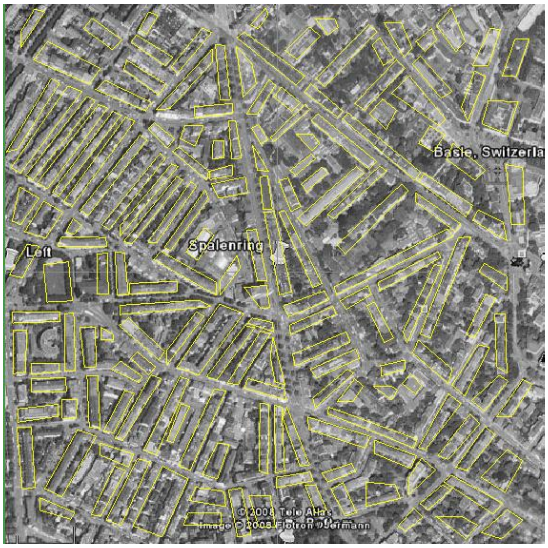


(b) Interpolated topography

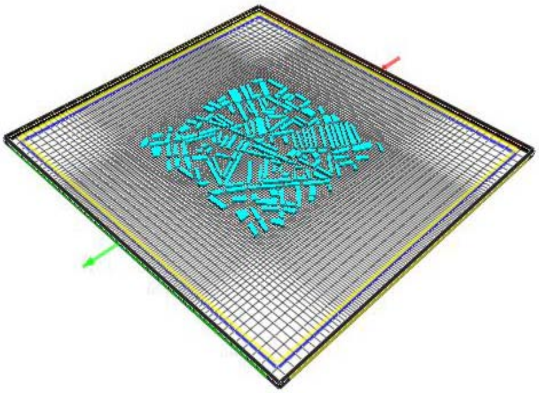
Figure 7: Interpolation of topography

3-D geometry

The final data requirement of our multiscale modeling methodology relates to the geometry of buildings as input to microscale simulations. For this we produce an abstracted form of buildings' geometry using the NURB (Non-Uniform Rational BSpline) based 3-D modelling software Rhinoceros. For this an aerial view of the city is obtained from Google Earth image (Figure 8(a)). The corresponding 2D geometry is sketched (Figure 8(b)) using Rhinoceros. The resultant polygons are then vertically extruded according to the building heights estimated from visual surveys.



(a) Google image

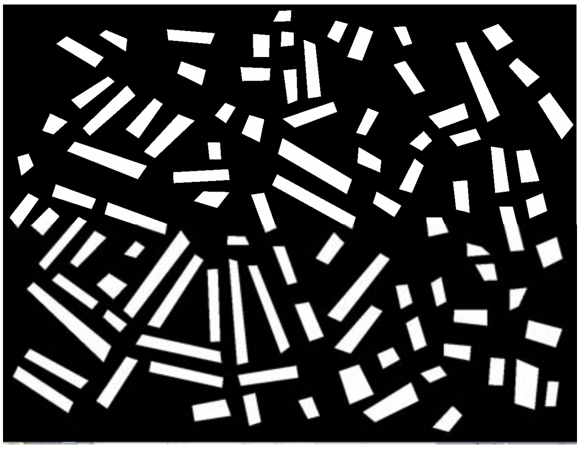


(b) Sketched geometry using Rhino

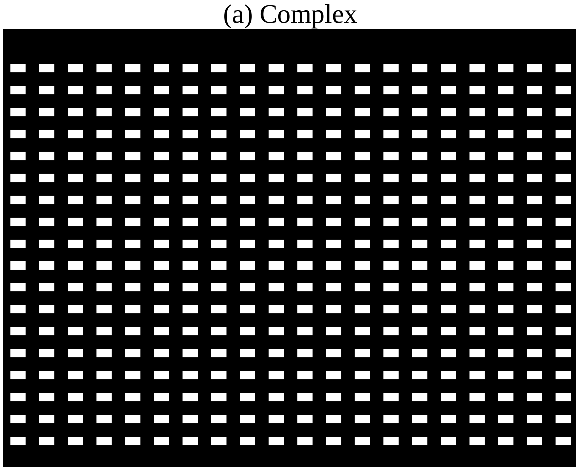
Figure 8: 3-D geometry for microscale simulation

Simplified geometry fitting

The inputs to the mesoscale model, which include street width, building width, building density and a statistical representation of the buildings' heights, are generally obtained through quantitative field surveys (which are very slow and time consuming to perform) or qualitative estimates. But in performing this geometric abstraction there is no way to ensure that the total built surfaces and volumes of the simplified geometry match those of the actual city. Here we describe a method, which not only eliminates the need of time-consuming field survey but also reduces a complex representation of a city to an "equivalent" simplified representation. To accomplish this we choose a mesoscale cell and download a Google image of its ariel view. The view is then used to create a three dimensional model. The SRA is used to compute the distribution of radiation on different types of surface (roofs, grounds and walls) while the IB technique is used to compute drag and spatially averaged quantities (velocity and turbulent kinetic energy profiles) for the same domain. We then search for a simplified representation (consisting of a regular array of cubes) which has similar characteristics as the complex one. Figure 9 presents an example to demonstrate the concept.



(a) Complex



(b) Simplified

Figure 9: Equivalent Simplified Geometry

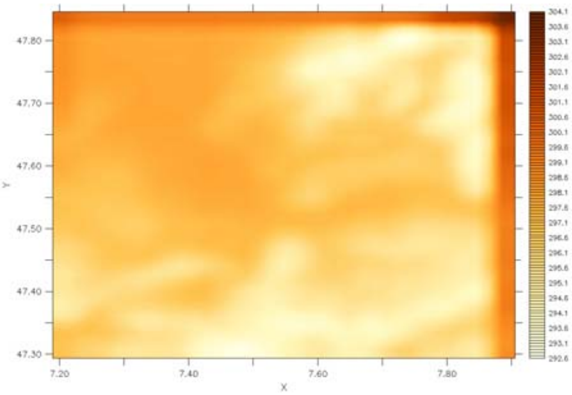
In both the geometric representations of Figure 9 the total built surfaces, built volume, the distribution of shortwave radiation amongst different surfaces and the average velocity profile are similar. Thus the complex representation shown in Figure 9(a) can be replaced by the simplified representation shown in Figure 9(b) and can be used in a mesoscale simulation.

RESULTS

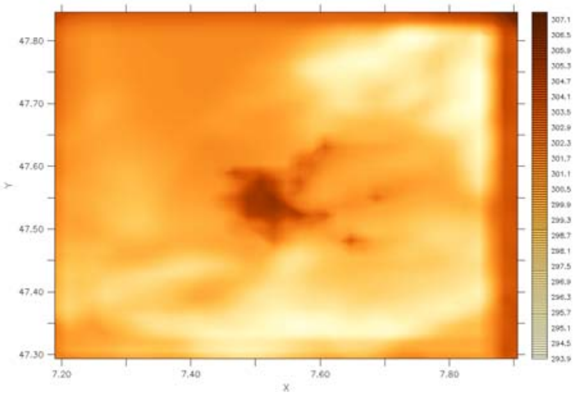
Mesoscale Results

In Figure 10(a) we have assumed a hypothetical situation where the whole of Basel and its surrounding area is 100% rural, implying no urban structures.

In Figure 10(b) we have presented the impact of introducing a simplified urban representation of the city; the result corresponding to midday at a height of 5meters above the ground. Here one can clearly see a rise in temperature in and around the city. This can be attributed to the increased absorption of radiation by the urban structures, to the change in surface thermophysical properties and a damping of air flow in the city. The UHI intensity is around 5-6C which can have a significant impact on energy demands for cooling or heating.



(a) Rural

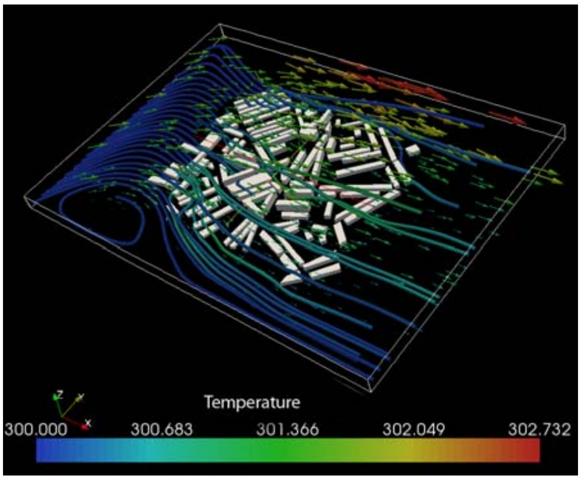


(b) Urban

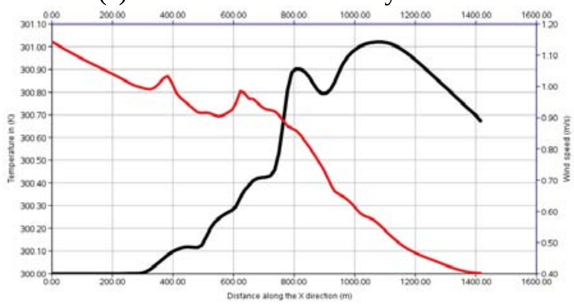
Figure 10: Temperature profiles for rural and urban simulations for the city of Basel

Microscale Result

In Figure 10 we present results relating to the district of Matthäus in Basel. For this the boundary conditions have been forced on the microclimate model using the results of the mesoscale model. The ambient temperature tends to be higher in the regions where the velocity is lower (Figure 11(b)); the more a packet of air circulates around a built structure the more time it has to exchange energy with the buildings, thus becoming warmer. As can be observed in Figure 11(a) streams of air flowing through the city attain a higher temperature compared to the stream that avoids contact with built surfaces.



(a) Streamlines and velocity vectors



(b) Temperature and velocity profiles along a line stretching from one end of the domain to the other along the direction of flow.

Figure 11: Microscale Simulation Results

CONCLUSIONS

In this paper we describe a new solution to handling the range of time and length scales which influence urban climate predictions in a computationally tractable way. This involve the use of results from a global meteorological model to force the boundary conditions of a mesoscale model, in which a model of the urban canopy is embedded. These mesoscale predictions may then be used to force the boundary conditions of a local microscale model, so that good quality local urban climate predictions may be achieved whilst accounting for large scale climatic tendencies such as the urban heat island effect.

This multiscale urban climate modelling method will be of use for building and urban scale performance predictions as well as for the future simulation of pedestrian comfort.

ACKNOWLEDGEMENTS

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NOMENCLATURE

ρ Density of Air

U_i Velocities in three directions

p Pressure

U_i' Velocity fluctuations

W' Velocity fluctuation in the vertical direction

θ_0 Reference potential temperature

θ Potential Temperature

θ' Fluctuation in potential temperature

R Gas Constant

C_p Specific Heat Capacity of Air

R_l Longwave radiation

D_{ui} Source term for the momentum equation

D_θ Source term for the energy equation

E Turbulent Kinetic Energy

E' Fluctuation in turbulent kinetic energy

K_z Turbulent diffusivity

U_x , U_y Horizontal Mesoscale Velocites

g acceleration due to gravity

C_ε, C_k Constants

l_ε Dissipative length scale

l_k Length scale

D_E Source term for the turbulent kinetic energy

u , v Horiontal velocities in the canopy

z_c vertical distance in the canopy

K_{zu} , $K_{zv}, K_{z\theta}$ diffusivity

C_d constant

B_1, B_2, W_1, W_2

$P_b(z)$ probability of having a building of height z

κ von karman constant

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