THE NOAH / URBAN CANOPY MODEL IN WRF V3.1: INPUT PARAMETERS AND SENSITIVITY ANALYSIS USING THE MOSCEM OPTIMIZATION ALGORITHM

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1 INTRODUCTION

With the state-of-the-art Numerical Weather Prediction (NWP) models now able to resolve at the order of 1-4 km to 250 m, the impact of urbanized areas on the atmospheric flow becomes a critical issue. This concern has been highlighted by recent efforts to include a separate representation of urban surfaces in operational mesoscale models (e.g.*Taha*, 1999; *Masson*, 2000) or global climate models (*Oleson et al.*, 2008). The objectives here are **(1)** to analyze in detail, and where possible simplify, the list of input parameters required by the urban parameterization implemented in the Weather Research and Forecasting model (WRF), and **(2)** to identify the critical parameters whose correct estimation drives the modelling of the Surface Energy Balance (SEB) using the Multiobjective Shuffled Complex Evolution Metropolis (MOSCEM) algorithm of *Vrugt et al.* (2003).

2 THE MODIFIED NOAH / URBAN CANOPY MODEL

For WRF, the Noah Land Surface Model (*Chen and Dudhia*, 2001) is coupled to the Single-Layer Urban Canopy Model (*Kusaka et al.*, 2001; *Kusaka and Kimura*, 2004) using a tile-approach (*Tewari et al.*, 2006). The parameters required are a fine balance between the need to parameterize urban-atmosphere energy exchange processes and the information realistically procurable at the scale resolved. The amendments, summarized in Table 1, were integrated in the latest WRF release (version 3.1, March 2009) to allow for more consistency between the assigned values and clarify their physical meaning.

The inputs are simplified to the basic dimensions required to define a two dimensional canyon. This consists of the height (Z_R) and the width of both its street (W_{road}) and roof (W_{roof}). The normalized building fractions of canyon surfaces covered by walls (F_{walls}), roads (F_{road}) and roof (F_{roof}) as well as the normalized building height (Z_{norm}) are then internally derived from this information. The building's plan area fraction λ_P and frontal area index λ_F are expressed as a function of F_{roof} and Z_{norm}. The original relations for the wall to sky ($\Psi_{wall\to sky}$), road to sky ($\Psi_{road\to sky}$), wall to road ($\Psi_{wall\to road}$) and wall to wall ($\Psi_{wall\to wall}$) view factors required to represent the trapping of radiation inside an infinitely long canyon are kept (*Kusaka et al.*, 2001):

$$\Psi_{wall\to sky} = \frac{2}{N}\sum_{k=1}^{N}\left[\frac{1}{4}\left(1+\frac{\left(Z_{norm}-\frac{d_z}{2}\right)-kd_z}{\sqrt{[\left(Z_{norm}-\frac{d_z}{2}\right)-kd_z]^2+{F_{road}}^2}}\right)\right]$$

$$\Psi_{road\to sky} = 1-\left(\frac{F_{walls}}{F_{road}}\right)\Psi_{wall\to sky};\ \Psi_{wall\to road} = \Psi_{wall\to sky};\ \Psi_{wall\to wall} = 1-(\Psi_{wall\to sky}+\Psi_{wall\to road})$$

where the iteration limit is set to N=100, and the integration step to $d_z=Z_{norm}/(N+1)$.

Similarly, the canyon roughness length for momentum Z_{0C} and the corresponding zero plane displacement height Z_{DC} previously required as input to the scheme are now parameterized as a function of the canyon geometry (*Macdonald et al.*, 1998), using a value of C_d=1.2 for the drag coefficient, κ=0.4 for von Kármán's constant and α_m=4.43, β_m=1.0 for the two empirical parameters used (*Macdonald et al.*, 1998; *Grimmond and Oke*, 1999; *Kastner-Klein and Rotach*, 2004). Not only does such addition allow for some consistency between the specification of canyon geometry and roughness, but it also enables the suppression of Z_{0C} and Z_{DC} from the list of required inputs.

The wind is assumed to follow the logarithmic profile from the forcing level (Z_A) down to the roof (Z_R), and then decrease exponentially to a height Z_C inside the canyon. The wind velocity inside the canyon (U_C) is therefore parameterized as a function of its forcing value (U_A) and the roof level (U_R). The derivation of the attenuation coefficient *a* which appears in the exponential follows the parameterization from *Inoue* (1963) initially developed for vegetation canopies. In order to avoid the use of vegetation related parameters without clear physical meaning in urban environments, the relation is now based on an estimation of the mixing length l_m using available parameters (*Di Sabatino et al.*, 2008).

Finally, the ratios of the roughness length of momentum to heat for roof surfaces (Z_{0R}/Z_{0HR}) and the canyon space (Z_{0C}/Z_{0HC}) are set to 10 to account for the increased aerodynamic resistance in heat transfer with the presence of bluff bodies (*Brutsaert*,1982). Consequently, the only roughness parameter requiring an input value is Z_{0R} which is still being considered for replacement.

Altogether these modifications have resulted in a reduction of eight input parameters and ensure that if individual characteristics are changed all others that should change are also appropriately recalculated. The two main contributions are **(i)** a smaller, physically more meaningful list of input parameters and **(ii)** more consistency in the main parameterizations involved in the UCM as they are now explicitly linked to the canyon geometry. The online implementation of the scheme directly benefits from both aspects.

Modification	Motivation	Description
Canyon height, width and roof width are now read as input	To clarify the physical meaning of input parameters	*Z_R: canyon height [m]* *W_{road}: road width [m]* *W_{roof}: roof width [m]*
Normalized ratios are now derived from canyon geometry	To homogenize the description of canyon morphology	$Z_{norm} = Z_R/(W_{roof} + W_{road})$ $F_{walls} = 2Z_{norm} = 2\,Z_R/(W_{roof} + W_{road})$ $F_{roof} = W_{roof}/(W_{roof} + W_{road})$ $F_{road} = W_{road}/(W_{roof} + W_{road})$
Canyon roughness from *Macdonald et al.* (1998)	To link canyon geometry to its roughness	$\lambda_P = F_{roof}; \lambda_F = Z_{norm}$ $Z_{DC} = Z_R[1 + \alpha_m{}^{-\lambda_P}(\lambda_P - 1)]$ $Z_{0C} = Z_R\left(1 - \frac{Z_{DC}}{Z_R}\right)\exp\left(-[0.5\beta_m \frac{C_d}{\kappa^2}\left(1 - \frac{Z_{DC}}{Z_R}\right)\lambda_F]^{-0.5}\right)$
Attenuation coefficient in wind profile now a function of mixing length	To remove vegetation parameters without clear meaning in urban areas	$U_C = U_R \mathrm{e}^{-a(1-\frac{Z_C}{Z_R})}; U_R = U_A \frac{\ln(\frac{Z_R - Z_{DC}}{Z_{0C}})}{\ln(\frac{Z_A - Z_{DC}}{Z_{OC}})}$ $a = \frac{\kappa\, Z_R}{l_m \ln(\frac{Z_R - Z_{DC}}{Z_{0C}})}; l_m = \kappa(Z_R - Z_{DC})$
Ratios of roughness length of momentum to heat (*Brutsaert*,1982)	To account for increased aerodynamic resistance in heat transfer	$\frac{Z_{0R}}{Z_{0HR}} = 10; \frac{Z_{0C}}{Z_{0HC}} = 10$

Table 1: List of recent modifications to the Noah/UCM scheme. See text for details on notation.

3 OFFLINE SENSITIVITY ANALYSIS USING MOSCEM

An offline version of the Noah/UCM is used as extracted from WRF. When compared with surface energy flux measurements at a scale suitable for the model, a direct evaluation of the scheme is possible. The analysis presented here is conducted using hourly data from a measurement campaign in Marseille (*Lemonsu et al.*, 2004; *Grimmond et al.*, 2004) to force the scheme and evaluate its outputs. Default parameter values for the site are obtained from similar offline runs performed at the same location with the Town Energy Balance (TEB) model (*Lemonsu et al.*, 2004). A good knowledge of the extent to which such a choice of values influences the model performance is fundamental for its online implementation.

Three urban classes (commercial, high-density and low-density residential) are currently used in WRF to characterize the range of cities in a model domain. Each requires a set of input parameter values. The identification of parameters on which the estimation of the fluxes relies is therefore of particular importance. Sensitivity tests which enable a ranking of the influence each parameter has on the simulated fluxes are usually performed by monitoring the model response to a perturbation in its inputs. Here the optimization algorithm Multiobjective Shuffled Complex Evolution Metropolis (MOSCEM) (*Vrugt et al.* 2003) is used.

Designed to provide a calibration tool for hydrological models, the principle behind the MOSCEM algorithm is to iteratively update a set of model input parameters while minimizing several optimization criteria (multi-objective optimization). The criteria, or objective functions, used here is the Root Mean Square Error (RMSE) for the net all-wave radiation (Q^*) and the turbulent sensible (Q_H) and latent heat (Q_E) fluxes. The influence of a change in parameter values is assessed based on the impact it has on these objective functions.

In the current version of Noah/UCM 67 input parameters are required (after modifications outlined in section 2). After preliminary tests on their influence on the RMSE statistics, 47 were selected to be optimized: 32 are related to the urban tile while the remaining 15 characterize the soil and vegetation in Noah. Each of the parameters is given a default value and limits between which it can evolve. For the *p* selected parameters ($1 \le p \le 47$) the MOSCEM algorithm initializes *s* samples (*s* different sets of the *p* parameter values) and iteratively updates their values towards *s* optimized samples minimizing the chosen objective functions.

To analyze the model sensitivity, one (p=1) of the 47 parameters is optimized at a time. Allowing the entire set of parameters to be optimized (p=47) would potentially lead to a greater improvement in the model performance but also considerably complicates the interpretation of its response. As the current objective is not to calibrate the Noah/UCM for a particular dataset but rather to understand its response to specific changes in its input such a multi-parameter optimization is left for later work. Three sets of MOSCEM runs are performed here:

1. Using the RMSE for Q^* and Q_H as objective functions, the key parameters in modelling Q^* are identified while providing some insight on the processes transferring the energy towards Q_H
2. A similar analysis for the transfer towards Q_E is obtained when optimizing for Q^* and Q_E
3. Optimization on Q_H and Q_E allows trade-offs in the partitioning between the turbulent fluxes to be identified

For all runs the performance attained in terms of RMSE are related to a reference run with all parameters set to their 'default' value. Figure 1 provides ensemble average plots over the period and default RMSE for Q^* and Q_H. The extent of the RMSE improvement translates the sensitivity of the model to a particular input. Thus, a ranking of the 47 parameters selected for the optimization can be obtained in terms of their impact on the default RMSE. Ranking for Marseille shows a strong dependence of the model on roof related parameters; in particular the roughness length for momentum whose default value is set to 0.01 m. Fig. 2 shows the impact when Z_{0R} =0.1 m. All runs are performed using a 10 minute time step with hourly forcing data. Model outputs are averaged back to hourly before evaluation against observation.

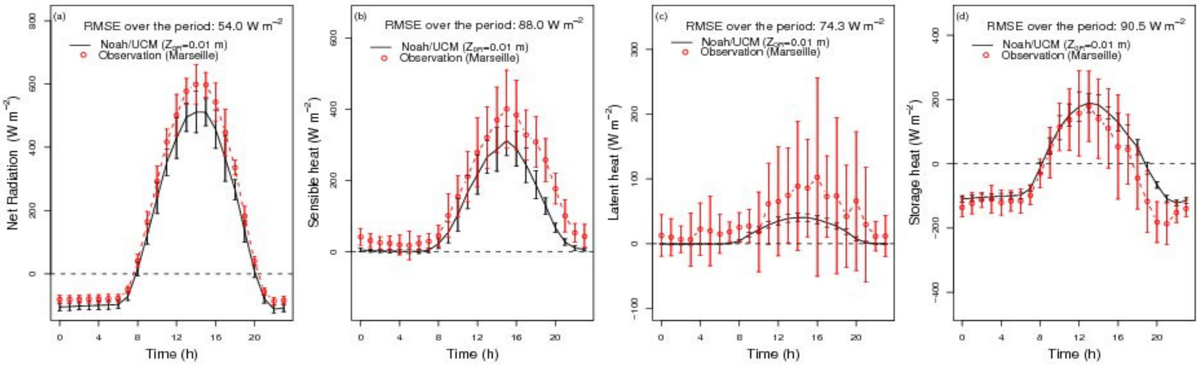

Figure 1: Diurnal mean and standard deviations for (a) Q*, (b) Q_H (c) Q_E and (d) the storage heat as modelled by the Noah / UCM with all parameters set to their default values (solid black) and observed fluxes (dashed red).

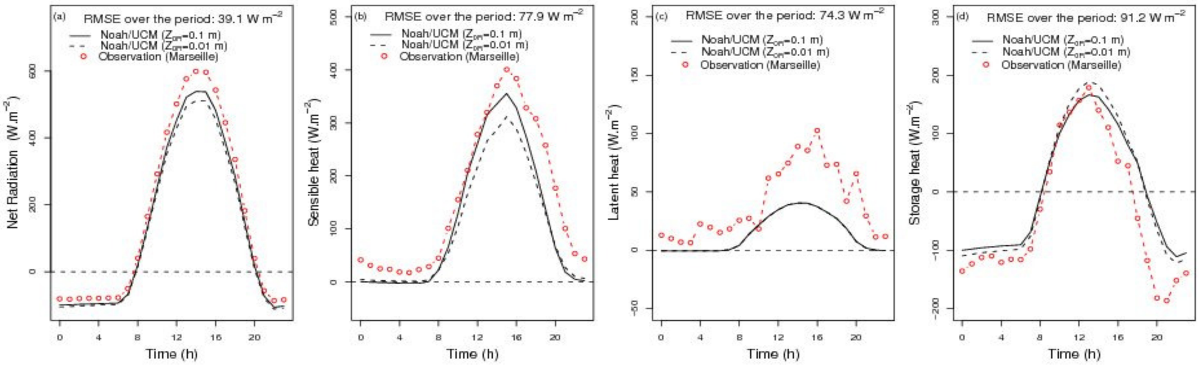

Figure 2: Modelled diurnal mean with all parameters set to their default values (dashed black) and when Z_{0R} is increased to 0.1 m (solid black) for (a) Q*, (b) Q_H (c) Q_E and (d) ΔQ_S.

The major strength of a multi-objective procedure such as MOSCEM is that beyond this initial aim to test model sensitivity it also enables a direct assessment of unavoidable trade-offs in the modelling of the surface energy balance fluxes. A detailed analysis of such 'trade-off effects' for the site of Marseille indicates some difficulty in correctly partitioning energy between turbulent fluxes when using a tile approach.

Results from the multi-objective runs, with respect to Q* and Q_H, are presented in Figure 3 for four of the parameters defined in section 2. Figure 4 shows some results for four parameters related to the vegetation tile when optimizing with regards to Q_H and Q_E. The scatter plots of the RMSE attained by the *s* samples identified as optimum by MOSCEM (*s*=100) were chosen to illustrate the two distinct behaviours arising among the 47 parameters:

- For many of the parameters an optimum state emerges: the *s* solutions are clustered in a very compact area of the objective space, and at least one of the RMSEs is improved from the default run.
- For the remaining parameters, no optimum state can be objectively identified: they represent 'trade-offs' in the modelling of the two fluxes and appear on the scatter plots as lines of optimum samples.

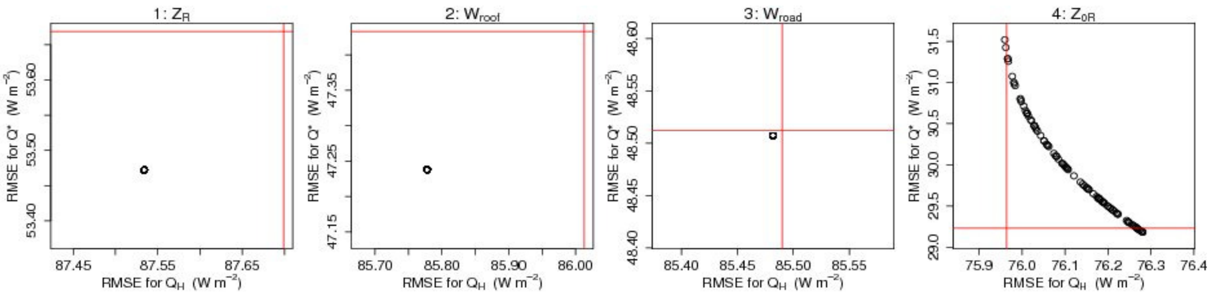

Figure 3: RMSE for 100 samples identified as optimum by MOSCEM when optimized for Q* and Q_H. Four of 47 parameters shown: (1) roof height (2) roof width (3) road width (4) roughness length for momentum of roof surfaces. Solid lines are the lowest RMSE attained by single-objective runs.

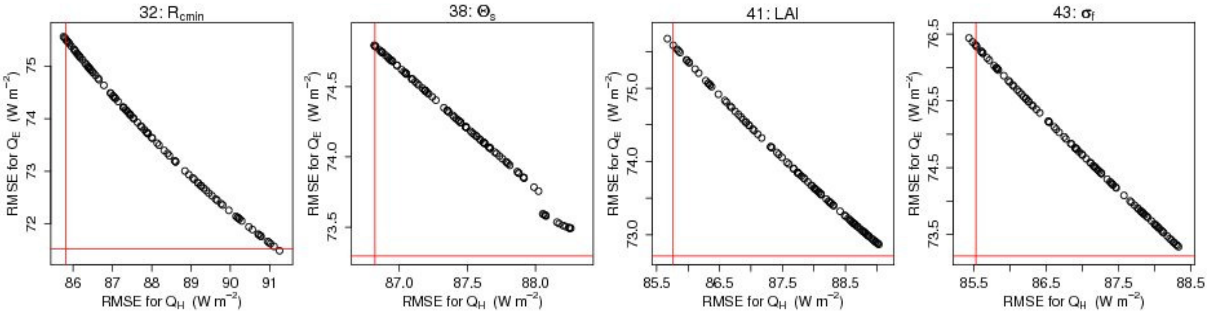

Figure 4: RMSE for 100 samples identified as optimum by MOSCEM when optimized for Q_H and Q_E. Four of 47 parameters shown: (32) vegetation stomatal resistance (38) maximum soil moisture content (41) Leaf Area Index (43) green vegetation fraction. Solid lines are the lowest RMSE attained by single-objective runs.

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References

Brutsaert, W., 1982. *Evaporation into the atmosphere*, D. Reidel, 299 pp.

Chen, F., Dudhia, J., 2001. Coupling an advanced land surface-hydrology model with the Penn state-NCAR MM5 modelling system. Part 1: model implementation and sensitivity, *Monthly Weather Review*, *129*, 569–585.

Di Sabatino, S., Solazzo, E., Paradisi, P., Britter, R., 2008. A simple model for spatially-averaged wind profiles within and above an urban canopy, *Boundary-Layer Meteorology*, *127*, 131–151.

Grimmond, C.S.B., Oke, T.R., 1999. Aerodynamic properties of urban areas derived from analysis of surface form, *Journal of Applied Meteorology*, *38*, 1261–1292.

Grimmond, C.S.B., Salmond, J.A., Oke, T.R., Offerle, B., Lemonsu, A., 2004. Flux and turbulence measurements at a densely built-up site in Marseille: Heat, mass (water and carbon dioxide), and momentum, *Journal of Geophysical Research, Atmospheres*, *109*, D24, D24101, 19pp doi:10.1029/2004JD004936.

Inoue, E., 1963. On the turbulent structure of airflow within crop canopies, *Journal of the Meteorological Society of Japan*, *41*, 317–326.

Kastner-Klein, P., Rotach, M.W., 2004. Mean flow and turbulence characteristics in an urban roughness sublayer, *Boundary-Layer Meteorology*, *111*, 55–84.

Kusaka, H., Kimura, F., 2004. Thermal effects of urban canyon structure on the nocturnal heat island: Numerical experiment using a mesoscale model coupled with an urban canopy model, *Journal of Applied Meteorology*, *43*, 1899–1910.

Kusaka, H., Kondo, H., Kikegawa, Y., Kimura, F., 2001. A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models, *Boundary-Layer Meteorology*, *101*, 329–358.

Lemonsu, A., Grimmond, C. S. B., Masson, V., 2004. Modeling the surface energy balance of the core of an old Mediterranean city: Marseille, *Journal of applied meteorology*, *43*, 312–327.

Macdonald, R., Griffiths, R., Hall, D., 1998. An improved method for estimation of surface roughness of obstacle arrays, *Atmospheric Environment*, *32*, 1857–1864.

Masson, V., 2000. A physically-based scheme for the urban energy budget in atmospheric models, *Boundary-Layer Meteorology*, *94*, 357–397.

Oleson, K. W., Bonan, G. B., Feddema, J., Vertenstein, M., Grimmond, C. S. B., 2008. An urban parameterization for a global climate model. Part 1: Formulation and evaluation for two cities, *Journal of Applied Meteorology and Climatology*, *47*, 1038–1060.

Taha, H., 1999. Modifying a mesoscale meteorological model to better incorporate urban heat storage: A bulk-parameterization approach, *Journal of Applied Meteorology*, *38*, 466–473.

Tewari, M., Chen, F., Kusaka, H. 2006. Implementation and evaluation of a single-layer urban canopy model in WRF/Noah, *WRF users workshop 2006*.

Vrugt, J. A., Gupta, H. V., Bastidas, L. A., Bouten, W., 2003. Effective and efficient algorithm for multiobjective optimization of hydrological models, *Water Resources Research*, *39*, 12014, doi:10.1029/2002WR001746.