Chapter 11
Urban Surface Energy Balance Models: Model Characteristics and Methodology for a Comparison Study

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Abstract Many urban surface energy balance models now exist. These vary in complexity from simple schemes that represent the city as a concrete slab, to those which incorporate detailed representations of momentum and energy fluxes distributed within the atmospheric boundary layer. While many of these schemes have been evaluated against observations, with some models even compared with the same data sets, such evaluations have not been undertaken in a controlled manner to enable direct comparison. For other types of climate model, for instance the Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS) experiments (Henderson-Sellers et al., 1993), such controlled comparisons have been shown to provide important insights into both the mechanics of the models and the physics of the real world. This paper describes the progress that has been made to date on a systematic and controlled comparison of urban surface schemes. The models to be considered, and their key attributes, are described, along with the methodology to be used for the evaluation.

11.1 Introduction

The world's population is becoming increasingly urbanised. The fraction of the global population living in cities now exceeds 50% and urban dwellers are expected to reach 6 billion people, or two-thirds of the global population, by the year 2050 (UN, 2004). On the same timescale, climate change predictions estimate an increase in global mean temperature of 0.5–1.5 °C (IPCC, 2001). Whilst predicting human induced climate change on a regional scale is still uncertain, one climate

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phenomenon which is clearly attributable to human activity is the urban heat island (UHI). Urban areas often are several degrees warmer than the surrounding countryside, particularly at night under clear, calm conditions (Oke, 1973; Grimmond, 2007). Enhanced urban temperatures affect energy demand, air pollution concentrations and chemistry, water use, and human comfort, and have implications for human health and well being. The development of sustainable cities over the next century requires a clear understanding of how urban areas influence the local climate and increasingly, surface energy balance models are being used as tools in urban design and performance evaluation (e.g. Hacker et al., 2004). A consequence of warm surface temperatures is that air is more vigorously mixed upward, hence air pollution dispersion modelling benefits from better representation of the urban surface energy balance. Moreover, as atmospheric boundary layer motions (for heights less than 1–2 km) are very sensitive to the surface energy balance, an improved understanding of urban surface-atmosphere exchanges will better allow the impact of cities on regional scale weather systems to be determined (Taha, 1999; Bornstein and Lin, 2000).

The fundamental processes that need to be modelled are the surface-atmosphere exchanges of heat, mass and momentum at the local-scale. In cities these exchanges are altered by the materials and morphology of the urban environment, human behaviour, and the addition of anthropogenic heat flux (Q_F) to the available energy:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S$$

where Q^* is net all wave radiation, Q_H is the turbulent sensible heat flux, Q_E is the turbulent latent heat flux and ΔQ_S is the net heat storage flux associated with heating/cooling of this mass (gas, liquids, and solids).

Recently there has been a rapid increase in the number of land-atmosphere exchange models that explicitly parameterize urban surfaces (see reviews of Brown, 2001; Best, 2006; Masson, 2006; Martilli, 2007; Lee and Park, 2008). These have been developed with the aim of predicting temperatures at different spatial scales, guiding more energy efficient design and construction, and improving air quality, meteorological and regional climate forecasting. The models differ significantly in the exchanges they explicitly consider and in the approach taken to modelling each flux. Applications and evaluations illustrate that the inclusion of even simple urban surface parameterizations leads to improved temperature predictions (e.g. Taha, 1999). However, while evaluations of individual models have been undertaken, there has been no systematic evaluation addressing questions such as:

- Do the models produce physically realistic simulations of urban heat exchange?
- How complex do parameterizations of heat exchange need to be to simulate physically realistic fluxes and temperatures?
- What are the costs (processing time, data requirements) versus the benefits (improvements in model prediction) between different types of models?

- And, in terms of observational studies, are we measuring the correct variables at the appropriate spatial and temporal scales to evaluate models?

Here we outline a methodology to undertake a comprehensive and controlled evaluation of a range of urban surface energy balance schemes using a staged methodology and carefully released evaluation data. The overall aim of the project is to gain insight into the strengths and weaknesses of different classes of urban models, with particular focus on the level of complexity (physical understanding, data requirements, spatial detail and temporal resolution) relevant for different applications. The purpose of this initial paper is two-fold: first, to describe the characteristics of the urban models to be compared; and second, to outline the methodology to be used in the overall study. Structured model evaluations such as this have inherent value in identifying deficiencies in a community's modelling capabilities (see for example, the outcomes of PILPS, Henderson-Sellers et al., 1993) and in supporting the design of field experiments to collect key data for model runs and evaluations.

11.2 Urban Surface Energy Balance Models

A wide range of approaches have been adopted to represent the surface energy balance in urban areas. Here we present a broad list of urban surface energy balance models (Table 11.1) for which each is given a code or acronym used hereafter to describe it. Where multiple versions of the models exist, they are differentiated.

11.2.1 Model Outputs

To be included in this comparison, a model must be able to predict the surface energy balance fluxes representative of the local (or neighbourhood) scale. Many of the models are also capable of calculating additional terms, typically air and surface temperatures and wind speed, and providing more detailed flux information, for example by facet, and these are recorded in Table 11.2. Notable differences between models relate to whether the canyon is assumed to have an orientation and thus, sunlit or shaded walls at appropriate times of the day (e.g. CLMU, CAT, SUNBEEM), or if the model is without orientation so that only one 'wall' is resolved and considered representative of the integrated urban domain (e.g. TEB). In the latter case, there are three distinct built facets: wall, roof, and road. Obviously, the issue of sunlit or shaded facets also relates to roads (the floor of the canyon). The most detailed models can calculate the spatial variability along facets (e.g. TUF3D). As an aside, it should be noted that there are other models (e.g. CFD models) that simulate within-canyon variations in more detail, although such micro-scale variations are not the focus of this work.

Table 11.1 Urban surface energy balance models. Acronyms, model names and publications with key details

CODE	Model name	Reference with details of model
BEP02*	Building Effect Parameterization	Martilli et al. (2002)
BEP05	Building Effect Parameterization	Hamdi (2005); Hamdi and Schayes (2007)
CAT*	Canyon Air Temperature	Erell and Williamson (2006)
CLMU*	Community Land Model – Urban	Oleson et al. (2008a, b)
ENVImet*	*Envi*ronmental Meteorology Model	Bruse and Fleer (1998)
GCTTC*	Green Cluster Thermal Time Constant model	Shashua-Bar and Hoffman (2002, 2004)
HIM	Heat Island Model	Saitoh et al. (1996)
HIRLAM-U*	Urbanised version of DMI-HIRLAM model	Baklanov et al. (2006, 2008); Mahura et al. (2006); Zilitinkevich et al. (2006)
LUMPS*	Local-scale Urban Meteorological Parameterization Scheme	Grimmond and Oke (2002); Offerle et al. (2003)
MM5u*	Penn State/NCAR Mesoscale Model model, where urban modifications have been incorporated	Dandou et al. (2005)
MOSES1T*	Met. Office Surface Exchange Scheme 1 Tile	Best (2005); Essery et al. (2003)
MOSES2T*	Met. Office Surface Exchange Scheme 2 Tile	Best et al. (2006); Essery et al. (2003)
MOUSES*	Met Office Urban Surface Exchange Scheme	Harman et al. (2004a, b)
MUCM*	Multi-layer Urban Canopy Model	Kondo et al. (2005); Kondo and Liu (1998)
MUKLIMO*	Microscale Urban Climate Model	Sievers (1995)
NSLUCM	Noah land surface model/Single-layer Urban Canopy Model	Kusaka et al. (2001); Chen et al. (2004)
PTEBU	Photovoltaic Town Energy Balance for an Urban Canopy	Tian et al. (2007)
R-AUSSSM	Revised Architecture-Urban-Soil-Simultaneous Simulation Model	Tanimoto et al. (2004)
RUM*	Reading Urban Model	Harman and Belcher (2006)
SEBM	Surface Energy Balance Model	Tso et al. (1991)
SHIM	Surface Heat Island Model	Johnson et al. (1991)
SLUCM	Simple Single-layer Urban Canopy Model	Kusaka et al. (2001)
SM2U*	Soil Model for Submesoscales, Urbanized Version	Dupont and Mestayer (2006); Dupont et al. (2006)
SUEB*	Slab Urban Energy Balance Model	Fortuniak et al. (2004, 2005)
SUMM*	Simple Urban Energy Balance Model for Meso-Scale Simulation	Kanda et al. (2005a, b)
SUNBEEM	Simple Urban Neighbourhood Boundary Energy Exchange Model	Arnfield (2000)
TEB*	Town Energy Balance	Masson (2000); Masson et al. (2002); Lemonsu et al. (2004)
TEB07*	Town Energy Balance 07	Hamdi and Masson (2008)
TUF2D*	Temperatures of Urban Facets in 2D	Krayenhoff and Voogt (2007)

Table 11.1 (continued)

CODE	Model name	Reference with details of model
TUF3D*	Temperature of Urban Facets in 3D	Krayenhoff and Voogt (2007)
UCLM*	Urban Canopy Layer Model	Mills (1997)
UCM	Urban Canyon Model	Sakakibara (1996)
UEB	Urban Energy Balance	Montávez et al. (2000)
UHSM	Urban Heat Storage Model	Bonacquisti et al. (2006)
VUCM*	Vegetated Urban Canopy Model	Lee and Park (2008)

*indicates confirmed participant in comparison project.

11.2.2 Representation of the Urban Environment

There are a number of different ways to model the urban surface to predict local scale energy balance fluxes. First, there is the issue of whether the surface consists of purely built surfaces or whether vegetation is also taken into account (Table 11.3). Generally, there are two different methods to incorporate vegetation: (1) it is treated as a separate surface (referred to here as 'tiles') that does not interact with other surface types until the first layer of the meso-scale model (e.g. TEB, MOSES); or (2) it is embedded into the urban area so that it affects, and is affected by, the built environment (e.g. CLMU, SUNBEEM, LUMPS) (referred to here as 'integrated'). Some models have both capabilities (Table 11.3). Vegetation is modelled using separate vegetation models that have been well tested, such as in the PILPS comparisons, in extensively vegetated areas (Yang and Dickinson, 1995; Shao and Henderson-Sellers, 1996; Qu et al., 1998; Schlosser et al., 2000; Henderson-Sellers et al., 2003; Irranejad et al., 2003) and resistance schemes that have been developed for urban areas (e.g. Arnfield, 2000; using Grimmond and Oke, 1991).

Second, is the issue of how the built environment is modelled. As indicated in Sect. 11.2.1, a wide range of variables is modelled (resulting in outputs). Alternatively models can be described in terms of their representation of the surface: either slab, single layer, or multi-layer (Table 11.4). *Slab models* (e.g. Best, 2005) represent the urban area in terms of a surface (e.g. concrete) with appropriate thermal characteristics. *Single layer models* represent a city as a layer of buildings with the overall surface heat exchange being the sum of exchanges on individual surfaces. This allows for more realistic representations of radiative trapping and turbulent exchange (Masson, 2000; Kusaka et al., 2001; Harman et al., 2004a). *Multi layer models* use a similar approach to single layer models, but model energy exchanges at multiple levels within the canopy, thereby allowing for varying building heights (e.g. BEP, TUF3D). Single and multi-layer models also differ in their spatial representation of the urban morphology, modelling one temperature and set of energy exchanges per facet versus multiple temperatures and energy exchanges per facet (the latter).

Table 11.2 Model outputs in addition to the local-scale fluxes. Net all-wave radiation (Q^* – W m^{-2}); Sensible heat flux (Q_H W m^{-2}); Latent heat flux (Q_E – W m^{-2}); Storage heat flux (ΔQ_S – W m^{-2}); Air temperature (T_a K/C), Surface temperature (T_s K/C), Wind speed (WS m s^{-1}). Ud indicates user dependent; typ. – typically; P – partial. See text for further explanation and Table 11.1 for key to model codes

		Canyon							Facet							Facet with orientation						
CODE	Time step	Q^*	Q_H	Q_E	Q_S	T_a	T_s	WS	Q^*	Q_H	Q_E	Q_S	T_a	T_s	WS	Q^*	Q_H	Q_E	Q_S	T_a	T_s	WS
BEP02	Ud	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N
BEP05	Ud	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N	N	N	N	N	N	N	N
CAT	1 h	N	Y	Y	N	Y	N	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y
CLMU	1200–3600 s	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	N	N
ENVImet	typ. 2–10 s	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GCTTC	24 h	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N
HIRLAM-U	Ud, typ. 300 s	N	N	N	N	N	N	Y	N	N	N	N	N	N	Y	N	N	N	N	N	N	N
LUMPS	1 h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM5u	Ud	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MOSES1T	Ud	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MOSES2T	Ud	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MUCM	10–120 s	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	P	p	p	p	p	N	p	N
MUKLIMO	Ud, typ. 3 h	N	N	N	N	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N
NSLUCM	Us (few minutes to 3600 s)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	p	p	p	p	N	p	N
SM2U	Ud, typ. 300 s	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MOUSES	Ud	Y	Y	Y	Y	N	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N
SUEB	1 s	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
SUMM	Ud	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N
SUNBEEM	U d	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
TEB	60–900 s, typ. 300 s	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	N	N
TEB07	Ud	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	N	N
TUF2D, TUF3D	Variable (typ. 10–100 s)	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
UCLM	1 h	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
VUCM	Ud	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	N	N

Table 11.3 Approach to vegetation modelling. See text for further explanation and Table 11.1 for key to model codes

Approach	Model
Canopy layer at the ground, leaves in the atmosphere	MUKLIMO
Integrated	CAT, LUMPS, ENVImet, GCTTC, MUCM, SUES, SUNBEEM
Integrated (separately included)	VUCM
Integrated or separate tile	CLMU, SM2U
None	TUF2D, TUF3D, SUEB, UCLM
Separate tile	BEP02, BEP05, HIRLAM-U, NSLUCM, MM5u, MOSES1T, MOSES2T, MOUSES, TEB, TEB07, SUMM

Table 11.5 provides a summary of the features of the urban surface that are actually resolved by the models; for example, whether the canyon is a whole unit or if walls and roofs are separate facets. Also included is whether each of these elements has a specific orientation and whether they can be sunlit and shaded. Some models assume an infinitely long canyon with no orientation and therefore only one wall needs to be modelled (e.g. TEB); others have infinitely long canyons that run in two cardinal directions each with varying sunlit and shaded wall areas through the day (and at different times of year). To date, the intersection of such canyons has received less attention (except in SUNBEEM) although it will be included in some way when the site attributes are calculated and used in the model descriptions (see Sect. 11.2.4).

Table 11.4 Categorisation of models in terms of slab, single layer, or multiple layer. See text for further explanation and Table 11.1 for key to model codes

Slab	Single layer	Multiple layer
MOSES1T	AUSSSM	BEP02
MOSES2T	CAT	BEP05
SUEB	CLMU	ENVImet
SM2U	GCTTC	MUCM
	HIRLAM-U (+ analytical profile in canopy)	MUKLIMO (ground)
	LUMPS	R-AUSSSM
	MOUSES	SUEB
	MUKLIMO (walls, roof, canopy)	SUMM
	NSLUCM	SUNBEEM
	RUM	TEB07
	SLUCM	TUF2D, TUF3D
	SUES	UCLM
	SUNBEEM	
	TEB	
	VUCM	

Table 11.5 Levels modelled and features resolved in each model. Y – yes, N – no P – partial. See text for further explanation and Table 11.1 for key to model codes

Model	Levels			Features resolved							
							Walls			Road	
	Within canyon	Above canyon	Canyon top	Canyons	Turbulence within canyon	Roof	Walls	Sunlit/Shaded	Orientation	Road	Sunlit/Shaded
BEP02	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
BEP05	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
CAT	Y	N	N	Y	N	N	Y	Y	Y		Y
CLMU	Y	N	N	N, C1	N	Y	Y	Y	N		N
ENVImet	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GCTTC	N	N	N	Y	Y	Y	Y	Y	Y		N
HIRLAM-U	P	Y	P	P	P, C2	P	N	N	N	P	N
LUMPS	N	Y	N	N	N	N	N	N	N	N	N
MM5u	N	N	N	N	N, C2	N	N	N	N		N
MOSES1T	N	N	N	N	N	N	N	N	N	N	N
MOSES2T	N	N	N	Y	N	Y	N	N	N		N
MOUSES	N	N	N	Y	Y	Y	N	N	N	N	N
MUCM	Y	Y	Y	Y	P	Y	Y	P	N	Y	P
MUKLIMO	Y	Y	Y	Y	N	Y	Y	N	N	Y	N
NSLUCM	Y	N	N	C1	N				Y		
SM2U	N	N	Y	P	N	Y	P	P	Y	P	P
SUEB	N	N	N	N	N	N	N	N	N	N	N
SUMM	N	Y	N	Y	N	Y			Y		
SUNBEEM	Y	P	Y	Y	N	Y	Y	Y	Y	Y	Y
TEB	Y	N	N	N	N	Y	Y	N	N	Y	N
TEB07	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N
TUF2D, UF3D	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
UCLM	Y	N	Y	Y	Y				Y		
VUCM	Y	N	N	N	N				N		

C1 pervious and impervious canyon floor; C2 turbulence is resolved in the surface layer in total.

11.2.3 Model Inputs

Inputs consist of three general types: (1) the parameters to describe the site; (2) the variables required to drive the model; and (3) the initial conditions required to initiate the model runs. Obviously, the first set of information is needed in any type of model run, so there is no difference between a typical run and an offline model evaluation run. For the second set of data, for a normal online run, would be the meso- (or larger-) scale model with data 'passed down' to the surface scheme to force it. These data are therefore updated at each time step. The third set of input, initial conditions, are explicitly related to the surface scheme rather than to wider models of which these schemes may be a part. For some models and some variables these may be the same as (2) but for others there are additional requirements.

The complexity of urban areas demand a large number of model parameters; here they are sub-divided into two groups: the built environment (Table 11.6) and urban vegetation (Table 11.7). In terms of the morphometric characteristics of the built form, inputs vary greatly depending on whether basic information is used (e.g. height and width) from which the required parameters are calculated (e.g. canyon aspect ratio, sky view factor), or if 'higher' level parameters are inputs. This can give the impression that there are larger differences in the model inputs than there really are. Other parameters of the built environment relate to the nature of the materials used and include parameters that are concerned with radiative transfer (e.g. albedo, emissivity) and conductive characteristics. These characteristics may be specified in different ways relative to urban form; for example, relative to mass (specific heat capacity) or volume (volumetric heat capacity). Alternatively, materials may be specified and model 'look-up' tables used to assign the appropriate parameters. The details of the tiled-models that draw on vegetation schemes are not summarised in Table 11.7 because they are extensively evaluated (see Sect. 11.2.2). Typically, the vegetation characteristics are assigned by using a default number of classes (e.g. 11 in SM2U, 5 in MOSES).

Anthropogenic heat flux is dealt with in a wide variety of ways. For example, some schemes capture this flux by specifying fixed internal temperatures and traffic counts (Table 11.6), which provides temporal dynamics to the flux estimates. Other models require the flux to be provided as a direct input (e.g. GCTTC, CAT).

The variables that are used to drive the models are listed in Table 11.8 . These relate to wind, temperature, humidity, radiation, and soil characteristics and as noted above, some models also require the anthropogenic heat flux to be directly supplied as an input. From the nature of the inputs, it is evident that a wide variety of approaches is used, for example, to determine the radiative forcing. Some models calculate radiation, others take the short and long wave radiative fluxes as a direct input, while others add further detail by differentiating between direct and diffuse components (e.g. MUCM, CLMU, VUCM, CAT, SUNBEEM).

The final set of inputs relates to the initial conditions. The information required about temperature profiles within a building or the soil may be the most significant for some of the models. Such data are typically difficult to obtain. One consequence

Table 11.6 Parameters related to the 'built environment' (Y – yes; N – No). See text for further explanation and Table 11.1 for key to model codes

Model	λp	λ_f	ψ	F	A_w	A_O	z_r	$\mathbf{z_f}$	z_B	z_{or}	W_B	D_B	Fl_D	S L/W/ d/N	LAA	Traf	T_{intW}	T_{intR}	T_i	T_{DS}	Mat	HT	MT	ε_{fac}	α_{fac}	α	LL	τ	z_{ofac}
BEP02	N	N	N	N	N	N	N	N	Y	N	Y	Y	Y	Y	Y	N	N	N	Y	Y	N	K,Cp		Y	Y	N	Y	N	Y
BEP05	N	N	N	V	N	N	N	N	Y	N	Y	Y	Y	YL/d/N	N	N	N	N	Y	Y	Y	K, Cp	N	Y	Y	N	N	N	Y
CAT	N	N	Y	N	N	N	Y	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	Y	N	N	Y	Y	Y	Y	N	N
CLMU	Y	N	N	RVRCp	N	N	Y	Y	Y	N	N	Y	N	N	N	Y,C5	N	N	Y	Y	N	C_R, K, VHC	Y	Y	Y	N	Y	N	N
HIRLAMU	Y	Y	N	RVRC	N	N	N	N	Y	Y	N	N	N	N	Y	N	N	N	N	Y	Y	C_R, K		N	N	Y	Y	N	N
ENVImet	N	N	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		N	N	N	N	N	N
LUMPS	Y	N	N	RVRC	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N
GCTTC	Y	Y	Y	RVRCt	Y	Y	N	N	Y	Y	Y	N	N	Y	Y	Y, C1	N	N	N	N	Y	CR, Cp K, VHC		Y	Y	Y	Y	N	N
MM5u	N	N	N	RVRC	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	Y	Y	C_R, K		N	N	Y	Y	N	N
MOSES1T	N	N	N	RV	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	Y	N	C_R K,VHC		N	N	Y	Y	N	N
MOSES2T	Y	Y	N	RVRC	N	N	N	Y	Y	N	N	N	N	N	N	N	N	N	N	Y	N	C_R K,VHC		Y	Y	Y	Y	N	Y
MOUSES	Y	Y	N	RVRC	N	N	N	Y	Y	N	N	N	N	N	N	N	N	N	N	Y	N	C_R K,VHC		Y	Y	Y	Y	N	N
MUCM	Y	Y	Y	RVRCt	Y	Y	N	N	Y	N	Y	Y	Y	N	N	N	Y	Y	Y	Y	Y	C_R,K Cp, VHC, κ	Y	Y	Y	Y	Y	Y	Y
MUKLIMO	Y	Y	Y	RV	N	N	N	Y	N	Y	N	N	N	N	N	N	Y	Y	N	N	N	C_R,K Cp		N	N	N	Y	N	Y
NSLUCM	Y	Y	Y	RVRC	N	N	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y	C_R K,VHC	N	Y	Y	N	Y	N	Y
SM2U	Y	N	N	RVRC	N	N	N	Y	Y	Y	N	N	N	N	Y	Y, C2	Y	Y	Y	Y	Y, C3	C_R K,VHC	Y	Y	Y	N	Y	N	Y
SUEB	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	C_R K, VHC, κ		N	N	Y	Y	N	Y
SUMM	Y	Y		RVRCt	N	N	Y	Y	Y	N	N	N	N	N	Y	N	N	N	N	Y	N	C_R, K, C, VHC	Y	Y	Y	N	Y	N	N
SUNBEEM	N	N	N	N	N	N	Y	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y	N	C_R, K, VHC	Y	Y	Y	N	Y	Y, C6	N
TEB	Y	Y	N	RVRCt	Y	N	Y	Y	Y	Y	N	N	N	N	N	Y, C2	N	N	Y	Y	Y	C_R K, VHC	Y	Y	Y	N	Y	N	Y

Table 11.6 (continued)

Model	λp	λ_f	ψ	F	A_w	A_O	z_r	z_f	z_B	z_{or}	W_B	D_B	Fl_D	S L/W/ d/N	LAA	Traf	T_{intW}	T_{intR}	T_i	T_{DS}	Mat	HT	MT	ε_{fac}	α_{fac}	α	LL	τ	z_{ofac}
TEB07	Y	Y	N	RV	N	N	N	Y	Y	Y	N	N	N	N	N	Y,C2	N	N	Y	Y	Y	C_R K, VHC	Y	Y	Y	N	Y	N	Y
TUF2D, TUF3D	Y	Y	N	N	N	N	N	Y	Y	N	N	N	N	d/N	Y	N	N	N	Y	Y	Y	VHC, K	Y	Y	Y	N	Y	N	Y
UCLM	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	C_R,K Cp, VHC	Y	Y	Y	Y	Y	N	Y
VUCM	Y	N	N	RVRC	Y	Y	Y	Y	Y	N	Y	Y	N	N	N	N	N	N	N	Y	Y	C_R K,VHC	Y	Y	Y	N	Y	N	Y

λ_p – building (roof) plan area ratio; λ_f – building frontal area ratio; ψ – Sky view factors (wall, ground);
F – areal fractions of RVRCt/p – road/vegetated/roof/canyon/typical/three surfaces on each facet (e.g., window/pervious canyon floor) A_w – Areas of wall;
A_O – Area open ground; z_r – Reference height; z_f – Height of forcing; z_B – Building height; z_{or} – Orographic height;
W_B – Average building width; D_B – Averaged building separation; Fl_D – Floor density distribution of the buildings in vertical direction; S L/W/d/N – Street length/width/direction/number of street directions; LAA – Long axis azimuth of the site; Traf – Traffic Vehicles
T_{intW} – Temperature inside buildings behind wall; T_{intR} – Temperature inside buildings behind roof; T_i – Room temperature; T_{DS} – Deep soil/road temperature; Mat – Materials (look-up table);
HT – heat transfer; CR – Heat capacity for soil, roofs or walls; K – Thermal conductivity of soil, wall or roof materials; Cp – Specific heat; VHC – Volumetric heat capacity of wall, street, roof materials; – Thermal diffusivity of ground/wall /road;
MT – material thickness by layers; α – Albedo; ε_{fac} – emissivity by facet; LL – Latitude and Longitude; τ – Turbidity; z_{ofac} – Roughness length of each facet.
C1 N/hr crossing the street.
C2 Sensible and latent heat fluxes due to traffic (W m^{-2}).
C3 Additional requirements: soil composition (%), pavement infiltration capacity (m s^{-1}), amount of impervious surface connected to draining network (%), Vegetation, roof, pavement max. water storage (mm).
C5 Sensible heat flux due to traffic W m^{-2}.
C6 Turbidity specified indirectly by choice of solar radiation model parameters.

Table 11.7 Vegetation related parameters (Y – yes included; N – no)

Model	LAI_{CV}	g_w	Veg	z_{CV}	α_{CV}	τ_{cv}	C_V
BEP02	N	N	N	N	N	N	N
BEP05	N	N	Y	N	Y	N	Y
CAT	N	N	N	N	N	N	N
CLMU	N	N	N	N	N	N	N
ENVImet	LAD	N	Y, 2t	N	N	N	N
GCTTC	N	N	Y	Y	Y, C1	Y, C1	N
HIRLAM-U	LAD	N	Y	N	Y	N	N
LUMPS	N	N	N	N	N	N	N
MM5u	N	N	Y	N	Y	N	N
MOSES1T	Y	N	Y, 5t	Y	N	N	N
MOSES2T	Y	N	Y, 5t	Y	N	N	N
MOUSES	Y	N	Y, 5t	Y	N	N	N
MUCM	N	Y	N	N	Y	N	N
MUKLIMO	y	Y	N	Y	Y	Y	N
NSLUCM	Y	Y	Y	N	Y	N	N
SM2U	Y	N	Y, 11t	Y	Y	N	Y
SUEB	N	N	N	N	N	N	N
SUMM	N	N	N	Y	Y	N	N
SUNBEEM	N	Y	N	N	Y,C2	N	Y
TEB	Y	N	Y, 3t	N	Y	N	N
TEB07	Y	N	Y	N	Y	N	N
TUF2D, TUF3D	N	N	N	N	N	N	N
UCLM	N	N	N	N	N	N	N
VUCM	Y	N	N	Y	Y	N	Y

LAI_{CV} – LAI of canyon vegetation; LAD leaf area density g_w – Water vapor conductance of plant canopy; Veg – Vegetation species (2t [C3/C4 vegetation],3t,5t,11t number of types); z_{CV} – Canyon vegetation height; α_{cv} –Albedo of canopy leaves; τ_{cv} – Canopy solar transmissivity; C_V – Heat capacity of vegetation.

C1 requires vegetation coverage (net of sunny spots), as a percentage of the total ground area
C2 also canopy emissivity.

is that for some models a long initialization period (spin-up) time is needed to ensure that the temperature profiles are stable and representative of conditions.

11.2.4 Methods of Calculation

Here the methods used by the different urban schemes to calculate the various fluxes are considered. Complete information is provided in the original papers. The analysis here is cursory; as the project proceeds, a more complete analysis will be undertaken.

In the model simulations, the incoming radiative fluxes will be prescribed, so the critical issue is how the outgoing radiative fluxes are determined. The major differences relate to the number of reflections the models assume and the degree of detail in assigning the surface characteristic parameters (Table 11.9). The simplest

Table 11.8 Required model input variables. (init- initial condition only) (Y – yes included; N – not included)

	Wind			Temperature				Radiation										Soil			
Code	WS	WD	TKE	T_s	T_a	Tpot	Humidity	K↓	$K{\downarrow}_D$	$K{\downarrow}_S$	L↓	CC	Z	Cp	P	ρ	R	T profile	θ	T_{water}	Q_F
BEP02	Y	Y	Y	N	N	Y		Y	N	N	Y	N	N	N	N	N	N	N	N	N	N
BEP05	Y	Y	Y	N	N	Y	U4	Y	N	N	Y	N	N	N	Y	N	N	N	N	N	N
CAT	Y	Y	N	N	Y	N	RH	Y	Y	N	N	Y	Y	N	Y	N	Y	N	N	N	Y
CLMU	Y	N	N	Y,r,w,R,S, Init	Y	N	U2	Y	Y/N	Y/N	Y	N	N	N	Y	N	Y	Yinit	Yinit	N	N
ENVImet	Y	Y	N	Y	Y	N	U1	N	Y/N	N	N	N	N	N	N	N	N	Yinit	Yinit	Y	N
GCTTC	Y	Y	N	Y, w,g,r	Y	N	Tw	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	Y
HIRLAM-U	Y	Y	N	N N	Init	Y	RH, e_a	N	N	N	N	Init	N	N	Y	N	N	N	N	Y	Y
LUMPS	N	N	N		Y	N	N	Y	N	N	N	N	N	N	Y	N	Y	N	N	N	N
MM5u	Y	N	N	N	Y	N	RH	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y
MOSES1T	Y	Y	N	Y,U	Y	N	U2	Y	N	N	Y	N	N	N	Y	N	Y	Y	Y	N	N
MOSES2T	Y	Y	N	Y,r,U	Y	N	U2	Y	N	N	Y	N	N	N	Y	N	Y	Y	Y	N	N
MOUSES	Y	Y	N	Y, r,U	Y	N	U2	Y	Y	Y	Y	N	Y	N	Y	N	Y	Y	Y	N	N
MUCM	Y	N	N	N	N	Y	U1	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N	N	Y
MUKLIMO	Y	N	N	N	Y	N	U2	N	N	N	N	Y	Y	N	N	N	N	N	N	N	N
NSLUCM	Y	N	N	Y, w,g,r,s	Y	Y	SH	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y	Y
SM2U	Y	Y	N	Y, r,w,R,s,V	Y	N	U2	Y/N	Y/N	Y/N	Y/N	N	N	N	Y	N	Y	N	Y	Y	Y
SUEB	Y	N	N	Y, U	Y	Y	SH	Y	N	N	Y	N	N	Y	N	Y	N	Y	Y	N	N
SUMM	Y	Y/N	N	Y, r,R,w init	Y	N	Y	Y	Y/N	Y/N	Y	N	N	Y	N	Y	N	N	N	N	N
SUNBEEM	Y	Y	N	N	Y	N	e_a	Y	Y	Y	Y	Y	N	N	Y	N	N	N	N	N	N
TEB	Y	N	N	Y,r,w,R,s,V	Y	N	U2/U3	Y	Y	Y	Y	N	N	N	Y	Y	Y	Yinit	Yinit	N	Y(traf)
TEB07	Y	N	N	N	Y	N	U2/U3	Y	Y	Y	Y	N	N	N	Y	N	Y	Yinit	Yinit	N	Y(traf)

Table 11.8 (continued)

Code	Wind			Temperature			Humidity	Radiation										Soil			
	WS	WD	TKE	T_s	T_a	Tpot	Humidity	K↓	$K{\downarrow}_D$	$K{\downarrow}_S$	L↓	CC	Z	Cp	P	ρ	R	T profile	θ	T_{water}	Q_F
TUF2D, TUF3D	Y	Y	N	N	Y	N	e_a	Y/N	N	N	Y/N	N	N	N	Y	N	N	N	N	N	N
UCLM	Y	Y	N	N	Y	N	e_a	N	N	N	N	Y	N	Y	Y	Y	N	N	N	N	N
VUCM	Y	N	N	Y r,w,R,s,V	Y	N	U2	N	Y	Y	Y	N	N	N	Y	Y	Y	Y	Y	N	Y

Wind related: WD – Wind direction (degrees); WS – Wind speed (m s^{-1}), TKE – Turbulent kinetic energy (m^2 s^2);
Temperature related: Tpot – Potential temperature (K); Ta – Air temperature (T_s) – Temperature of the surface w walls, g ground and r roof, R road, s soil, V vegetation; U urban slab, Init – initial condition;
Humidity: T_w – Wet Bulb T (C); e_a – Water vapour pressure (hPa); RH – Relative humidity (%); SH – Specific humidity (units U1: g kg^{-1}, U2: kg kg^{-1} U3: kg m^{-3}, U4: g m^{-3});
Radiation: K↓ – incoming shortwave radiation; S – direct radiation; D – diffuse radiation; L↓ – incoming longwave radiation; CC – cloud cover; Z – Solar zenith angle; C_p – specific heat; P – Atmospheric pressure (hPa); ρ – Air Density (kg m^3); R – Precipitation (kg m^2 s^{-1});
Soil: Tprofile – temperature profile; θ – Soil moisture content; T_{water} – Water temperature (K/C);
Q_F – Anthropogenic heat flux (W m^{-2}).

Table 11.9 Methods used to model outgoing shortwave and long wave radiation

Model	Number of reflections	Albedo	L↑
BEP02	multiple	canyon	Result of multiple reflections in the canyon, from walls and canyon floors at each grid level
BEP05	multiple	canyon	Result of multiple reflections in the canyon
CAT	one	by facet	By facet, with one emission and one reflection among facets
CLMU	multiple	by facet	By facet with multiple reflections and one emission
ENVImet	one	by facet	From energy balance of all facets
GCTTC	multiple	by facet	Prescribed
HIRLAM-U	one	bulk/town	Fast broadband schemes for solar and termal radiation (Savijärvi, 1990). emissivity function and Stefan-Boltmann law, STRACO scheme for clouds, water vapour (Sass, 2001)
LUMPS	one	bulk	Prata (1996)
MM5u	one	bulk/town	Stefan-Boltmann law, plus parameterization schemes for the clouds and water vapour (e.g. Stephens, 1978; Garand, 1983)
MOSES1T	one	bulk	Prescribed bulk emissivity
MOSES2T	one	canyon, roof	Prescribed emissivity values for canyon and roof
MOUSES	multiple	bulk/effective	Effective emissivity by multiple reflections
MUCM	two	by facet	
MUKLIMO			From energy balance of all facets
NSLUCM	one	by facet	One reflection
SM2U	infinite	bulk/effective	Effective emissivity
SUEB	one	bulk/town	By emissivity
SUMM	multiple	facet	Result of multiple reflections
SUNBEEM	multiple	by facet	By facet with multiple reflection
TEB	infinite	canyon, roof	Result of two reflections in the canyon
TEB07	infinite	canyon, roof	Result of two reflections in the canyon
TUF2D, TUF3D	multiple (min 2)	patches/facet	Multiple reflection (minimum 2) between patches (and emission by patches initially)
UCLM	two	facet	Emitted longwave radiation computed for each facet (no reflections) using energy budget.
VUCM	three	canyon, roof	One reflection

models use a single assigned bulk value (e.g. albedo) and have just one reflection (e.g. LUMPS). Thus they do not account for the different material characteristics in urban area as do CLMU and TEB, for example.

As already noted there are a wide range of approaches to account for the anthropogenic heat flux (Table 11.10). Currently this is the flux for which the least sophisticated approaches are adopted. The term most typically is prescribed although some, but not all, components may be calculated (e.g. fixed or mobile sources) in

Table 11.10 Methods used to calculate anthropogenic heat flux (Q_F)

Model	Anthropogenic heat flux methods
BEP02, BEP05, SUNBEEM	Partially accounted for by imposing a fixed temp at the building interior
CAT	Prescribed, adjusted for diurnal variations
CLMU	Prescribed traffic fluxes, parameterized waste heat fluxes from heating/ air conditioning
ENVImet	From heat transfer equations through walls
HIRLAM-U	Calculated (offline) as a temporal & spatial function of available parameters by 4 methods (emission, night light, land-use, population) (Baklanov et al., 2005)
GCTTC	Prescribed per vehicle (for vehicles only)
MM5u, NSLUCM	Calculated (offline) as a temporal & spatial function of the anthropogenic emissions
MOSES2T, MOSES1T, MOUSES, SUEB	Not modelled itself but possible to be included for calculation of turbulent fluxes
MUCM	Modelled by Kikegawa et al. Offline
MUKLIMO	Heat fluxes through the walls and roofs computed with fixed temp at the buildings interior
TEB, TEB07 TUF2D, TUF3D	Domestic heating computed
UCLM	Not directly included. Heat can be added to building interior.
VUCM, SM2U	Prescribed bulk value

some models. This flux is most significant in the wintertime when the additional energy from human sources is most important relative to the net all wave radiation. That said, in many urban areas energy use is becoming increasingly significant in the summer due to air conditioning usage (Watson et al., 1997). Anthropogenic heat flux may only be significant in areas with very high flux densities (e.g. Tokyo, Ichinose et al., 1999). At key times of the day and night, and specifically at transitions between them, this flux could become more significant.

The turbulent sensible heat fluxes are typically modelled using some form of resistance scheme (Table 11.11). Differences depend on the degree of detail of the surface to be modelled; i.e. a bulk surface resistance or a resistance network accounting for differences between surfaces. Varying approaches are taken for these resistances, ranging, for example, from those based on the Penman-Monteith equation (e.g. LUMPS) to resistance networks that take into account changes in stability and the orientation of the surface that is shedding the heat (e.g. TUF3D). Correspondingly, a number of different resistance schemes are used (e.g. Rowley, 1930; Clarke, 1985; Zilitinkevich, 1995; Guilloteau, 1998; Harman et al., 2004b). The methods used to determine the stability functions are important because they feedback and impact on the outgoing longwave radiation. Many of the methods assume that Monin-Obukhov similarity holds, but this may not be applicable within the urban canyon (Roth, 2000). However, given the lack of well-tested alternatives, this may be the most appropriate set of assumptions.

Table 11.11 Methods to calculate turbulent sensible heat flux (Q_H)

Model	Turbulent sensible heat flux methods
BEP02, BEP05, SUNBEEM	For walls based on Clarke (1985)
CAT	Resistance between canyon surfaces and air based on Hagishima and Tanimoto (2003); at canyon top depends on stability, using empirical parameterization
CLMU	Resistance network accounting for differences between surfaces
ENVImet	From turbulence model (wall function) and surface energy balance
GCTTC	Calculated for each surface based on the attenuated radiation by the CTTC factor
LUMPS	deBruin and Holtslag (1982) modified Penman Monteith modified for urban areas (Grimmond and Oke, 2002)
HIRLAM-U, MM5u	Parametric formulation based on the specific heat capacity for moist air, the density of the atmosphere, the surface friction velocity and the surface temperature scale
MOSES2T, MOSES1T	Standard resistance, based upon MO similarity theory
MOUSES	Resistance network based on Harman et al. (2004)
MUCM	MO or Jurges
MUKLIMO	From surface energy balances at the soil, walls and roofs using MO laws
NSLUCM	MO based on Louis (1979) and Jurge's formulation, and calculated from each surface
SM2U	MO Resistance (Guilloteau, 1998; Zilitinkevich, 1995)
SUEB	MO similarity Louis (1979) modified by Mascart et al. (1995)
SUMM	Resistance (top-down method, Kanda et al., 2005)
TEB, TEB07	Resistance
TUF2D, TUF3D	Resistances based on flat-plate heat transfer coefficients (vertical patches) and based on MO similarity (horizontal patches)
UCLM	Exchange based on canyon air and surface temperature difference, wind speed and prescribed heat transfer coefficient.
VUCM	Parametric formulation

The storage heat flux methods involve, amongst others, empirically-based approaches such as objective hysteresis model (OHM)(e.g. MM5u, LUMPS, HIRLAM-U, CAT) and thermal diffusion approaches (Table 11.12). Models use varying numbers of layers to represent substrate materials, and as noted in the model inputs, materials are described in a wide variety of ways with implications for how the heat storage term can be calculated.

The methods used to calculate drag include roughness length approaches and distributed drag within the atmosphere (Table 11.13). Those that distribute the drag within the canopy might be expected to require more computational time and have greater data needs to describe the urban morphology.

A wide range of approaches are used to calculate the latent heat fluxes reflecting a range of possible representations of vegetated and/or wet surfaces. Some models assume that the urban area is dry and therefore ignore the latent heat flux completely; others have wet built surfaces but no vegetation; and some include vegetation as either a separate tile or as integrated (Table 11.3, 11.7, and 11.14). As with the

Table 11.12 Methods used to calculate storage heat flux (ΔQ_S)

Model	Storage heat flux methods
BEP02	Total storage heat flux is the sum of the storage heat flux of roofs, walls, and road. For each surface the storage comes from the energy budget that is solved
CAT, HIRLAM-U, MM5u, LUMPS	OHM scheme (Grimmond et al., 1991)
ENVImet	Soil 1D model, fully resolved, walls/building system no storage term
GCTTC	Residual from radiation after allowing for sensible and latent heat.
MUCM	Finite difference
MUKLIMO	Walls and roofs have a heat capacity
NSLUCM	Multi-layer thermal diffusion within wall/roof/road
SM2U	Budget + Conduction + Force restore
SUMM	Multi-layer thermal diffusion within walls/roof/road
SUEB	As Q_G in urban slab (solution of multi layer thermal diffusion equation)
SUNBEEM	1D finite difference solution of heat conduction equation for each facet
BEP05,TEB, TEB07, CLMU, BEP05, TUF2D, TUF3D, MOSES2T, MOSES1T, VUCM, MOUSES	Diffusion
UCLM	Model calculates substrate heat exchange and changes substrate temperatures accordingly.

Table 11.13 Methods used to calculate drag

Model	Drag
BEP02, BEP05, TEB07	Drag distributed within the atmosphere
CAT, GCTTC, TEB	Not included
CLMU, LUMPS, MM5u TUF2D, TUF3D, UCLM, VUCM MOSES1T, MOSES2T, SUEB	Prescribed Roughness length
ENVImet	3D Navier Stokes equation fully solved
HIRLAM-U	Roughness length with stability dependence Zilitinkevich et al. (2006)
MOUSES	Roughness length with MacDonald et al. (1998)
MUCM	Drag distributed within the atmosphere
MUKLIMO	Solving 3D Navier Stokes equation with roughness lengths at all material surfaces
NSLUCM	Exponential wind profile
SM2U	Roughness length Bottema (1995), Raupach (1994, 1995), Guilloteau (1998), MacDonald et al. (1998)
SUNBEEM	Roughness length

Table 11.14 Methods used to calculate latent heat flux (Q_E) and soil moisture

Model	Latent heat flux method	Soil moisture method
BEP02	Not included	Not included
CAT	Resistances based on the Penman-Monteith equation (Grimmond and Oke, 2002)	Not included
CLMU	Resistance network accounting for differences between surfaces	Layers
GCTTC	Evapotranspiration per 1 m^2 of vegetated coverage estimated empirically Shashua-Bar and Hoffman (2002) method	Not included
HIRLAM-U	Bulk method over each subgrid-scale surface type and tile method for flux aggregation	Force-restore, 2 soil layers + forest canopy, ISBA scheme (Noilhan and Planton, 1989)
LUMPS	deBruin and Holtslag (1982) modified Penman Monteith	Not included
ENVImet	Soil hydrological model, at Surface Halstead parameter calculated, Vegetation Photosynthesis/ Transpiration model	Prognostic 1-d multilayer model
NSLUCM	Using land-surface model for latent heat fluxes from natural surfaces, and bulk/slab model for evaporation from anthropogenic surfaces	Prognostic multi-layer soil model for natural surfaces and one-layer slab model for athropogenic surface
MUCM	Conductance based on Shulze et al. (1994)	Not included
MM5u	Parametric formulation based on the heat of vaporization, the available moisture, the molecular diffusivity, the depth of the molecular layer and the specific humidity at the surface and the lowest model level	Five-Layer Soil Model (Dudhia, 1996)
MOSES1T MOSES2T	Standard resistance based upon MO similarity theory	Prognostic 1-d multilayer model
MUKLIMO	Resistance law within the canopy, MO from there to the atmosphere	Prognostic 1-d multilayer model
SM2U	Resistance (Noilhan and Planton, 1989)	Force-restore, 2 layers + reservoir
MOUSES	Resistance	Prognostic 1D multilayer model
TEB	Resistance	Bucket
TEB07		Bucket
TUF2D, TUF3D	Not included	Not included
BEP05	Penman-Monteith formulation (Monteith, 1981)	Force-restore
SUEB	Resistances based on Best (1998)	Not included
SUMM	Resistance	Not included
SUNBEEM	Penman-Monteith formulation (Monteith, 1981)	No explicit soil moisture. Thermal properties for vegetated canyon floor may reflect soil moisture
UCLM	Not included	Not included
VUCM	Parametric formulation	Layers

calculation of the turbulent sensible heat flux, the methods for calculating the latent heat flux typically involve some form of resistance scheme whereas some prescribe a value based on areal extent of vegetation (e.g. GCTTC).

11.3 Methodology for the Model Comparison

The methodology to be adopted follows that used in PILPS, the Project for Intercomparison of Land-Surface Parameterization Schemes (Henderson-Sellers et al., 1993). This involves four stages. The models are all run offline so the forcing data are provided for the ‘top’ of the model and so there is no feedback to larger scale conditions within the modelling domain. The smallest time unit of analysis will be hourly and the spatial unit will be an area that is representative of the local scale (equivalent to one grid point in a meso-scale model). Initially participants will be provided with very limited information about the chosen site(s), only being given the forcing variables. In subsequent runs, more information will be provided to ensure that a controlled experiment is achieved. By undertaking this staged approach it should be possible to establish the required accuracy for each of the model parameters by comparing the quality of the simulation at each stage. This methodology is endorsed by the GEWEX Global Land Atmosphere System Study (GLASS) panel, which coordinates the PILPS experiments (A. Pitman, personal communication, 2006). More specifically the steps are:

1) *Forcing data only*: The models are run with no prior knowledge of the urban surface (i.e. each group determines their own default values for all of their parameters); only the main forcing data will be supplied, e.g. winds, temperature, solar radiation.
2) *Add urban morphology*: This involves releasing morphological information to the modellers, e.g. building density, mean building height, vegetation fraction. These data are more readily available on a global basis.
3) *Add urban fabric properties*: Details of building materials are then given, such as thermal properties, surface cover fraction and albedo. This information is specific to each city and is not generally known on a global basis. Reliance on these types of data makes a scheme such as this difficult for global applications.
4) *Add evaluation data*: At the final stage, the evaluation dataset is released to allow optimisation of model parameters for best fit to observations. At this stage, modelling groups will also return information on their optimised parameters as well as the standard outputs. The methods used by individual groups to determine what they regard as their optimized parameter set will be also gathered.

The model evaluations will involve statistical analysis of the *performance of the models relative to the observations*. The observations will be for one site and will consist of a range of data that varies seasonally. This assessment will be conducted flux-by-flux (radiative, turbulent sensible and latent heat fluxes) and will consist of an hour-by-hour evaluation along with comparisons over longer (daily, monthly, seasonal, annual) time periods. The statistics used will include a range of metrics (mean, standard deviation, probability distribution function, linear regression, root mean square error (systematic, unsystematic), index of agreement, mean absolute error, mean bias error, correlation coefficient, coefficient of determination, etc.). Each provides insight into different aspects of model performance.

The analysis will also assess the ability of each model to simulate known urban climatological phenomena. It is now well documented that the energy exchange processes in cities (relative to a rural area) are modified by the presence of buildings and other anthropogenic structures in the following key ways:

- urban areas reflect less shortwave radiation, due to trapping and multiple reflections between buildings (Arnfield, 1982)
- materials used in urban areas have high thermal heat capacity, i.e. there is 'storage heat flux' into the buildings by day (Grimmond and Oke, 1999a; Offerle et al., 2005) and significant release at night
- the surface area is increased, which combined with materials of a high heat capacity, means that more heat is absorbed and emitted (Harman et al., 2004b)
- the morphology of buildings affects flow, and thus determines the rate of exchange of heat with the air above (Barlow and Belcher, 2002; Barlow et al., 2004)
- buildings and traffic generate additional anthropogenic sources of heat (Grimmond, 1992; Sailor and Lu, 2004; Offerle et al., 2005)
- evaporative cooling is decreased due to reduction in vegetation cover; thus the latent heat flux may be relatively small (Grimmond and Oke, 1991; Grimmond and Oke, 1999b)
- positive sensible heat fluxes are more probable at night in highly built up areas (Grimmond and Oke, 2002)

Many of the models under consideration also predict variables beyond the surface energy balance terms. It is often these variables that are of specific interest in many applications. For example, air temperature and humidity are reported as part of a weather forecast but are also of interest for health and air quality applications. Similarly, atmospheric stability and wind speed are of interest in pollution dispersion applications.

By staging the comparison and considering model performance individually and across groups of models defined in terms of key attributes, we will aim to address the following four key questions:

1) *What are the main physical processes that need to be resolved to simulate realistically, urban energy balance exchanges?* This will be addressed by grouping models in terms of the processes that they represent, to determine whether models which represent certain processes produce significantly better results. By staging the comparisons so that the experiment finishes with the optimisation of the parameters for each model, it will be possible to determine

whether the optimized parameters actually represent the processes they are meant to, by assessing whether the parameters are within physically reasonable bounds.

2) *How complex does a model need to be in order to produce a realistic simulation of urban fluxes and temperatures?* More complex models tend to be more difficult to implement and require greater computational resources. By comparing the performance of models grouped in terms of complexity, it will be possible to determine the model complexity required to accurately represent known (observed) urban climatic features.
3) *Which input parameter information is required by an urban model to perform realistically?* An array of parameters, particularly related to the urban surface, is used in model simulations; specifically information on surface materials, building heights and shapes, distribution of heat sources, etc. Clearly, it is impossible to incorporate into a model, or even to collect data, on all aspects of the urban surface. Therefore guidance is needed to balance the complexity (and availability) of the input parameters with the veracity of the models output. To assess this, the models will be run in stages, with increasingly accurate parameter information provided at each stage. By assessing the quality of the simulations for each group at each stage, it will be possible to determine: the minimum number of parameters required for a realistic simulation; what these parameters are, and how accurately they need to be known.
4) *What are the main research priorities for future observational campaigns within urban areas?* By answering the third question, it will also be possible to determine whether the essential parameters are being measured in observational studies of cities, and whether techniques for determining these parameters actually exist. This will enable advice to be given to the measurement community in terms of prioritising future observational research campaigns and to determine the routine measurements to be assimilated into forecast or air quality models.

11.4 Conclusions

Given the broad range of applications in which urban surface energy balance schemes are being used (e.g. simulations of the UHI, evaluation of different building/development strategies, air quality modelling, regional weather forecasting) and the potential range of applications, a more systematic evaluation of existing models and areas of weakness is needed. This project will contribute to developing the science for a sustainable future, as urban land use increases globally and as increasing populations become exposed to microclimates with undoubted anthropogenic influences.

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