The PILPS-Urban experience: implications for introducing an urban tile in NWP models

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Abstract

Land surface schemes have been developed to model the distinct features of the urban surface and the associated energy exchange processes. A large number of these schemes exist making a range of assumptions both about the surface and processes that need to be incorporated. Here, the initial results from an international project comparing 33 sets of results from urban schemes are presented. This is the first systematic cross-model evaluation of urban land surface schemes. In Phase 1, participants were given a short set of forcing and observed data from an industrial site in Vancouver to run their models. Following analysis of model performance for this phase, participants were allowed to re-run their models. This resulted in improved model performance as measured by the mean RMSE. For example, across the 33 models the mean RMSE for net all wave radiation fell from 180 to 121 W m^{-2}. For Phase 2 participants were given 68 weeks of forcing data for an unknown site in an urban area to run their models. In the four stages of Phase 2, increasingly detailed information about the site was provided upon submission of model output. In general, net all wave radiation is the best modelled flux. Providing additional information does not result in improvement performance for all fluxes at each stage. As more information is provided the mean performance of the models does not always result in an improvement for all fluxes. Rather there is a drop in performance in the ability to model net all wave radiation associated with the improved ability to model the turbulent sensible heat flux. Overall the latent heat flux is the least well modelled flux. Neglecting this term, which some models choose to do, results in poor performance. Even in areas where the vegetated fraction is small, the assumption of no vegetation, or of no latent heat flux, is unsatisfactory. However, taking a simpler approach does not result in significantly poorer performance than more complex approaches.

Note: The material presented draws heavily on preprints submitted by Grimmond et al. to the Annual Meeting of American Meteorological Society Phoenix 2009 and International Conference for Urban Climate – 7 Yokohama 2009 [Grimmond et al. 2009a,b]. The material has been updated since those were submitted.

1. Introduction

Land surface schemes (LSS) model the energy exchanges between the surface and the atmosphere. They have been developed for a wide range of different environments (e.g. deciduous trees, coniferous tress, C3 grasses, frozen water, urban) and form the lowest layer of meso- and global scale atmospheric models. They are forced with data from the overlying model and, in turn, provide the energy flux conditions of the lower atmospheric boundary. Schemes developed for the urban environment, despite sharing the common objective, use a wide variety of approaches (Grimmond et al. 2009a,b,c). This includes, at the simpler end of the spectrum, representation of the urban surface as an impervious slab, to the more complex inclusion of the three dimensional geometry of buildings with varying heights and material characteristics (Table 1). In the process of simplification to represent the urban environment, urban LSS developers have chosen whether or not to include turbulent latent heat and anthropogenic heat fluxes. Increasing complexity, however, comes at a cost; requiring greater computational resources and larger numbers of model parameter values that need to be assigned.

Table 1: Description of model classes (modified from Grimmond et al. 2009d).

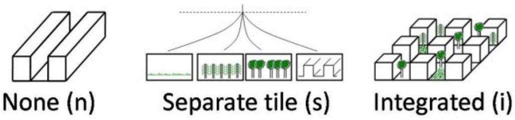
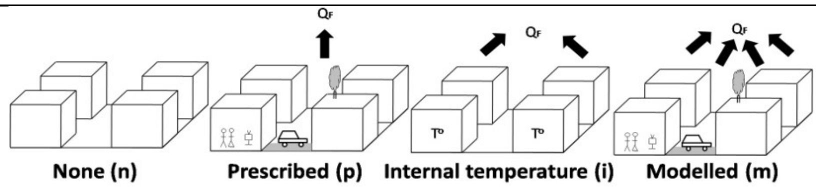
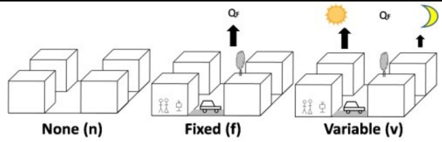
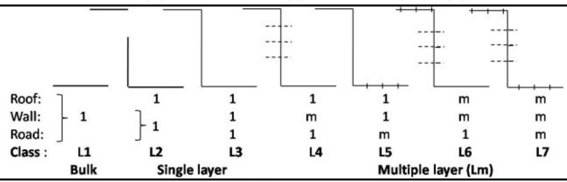
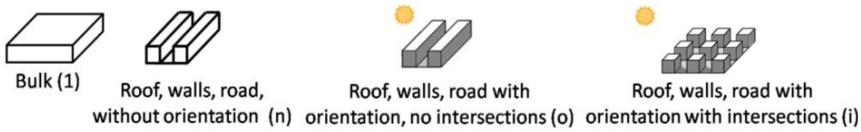
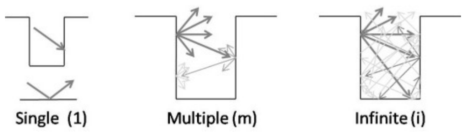
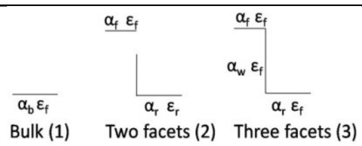
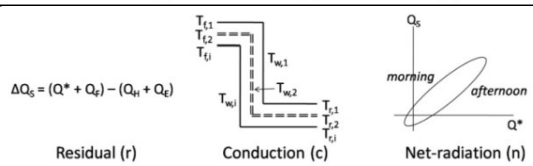
Class	Representation
Vegetation (V) Not included (n) Separate tile (s)* Integrated (i)*	
QF (AN) Negligible or ignored (n) Prescribed (p)* Internal Temp. (i)* Modelled (m)* i,p*	
Temporal QF variation (T) None (n) Fixed (f) Variable (v)	
Urban Morphology (L) Bulk (L1) Single layer (L2, L3) Multiple layer (Lm)	
Facets & orientation (FO) Bulk (1)* No orientation (n)* Orientation (o) no intersections† Orientation (i) with intersections†	
Reflection (R) Single (1) Multiple (m) Infinite (i)	
Albedo, Emissivity (AE) Bulk (1)* Two facets (2)* Three or more facets (f)	
ΔQ_S (S) Residual (r)* Conduction (c) Net radiation based (n)*	

Table 2: Models participating in the model comparison exercise. The number of versions of each model, and number of groups using it. Note that these are assigned anonymous numerical identifiers for analysis

**only participated in Phase 2.*

Code	Model Name	References	Versions	Groups
BEP02	Building Effect Parameterization	Martilli et al. (2002)	1	1
BEP_BEM08	BEP coupled with Building Energy Model	Martilli et al. (2002), Salamanca et al. (2009),Salamanca and Martilli (2009)	1	1
CLMU	Community Land Model – Urban	Oleson et al. (2008a, b)	1	1
GCTTC*	Green Cluster Thermal Time Constant model	Shashua-Bar and Hoffman (2002; 2004)	1	1
IISUCM	Institute of Industrial Science Urban Canopy Model	Kawamoto and Ooka (2006; 2009a; b)	1	1
JULES	Joint UK Land Environment Simulator	Essery et al. (2003), Best (2005), Best et al. (2006)	4	2
LUMPS	Local-scale Urban Meteorological Parameterization Scheme	Grimmond and Oke (2002), Offerle et al. (2003)	2	1
NKUA	University of Athens Model	Dandou et al. (2005)	1	1
MORUSES	Met Office Reading Urban Surface Exchange Scheme	Harman et al. (2004 a,b), Porson et al. (submitted)	2	1
MUCM	Multi-layer Urban Canopy Model	Kondo and Liu (1998), Kondo et al. (2005)	1	1
NJU-UCM-S	Nanjing University Urban Canopy Model-single layer	Masson (2000), Kusaka (2001)	1	1
NJUC-UM-M	Nanjing University Urban Canopy Model-multiple layer	Kondo et al.(2005), Kanda(2005a; b)	1	1
NSLUCM / NSLUCMK / NSLUCM-WRF	Noah land surface model/Single-layer Urban Canopy Model	Kusaka et al. (2001), Chen et al. (2004)	3	3
SM2U	Soil Model for Submesoscales (Urbanized)	Dupont and Mestayer (2006), Dupont et al. (2006)	1	1
SNUUCM	Seoul National University Urban Canopy Model	Ryu et al. (2009)	1	1
SRUM2/ SRUM4	Single Column Reading Urban Model tile version	Harman and Belcher (2006)	4	1
SUEB	Slab Urban Energy Balance Model	Fortuniak et al. (2004, 2005)	1	1
SUMM	SUMM (Simple Urban Energy Balance Model for Mesoscale Simulation)	Kanda et al. (2005b; 2007), Kawai et al. (2007, 2009)	1	1
TEB	Town Energy Balance	Masson (2000), Masson et al. (2002), Lemonsu et al. (2004)	1	1
TEB07	Town Energy Balance 7	Hamdi and Masson (2008)	1	1
TUF2D	Temperatures of Urban Facets 2D	Krayenhoff and Voogt (2007)	1	1
TUF3D	Temperatures of Urban Facets 3D	Krayenhoff and Voogt (2007)	1	1
VUCM	Vegetated Urban Canopy Model	Lee and Park (2008)	1	1

Previously, urban LSSs (ULSSs) have been evaluated individually against observational datasets (e.g. Grimmond and Oke 2002, Masson et al. 2002, Dupont and Mestayer 2006, Hamdi and Schayes 2007, Krayenhoff and Voogt 2007, Kawai et al. 2009, Loridan et al. 2009) but these studies did not include a structured comparison across models. Here, results from an international model comparison study which follows the PILPS (Project for Intercomparison of Land-Surface Parameterization Schemes) (Henderson-Sellers et al. 1993) methodology are presented. This comparison consists of the analysis of the results from 33 ULSSs (in Phase 1) and 32 (in Phase 2) (Table 2). Because LSSs are intrinsic to NWP models, the findings of this comparison are of importance in suggesting where improvements may be gained when applied in areas that include urbanized regions.

2. Methodology

Individual groups were provided with forcing data to run their model(s) 'offline'. This allows the performance of the LSSs to be examined while the atmospheric conditions are held fixed and are not a function of the performance of a larger scale model. In Phase 1, a short (14 day) dataset from a light industrial site in Vancouver (termed here 'VL92') was provided, consisting of the forcing data plus the observed energy balance fluxes (Voogt and Grimmond 2000, Grimmond and Oke, 2002). Participants had full knowledge of the site and its characteristics, and could also use results from previous modelling runs which had used this data (e.g. Masson et al. 2002, Best et al. 2006. Oleson et al. 2008).

In Phase 2, participants were initially (Stage 1) provided with 68 weeks of forcing data from an unspecified site (termed "alpha") which was urban. At subsequent stages, additional site information was provided (Table 3). This was released relative to the ease for obtaining these data sets on a city-wide, regional or global basis. At Stage 2 the relative fractions of pervious and impervious areas were provided. At Stage 3 information about the 3 dimensional characteristics of the urban morphology was released. At Stage 4 information about the urban materials was provided. In a final stage (Stage 5) the location of the site and the observed fluxes was provided, although this stage is not discussed here. From the information provided, modelling groups had to assign all the parameter values they required.

Table 3: Data provided at Stages 1-4 of Phase 2.

Stage	Category	Data provided
1	Observations	Incoming shortwave radiation, incoming long wave radiation, air temperature, station pressure, specific humidity, wind components, rainfall
	Site	Latitude, Longitude, Measurement height: 6.25 x mean roughness height
2	Plan area fraction	Pervious, impervious
3	Heights	Instrument height, roughness length for momentum, maximum height of roughness elements, mean building height, height:width, mean wall to plan area
	Plan area fraction	Buildings, concrete, road, vegetation (excluding grass), grass and other (bare, pools)
	Other	Urban climate zone; population density
4	Material characteristics	Thickness, specific heat, volumetric heat capacity, thermal conductivity, type: road, roof and wall layers

The models were classified using eight characteristics (Table 1) (see Grimmond et al. 2009d for more details). For presentation of results, each model was assigned a random identifier number so that model performance was anonymous but class performance could be seen. For Phase 1, the whole dataset is analyzed while for Phase 2, only the last 12 months of the dataset are analyzed so as to allow for an initialisation or 'spin-up' period. This alpha dataset consists of 8520 30-min periods where all fluxes are observed. Statistics used to assess model performance include: the root mean square error (RMSE) and the systematic ($RMSE_s$) and unsystematic ($RMSE_u$) RMSE and the Mean Bias Error (MBE). For these they all have the units of the variable being analysed and the ideal performance would be to have a value of 0. The analysis was performed for the net all wave radiation (Q^*), turbulent sensible heat flux (Q_H), the turbulent latent heat flux (Q_E) and the net storage heat flux (ΔQ_S). In both data sets the observed fluxes consisted of radiometer measurements and eddy covariance measurements for the turbulent fluxes. The net heat storage was determined as a residual so this means that all the measurement errors and the missing terms are accumulated in this flux. Anthropogenic heat flux was accounted for at the Alpha site but not at VL92.

3. Results

Using the Phase 1 dataset, 20 of the 33 participants chose to re-run their models following their initial submission. The primary reason given for re-running was the developments to their models made during the period of the model comparison. This was permitted as a number of the participants had this opportunity prior to the model comparison so this therefore ensured equity between groups. This resulted in improvements to the overall mean model performance, as assessed by the mean RMSE for all fluxes considered (Grimmond et al. 2009d).

The largest absolute RMSE is associated with modelling Q_H and the smallest with Q_E (Fig. 1). However, when compared to the mean observed fluxes it is clear that the most poorly modelled flux is Q_E. During the Phase 1 observation period, there was a drought and an irrigation ban (Grimmond and Oke, 1999). This, combined with a small area that was vegetated, resulted in small latent heat fluxes (mean observed = 15.5 W m^{-2}). The best performance is obtained for the net all wave radiation. For all but four models the RMSE for Q^* is less than 60 W m^{-2} whereas for Q_H only half the models have a RMSE of less than 60 W m^{-2}. The remaining models have RMSE values over 60 W m^{-2} to nearly 200 W m^{-2}. For the storage heat flux the ranked RMSE shows no clear groupings of performance but rather a steady decline (except for one model).

With the aid of Taylor diagrams, the correlation coefficient and standard deviation can be compared relative to the RMSE (Taylor, 2001) for each model. Fig. 2 confirms clearly that the net all wave radiation (Q^*) is the flux which is modelled best. The individual models (symbols) all cluster around the observation data point (green square), except for two outliers. In contrast, Q_E is the least successfully modelled, with all points at some distance from the observational data and some relatively small correlation coefficients and large RMSEs displayed. Interestingly, for ΔQ_S, the correlation coefficient is relatively uniform for all models, although with a wide variation in RMSE and standard deviation. The modeling of Q_H is less successful than for Q^* for the majority of models, although it is better than for both Q_E and ΔQ_S, with points clustered closer to the observational data point.

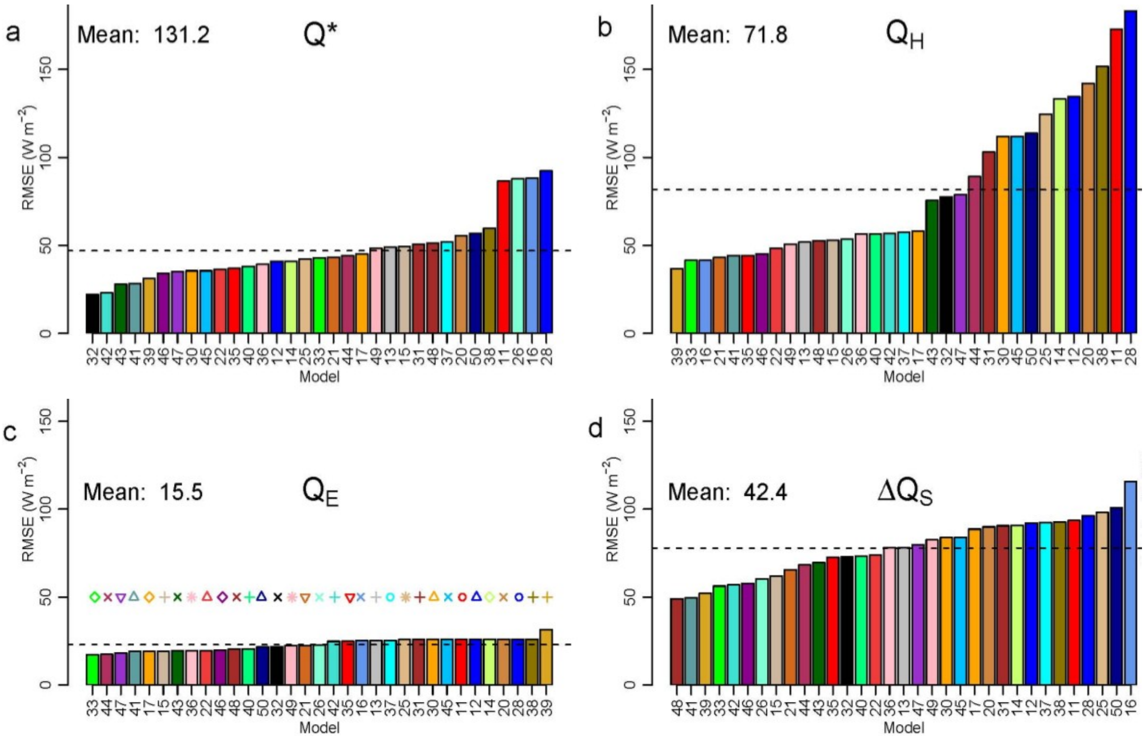


Figure 1: Ranked RMSE (W m^{-2}) for all models for Phase 1 for: (a) net all wave radiation (Q^*), (b) turbulent sensible heat flux (Q_H), (c) turbulent latent heat flux(Q_E) and (d) net storage heat flux(ΔQ_S). Models are assigned a random identifier that remains the same between fluxes and Phases.

For Phase 1, no individual model performed best or worst for all fluxes. Of the various ways to classify the modelling approaches (Table 1), the inclusion or neglect of vegetation had the greatest influence (Grimmond et al., 2009d) (Fig. 3). Those models which do not consider vegetation generally have a larger mean bias error (positive for Q^* and Q_E and negative for Q_E and ΔQ_S) than those which did consider it (either as a separate tile or as integrated within the urban surface). From Figure 2 it is also apparent that Q_H is consistently overestimated by most models and because of this the storage heat flux is consistently underestimated. For net all wave radiation the three vegetation classes show quite different behaviours. For those models that ignore vegetation (Vn) the median MBE is 18.8 W m^{-2} whereas for those treat it separately (Vs) the MBE is of the same order of magnitude but of the reverse sign (i.e.-21.1W m^{-2}). The remaining models which treat the vegetation as an integrated part of the urban surface which can interact (Vi) have median MBE of 0.6 W m^{-2}.

The results from Phase 2 are consistent with the results from Phase 1. When the individual model RMSE are ranked for Stage 1 (Fig. 4), the Q^* RMSE varies between 10.4 and 106.9 W m^{-2}. Again there are few models that show much poorer performance. All but four have RMSE less than 50 W m^{-2}. A similar pattern is evident for Q_H, although with higher RMSE values (36.5-129.0 W m^{-2}). Not unexpectedly, the three poorest performing models for Q_H are those that perform poorest for Q^*. For Q_E, model performance does vary (33.8-61.7 W m^{-2}), although without a stepped change. It is evident that models which perform well/poorly for one flux do not necessarily perform well/poorly for others.

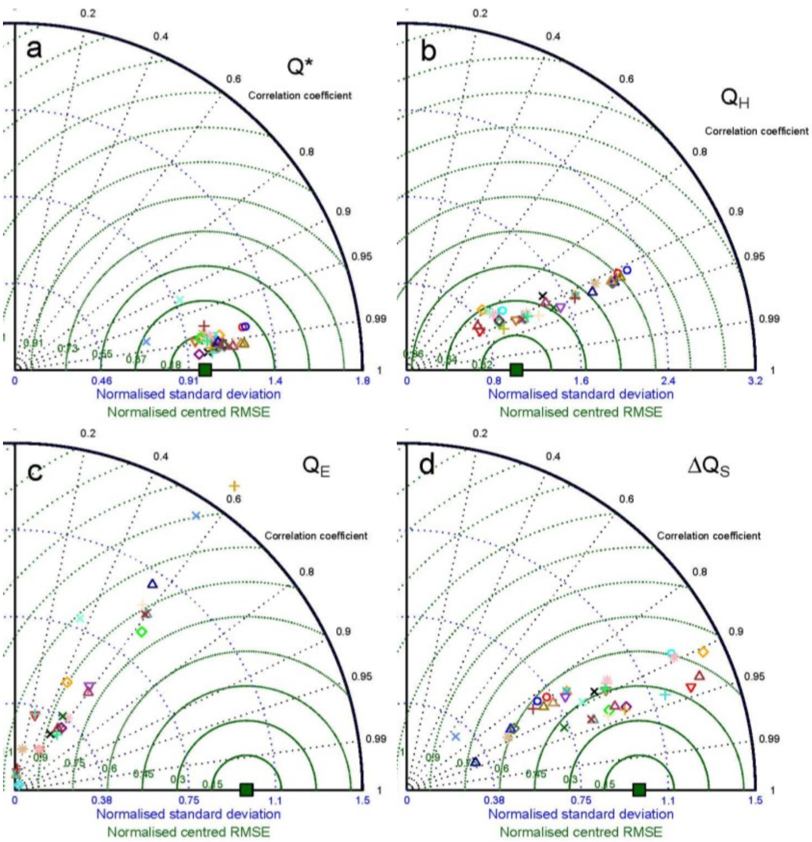


Figure 2: Normalised Taylor diagrams for modelled (a) Q, (b) Q_H (c) Q_E and (d) ΔQ_S for the Phase 1 model results for all hours. The correlation coefficient is given on the polar axis, the normalised standard deviation on the horizontal axis and the normalised RMSE is given by the internal circular axes. The greens square is the ideal performance whereas the other points are each of the individual models (see Fig 1 for key).*

Comparison of the model performance between Stages 2 and 4 (Table 4) shows that for Q^* and Q_H the maximum RMSE decreases, *i.e.* model performance improves. The mean RMSE shows an improvement in all stages for Q_H and Q_E. For Q^* and Q_H the models, on average, have a smaller $RMSE_s$ than $RMSE_u$ which suggests that the mean performance cannot be improved because of a systematic bias. However for Q_E the mean $RMSE_S$ is greater than $RMSE_u$ and, in fact, appears to be related to whether or not vegetation is included in the models, thereby corroborating the finding of the important influence of vegetation considerations on model performance for Phase 1.

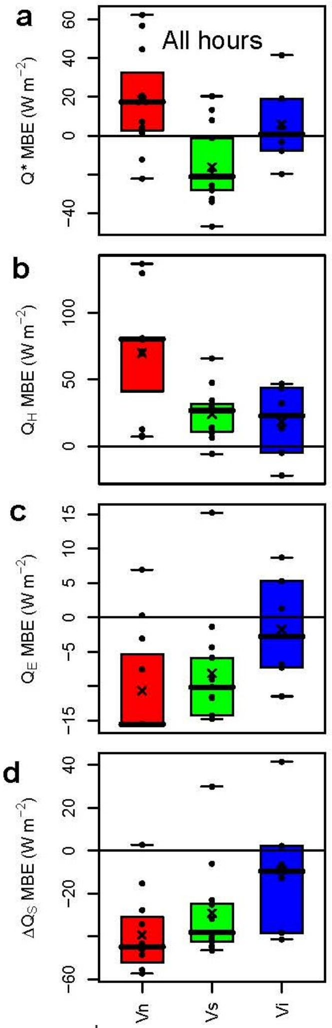


Figure 3: MBE (W m^{-2}) results when the models are classified by how they treat vegetation (Table 1) [Vn: Vegetation is not included ,Vs: Vegetation is modelled but as a separate tile which does not interact with the urban surface and Vi: Vegetaton is incorporated and conditions can impact (or be impacted) by the built characteristics] for (a) Q, (b) Q_H,(c) Q_E and (d) ΔQ_S for Phase 1. Each dot is an individual models results. The shaded bar shows the 25th and 75th percentile (or interquartile range) of the group of model results. The horizontal line indicates the median and the 'x' the mean model results. The triangles show best and poorest result for each class. Note that the vertical scale varies between graphs.*

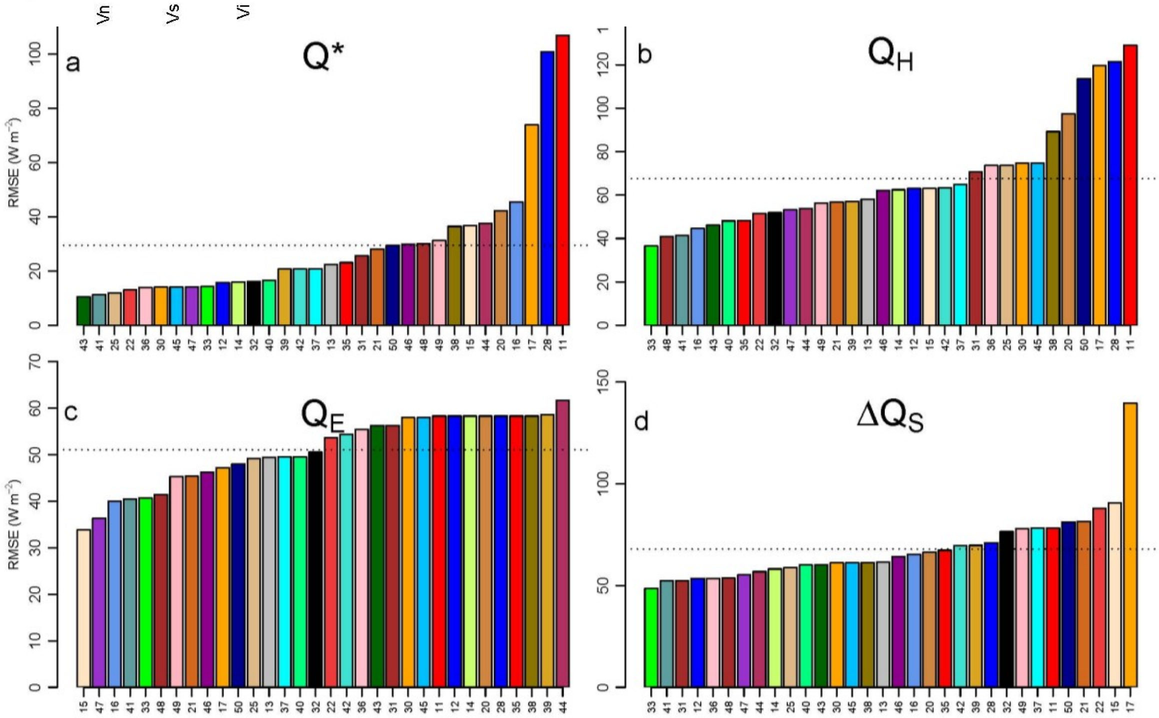


Figure 4: Ranked RMSE (W m^{-2}) for 32 models for Phase 2 site with Stage 1 information available for assigning parameters for (a) Q, (b) Q_H (c) Q_E and (d) ΔQ_S. Data analysed is 30 min periods for the last 12 months of the data set when all observations are available.*

Table 4: Summary of the mean, maximum and minimum statistical performance (see Table 7 Grimmond et al. (2009d) for definitions of statistics)for 32 models. Analysis is for all 30 min periods when all observed fluxes are available in the last 12 months of the analysis for the Phase 2 site with increasing amounts of surface information available (Stages 1 – 4). See Table 3 for what information was available at each stage.

Statistic		Q^*				Q_H				Q_E				ΔQ_S			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Observed (W m^{-2})		78.9				37.9				32.5				19.0			
$\bar{x}_{mod}$ (W m^{-2})	Max	144.6	120.0	120.0	99.3	124.1	125.7	125.7	106.3	61.9	66.8	68.1	68.1	31.0	54.7	15.6	27.1
	Min	47.9	49.1	57.3	49.5	15.3	3.7	16.8	14.6	0.0	0.0	0.0	0.0	-25.6	-31.6	-74.9	-22.0
	Mean	76.2	75.4	75.0	73.3	61.9	50.4	54.1	50.5	14.3	24.8	25.0	24.1	2.1	1.8	-1.5	0.3
σ_{mod} (W m^{-2})	Max	252.2	252.2	241.9	241.6	170.4	170.4	170.8	169.9	70.6	86.4	87.0	88.1	221.4	214.0	214.0	161.6
	Min	176.1	153.2	168.0	155.9	65.0	30.0	54.7	65.0	0.0	0.0	0.0	0.0	54.5	51.5	50.0	38.8
	Mean	214.9	212.7	208.8	204.3	117.5	109.8	109.0	119.8	23.6	33.9	34.2	et,	118.3	106.4	102.9	80.8
R^2	Max	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.5	0.5	0.5	0.5	0.8	0.8	0.8	0.8
	Min	0.8	0.8	0.8	0.8	0.4	0.4	0.3	0.5	0.0	0.1	0.1	0.1	0.6	0.6	0.6	0.4
	Mean	1.0	1.0	1.0	1.0	0.8	0.8	0.8	0.8	0.2	0.4	0.4	0.4	0.8	0.8	0.8	0.7
RMSE (W m^{-2})	Max	106.9	106.9	101.7	101.6	129.0	129.0	124.2	122.0	61.7	76.0	77.1	77.8	139.7	133.1	141.6	85.4
	Min	10.4	9.5	9.2	10.9	36.5	36.5	36.1	32.6	33.8	34.6	34.5	34.4	48.7	48.7	48.5	53.3
	Mean	29.5	28.9	29.1	30.4	67.5	62.7	60.9	58.4	51.0	47.7	45.9	45.7	67.9	64.8	64.3	65.4
$RMSE_s$ (W m^{-2})	Max	69.8	66.9	50.2	61.0	94.3	93.8	97.6	82.7	58.3	58.3	58.3	58.3	90.6	84.1	115.6	75.5
	Min	1.2	2.3	1.4	4.9	7.8	7.8	8.2	10.0	15.1	12.2	11.0	8.7	14.4	3.7	7.9	16.1
	Mean	15.5	14.9	14.9	16.4	39.8	37.1	35.5	32.4	43.2	33.5	31.8	31.4	32.1	35.2	37.4	47.1
$RMSE_u$ (W m^{-2})	Max	104.3	104.3	100.8	100.6	99.9	94.8	94.9	94.4	54.1	67.6	68.2	68.9	106.3	103.2	103.2	77.4
	Min	6.8	5.8	5.8	6.1	34.9	18.2	27.1	27.7	0.0	0.0	0.0	0.0	29.8	28.4	26.7	20.0
	Mean	22.2	22.1	22.4	22.7	52.8	48.0	46.9	46.9	20.0	25.8	26.0	26.0	58.1	52.1	49.7	41.8
MBE (W m^{-2})	Max	65.7	41.1	41.1	20.4	86.2	87.9	87.9	68.4	29.4	34.3	35.6	35.6	12.0	35.7	-3.4	8.1
	Min	-31.0	-29.8	-21.6	-29.4	-22.6	-34.2	-21.1	-23.2	-32.5	-32.5	-32.5	-32.5	-44.6	-50.6	-93.9	-41.0
	Mean	-2.7	-3.5	-3.9	-5.6	24.0	12.6	16.2	12.6	-18.2	-7.7	-7.5	-8.4	-16.8	-17.2	-20.4	-18.6

4. Conclusions

Depending on the characteristics and features of particular ULSSs, their ability to model energy balance fluxes varies greatly. Having been made aware of their model's performance in Phase 1, modellers were able to incorporate improvements in their models. Phase 1 strikingly shows the importance of considering vegetation in modelling urban energy balances – even in when vegetation cover is limited. Phase 2 demonstrates that having correctly specified parameter information generally results in improvements in model performance. Thus there is a need to develop appropriate databases of urban surface characteristics for describing urban areas for NWP purposes. Of the fluxes modelled, Q^* is most accurately estimated, while the modelling of Q_E appears to be the most troublesome. Good model performance for one flux in particular does not, necessarily, mean good performance for others and, indeed, in some cases the reverse is true.

Acknowledgements

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