Development of a GIS Data Model for Urban Microclimate and Building Energy Estimations

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Summary: An understanding of the energy exchanges occurring in urban areas is important to predicting the results of building and surface alterations. Typically, urban climate models are implemented as numerical models, but are often limited in their ability to accurately represent the area considered. This paper presents a model of an energy exchange for an urban building and develops a framework for implementing such a model in a GIS.

KEYWORDS Environmental modelling, GIS modelling, urban climate modelling, building energy, object-oriented programming

1 Introduction

It is well documented that urban areas have altered microclimates as compared to their suburban and rural surroundings (Chandler, 1970; Oke 1974). In order to understand the changes in heat storage fluxes, turbulent fluxes, and thermal comfort indices taking place in urban areas, a large body of work has been developed based on observational studies (Chang et al., 2007) analytical studies (Shashua-Bar & Hoffman, 2000) and numerical modelling approaches (Bruse & Fleer, 1998). In the last decade, numerical models have become the dominant tool in urban microclimate modelling, primarily due to their ability to handle the large amounts of data that are required in complex, non-linear urban systems. These models have greatly increased in sophistication due to advances in available computing power and advances in understanding of urban microclimate dynamics. Arnfield (2003, p.19) notes that numerical simulation is "a methodology perfectly suited to the complexities of the urban climate system." However, numerical models are also limited in that they often require extensive data input, such as digitising of the area being investigated, may rely on simplified reconstructions of an area (e.g., inability to assign individual building characteristics), and are difficult to validate against field data (ibid.).

With these limitations of numerical models, GIS-based models provide a number of advantages and opportunities for improving the capability of urban climate modelling. Advantages of a GIS model include: in-built tools for spatial analysis, model-building tools which are faster than traditional programming (Karssenberg & De Jong, 2005), and increased accuracy in representing the area being investigated due to available data from standard sources, such as UK MasterMap. The purpose of this paper is to present a data framework for a GIS-based urban microclimate model, which would build upon the methods developed in numerical simulations, while greatly decreasing the setup time and improving accuracy of models. The paper is based on ongoing research in developing an urban canopy layer (UCL) model that will integrate the urban microclimate and related impacts on building energy consumption, particularly for the UK.

The main issues to be addressed in developing a GIS model are: scale, temporal resolution, and GIS data handling approach - vector, raster, or a combination of both. Specific questions addressed in this paper include:

1. What is the appropriate scale for an urban microclimate model and how does it link to mesoscale processes?
2. What is the appropriate data type(s) for a GIS-based urban microclimate model and is the data truly 3-D?
3. How can urban energy balance equations be implemented in a GIS system; what are the appropriate architecture, equations, and programming language?

2 Model Architecture

2.1 Scale

One of the first problems encountered in urban microclimate modelling is that of scale. At which scale does the model resolve calculations given the different processes occurring simultaneously in different atmospheric layers – urban canopy layer (below roof level), urban roughness layer (from the surface up to 2-5 times the average canopy layer element), and urban boundary layer. This makes it important to be clear about the scale and to define how the model will interact (or not) with these additional layers.

The model proposed here is focused on the processes in the urban canopy layer (UCL), from ground level to roof level, and is aimed at urban planners and climatologists who are interested in the microclimate changes available at the block or neighbourhood level (100 m^2-1000 m^2). The methods could possibly be upscaled to simulate city-level change, but may be prohibitive in terms of simulation time due to the large number of computations required.

2.2 Data Model

Of primary concern in GIS data model development is the choice of raster or vector-based data and how this choice affects the model architecture (Wu, 2000). Ideally, an urban environment will be represented in 3D. Advantages can be found in both the raster and vector models. For a raster model, the surface, building, and radiative variables of the urban environment can be represented in each of the raster data layers (i.e., building height in one layer, building thermal properties in another, vegetation in a third, etc.) and many of these layers, such as Digital Elevation Models or Digital Terrain Models, can be readily obtained through public sources. Using raster calculations that are included in most GIS software, it is then possible to calculate interactions between these layers and move forward by timesteps to iterate a dynamic simulation of an area.

In contrast, a vector model is capable of storing many parameters in one layer. For instance, if a building is represented by a polygon, the additional attributes of height, age, floor area, wall albedo, roof albedo, etc. can all be described in a single data table. Additionally, the vector model allows a very accurate representation of urban geometry.

The disadvantage in both of these choices is that neither is truly 3D in that variation in the z-direction cannot be accurately recorded. For instance, while it might be possible to represent a raster grid cell as a tree with a certain height, or as vector polygon with height, type, root depth, etc., it is not possible to assign a variable, such as canopy area, at each z-value along the tree.

More recently, integration of GIS with object-oriented programming languages have spurred development of models that are more able to represent and manipulate 2.5D or 3D objects (Camara et al., 1996; Su, 1998). A building can be described in its x, y, and z components, with each element of the object (such as a wall or floor), being assigned its own properties. An object-oriented scripting language is then utilised to program the model's algorithms and will have the ability to update the state or value of an object at specified time intervals.

2.3 Example Model Implementation

While a range of models with differing objectives are applicable in an urban environment, this research has focused on the interactions between buildings and vegetation and will approach the solutions from the building energy balance calculations.

To calculate an energy budget for a building, including vegetation, such as a green roof or adjacent landscaping (equations adapted from Brown & Gillespie, 1995 and Gaffin et al., 2005):

$$Q_{net} = SW_{net} + LW_{net} + Q_{int} - Q_{conv} - Q_{cond} - Q_{lat} \quad (1)$$

Where

SW_{net} (net short wave) = (direct + diffuse + reflected)*(1-α) (2)

Direct (solar radiation falling on building and directly transmitted through the canopy, which includes the shading effects of vegetation)

Diffuse (from sky or reflected by trees) = $SVF*SW_{total\ diffuse}$ (3)

Reflected (by ground)

LW_{net} = net long wave

Q_{int} (internal free heat gains) = metabolic (from people) + electricity (lights and appliances) + solar heat gain (through windows) (4)

Q_{conv} (sensible heat from convection) = Area (wall or roof)*γ*(T_{air}-T_{wall}) (5)

Q_{cond} (heat from conduction) = Area (wall or roof)* κ*(T_{air}-$T_{wall\ or\ ground}$) (6)

$Q_{lat} = Q_{conv}/\beta$ (7)

Symbols used include: SVF = sky view factor, α=albedo, γ = convective heat parameter, κ = thermal conductivity (u-value), β = Bowen ratio.

Objects and attributes which are required for model implementation include:

- Buildings - area, plan area (deep plan, shallow plan), age, HVAC, material (albedo for walls and roof), glazing percentage, internal set point;
- Vegetation - type, height, root zone profile, canopy profile, leafing period, Leaf Area Index; and
- Surfaces – surface cover type (e.g., soil, asphalt, concrete) and DEM for determining direct and diffuse radiation.

The modelling is to be implemented in ArcGIS using the Python scripting language and an object-oriented approach. While some calculations, such as solar radiation, will require raster data, the overall energy balance will be calculated on the building object and updated at hourly intervals. General climate data, including air temperature and cloud cover, will be accessible through a look up table. The main limitation to the methods presented is that the objects will be constrained to 2.5D, rather than truly 3D. The research also considered storing objects in a 3D City Database (Institute for Geodesy and Geoinformation Science Technische Universität Berlin, undated), a free 3D geodatabase based on the City Geographic Markup Language (CityGML) (Kolbe, 2012), an OpenGIS© standard. Using CityGML, each object is assigned to a standard class, such as Building, Vegetation, LandUse, CityFurniture, etc. Whilst this would allow for a true 3D storage mechanism, the tools and scripting languages currently available through ArcGIS, such as the Solar Radiation tool, are considered as more useful to the modelling process.

3 Conclusions

Developing a GIS-based urban climate model is a challenging task, but one that would prove valuable to urban planners and climatologists. Developed here is a conceptual framework for dynamic simulation of a building energy balance in a GIS, utilising object-oriented programming to perform the dynamic routines required for determining change over time. While the model presented here focuses on one of many processes taking place in an urban environment, it provides a basis that can be later modified by adding objects and algorithms (wind or soil models, for instance) into the model flow. By developing these routines in a GIS, the initial data input and accuracy of input will be improved substantially, allowing the modeller to concentrate on the processes and system dynamics.

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Biography

Cynthia Skelhorn is a current PhD student at University of Manchester under studentship from the UK Energy Research Centre. Her current research focuses on the impacts of urban greenspace on the urban energy balance and particularly on the impacts of building energy consumption.

Dr. Sarah Lindley is a Senior Lecturer in Geography at University of Manchester who specialises in spatial analysis of human-environment interactions, particularly in the fields of air pollution and climate adaptation.

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