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EVALUATION OF URBAN PARAMETERIZATIONS IN THE WRF MODEL USING ENERGY FLUXES MEASUREMENTS

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Abstract: The performance of WRF model was investigated for the urban microclimate simulation, with focus on energy fluxes, using different urban surface parametrizations: UCM, LSM and SUEWS. Two case studies, with different land use characteristics, were considered: high and low intensity residential areas. UCM is the model that more accurately represent the turbulent energy partitioning (sensible and latent heat fluxes) which enhance the ability to modelled the meteorological variables. LSM results showed a considerable underestimation of latent heat flux and an overestimation of sensible heat flux. SUEWS model showed a good ability to represent energy fluxes at the low intensity residential area, while within the high residential area the model presented some limitations.

Key words: *Energy fluxes, meteorological variables, numerical modelling, urban areas*

INTRODUCTION

The continuous urban growth and its related environmental problems (e.g., increase of air pollution), linked to the challenges promoted by climate change, increase the need to consider sustainable designs (e.g. increasing green infrastructures) and planning, including the assessment of these strategies impacts on the urban microclimate (Lee et al., 2011; UN, 2014). For that, increase the accuracy of weather and air quality forecast at urban scale becomes crucial. This accuracy depends on the integration of urban representations into mesoscale models, mainly, on the level of accuracy of the urban processes modelling. A set of urban parameterizations have been proposed, with distinct levels of complexity, to achieve this progress, namely: i) empirical models; ii) modified land surface models; and iii) urban canopy models. The link between energy fluxes and meteorological variables has promoted the evaluation of energy and water balance fluxes as a key issue in urban research (Grimmond et al., 2011). Despite the efforts of the last decades, further investigation is needed to validate urban parameterization schemes, especially the use of measured energy fluxes for validation. In case of Weather Research and Forecasting model, one key requirement for urban applications is to accurately capture the influences of cities on local meteorology (Chen et al., 2011).

In this work, the performance of different urban surface parameterizations in the WRF model to simulate urban energy fluxes was investigated using measurements carried out, during August-December 2014, in high and low intensity residential areas in Portugal. The model simulations were conducted using an urban parametrization in the Noah land surface model (LSM), a single-layer urban canopy model (UCM), and a modelling setup composed by WRF-SUEWS (Surface Urban Energy and Water Balance Scheme model forced by Weather Research and Forecasting Model) models. The influence of these urban surface parameterizations in the accuracy of meteorological variables was also evaluated.

METHOD

Model description and configuration

The WRF model, version 3.7.1, was set up with five domains (see Figure 1). The outer domain (D1), covering Europe and North of Africa, has 173 x 142 horizontal grid cells with horizontal resolution of 27 km; the nested domain D2 covers the Iberian Peninsula and has a 175 × 166 horizontal grid cells with a horizontal resolution of 9 km; and D3 covers the Northwest of Portugal and has 121 × 109 horizontal grid cells with a horizontal resolution of 3 km. The two inner domains (D4 and D5) have 34 × 34 horizontal grid cells with horizontal resolution of 1 km, covering the Porto urban area [high intensity residential area] and Aveiro suburban area [low intensity residential area], respectively (Figure 1). The vertical grid was composed by 30 vertical layers up to the top of the computational domain (50 hPa). The two-way nesting technique was applied for the simulations (Skamarock et al., 2008). The Dudhia shortwave radiation scheme and the RRTM (Rapid Radiative Transfer Model) longwave radiation scheme was also used. The Yonsei University (YSU) scheme was used to calculate the vertical turbulent mixing of momentum and scalars. The YSU scheme has been widely applied to meteorological and environmental modelling due to its performance in a well-mixed atmospheric boundary layer and computational efficiency. Grid-scale clouds were resolved using the WRF single moment 5-class scheme, while subgrid-scale convective clouds (cumulus parameterization scheme) for higher resolution domains (D1, D2 and D3) were parameterized by the new Grell scheme.

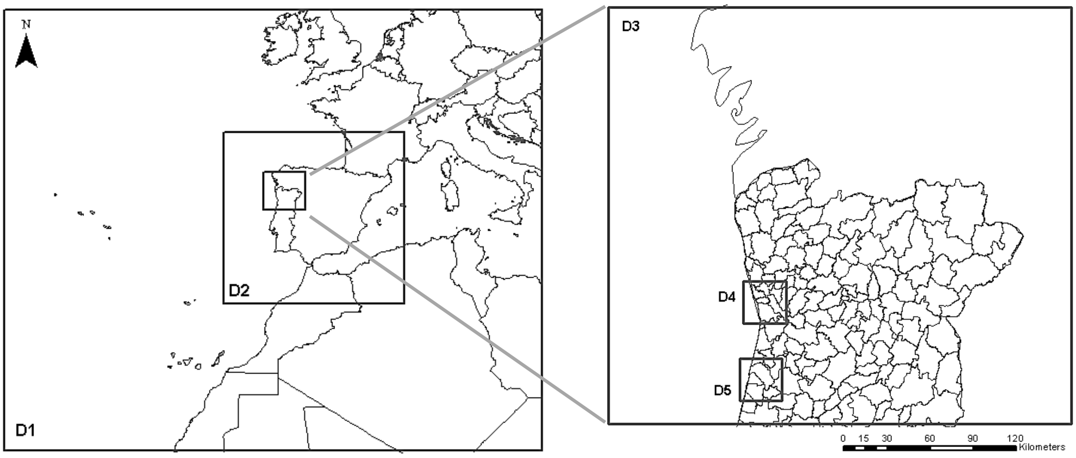

Figure 1. Configuration of the WRF model domains.

The meteorological boundary conditions were initialized with ERA-Interim data from the European Centre for Medium-Range Weather Forecasts (ECMWF) global analysis (horizontal resolution of 1° x 1º) with a temporal resolution of 6-h intervals. The sea surface temperatures and the soil moisture were also initialized using the ECMWF data. Information regarding the land use/land cover was taken from the Corine land cover project (Büttner et al., 2006) 2006 version (CLC2006), with a 3 arc-seconds horizontal resolution, remapped to the United States Geological Survey (USGS) 33 land use categories, following the methodology proposed by Pineda et al. (2004). The USGS 33 considers 3 different urban categories: High Intensity Residential, which includes highly developed areas where people reside in high numbers (apartment complexes, row houses, etc.); Low Intensity Residential, which includes areas with a mixture of constructed materials and vegetation where population densities will be lower than in high intensity residential areas (single-family housing units, etc); Industrial/Commercial, which includes infrastructures (roads, railroads, airports, harbours, etc.) and all other built areas that do not fit into residential categories. A set of simulations using different urban surface parameterizations were conducted for a five-month period (August-December of 2014), corresponding to the period of a flux measurement field campaign carried out in the two Portuguese cities. The different urban surface parameterizations analysed in this study comprises the Noah Land Surface Model (LSM) (Chen and Dudhia, 2001), the Single Layer Urban Canopy Model (UCM) (Chen et al., 2011), and the Surface Urban Energy and Water Balance Scheme (SUEWS) version 2014b (Järvi et al., 2011, 2014). The two first models are implemented as a WRF model module, whereas SUEWS is an individual model. Since UCM considers about 20 parameters, each of them influencing the magnitude and behaviour of the surface flux, the best numerical modelling method was used to be compared with LSM and SUEWS.

Measurements

Flux measurements were undertaken for a five-month period at the two sites under study. The measurements were performed using an eddy covariance system, installed at 32-m within the urban area, and 12-m, within the suburban area, above ground level, measuring the energy fluxes (latent and sensible heat fluxes) every 30-min intervals. The measured data were used for the evaluation of energy fluxes modelling performance. Two meteorological stations from the Portuguese monitoring network with an hourly averaged data were also used for the evaluation of modelled wind speed and air temperature.

RESULTS

A comparison between the modelled results, for both urban fluxes and meteorological variables (considering the different urban surface parameterizations in analysis), and the measured data is discussed in this section. A quantitative analysis, through the estimation of a set of statistic metrics, and a qualitative analysis, through representation of diurnal profiles, are provided.

Urban fluxes

Evaluation of energy heat fluxes is of crucial importance to interpret the modelled near-surface meteorology. Figure 2 shows the measured and modelled 5-month average profile of sensible and latent heat flux, for both low and high intensity residential areas, for the three urban surface parameterizations under study (LSM, UCM and SUEWS).

UCM and SUEWS show a better performance than LSM, being UCM the model that reproduces turbulent energy partitioning more accurately. The urban vegetation effects of suppressing latent heat flux are negligible with LSM, at both areas. This underestimation is quantified by a high bias of around -23.6 [high intensity residential area] and -37.2 W m^{-2} [low intensity residential area], and a poorer correlation between modelled and measured data. As result of this underestimation, LSM overestimates the sensible heat flux (Q_H), for both areas (22 W m^{-2} [high intensity residential area] and 34 W m^{-2} [low intensity residential area]), showing however a good correlation between measured and modelled data. Higher values of NMSE and RMSE are also found for both areas. The daytime turbulent energy partitioning enhances the conductive heat flux into the soil layers during the daytime, which can result in an amplified nocturnal urban heat island (Lee et al., 2011). SUEWS model shows different behaviours for each of the study areas. As discussed by Rafael et al., (2017), at low density residential area SUEWS is able to well reproduce the latent heat flux (Q_E) profile, despite a clear overestimation (MBE of 27 W m^{-2}), whereas, at the high intensity residential area, a poorer correlation is obtained linked to an underestimation (-12 W m^{-2}). Higher RMSE is obtained for both areas, similar to LSM, showing however lower values of NMSE (6.5 and 2.5 for the high and low intensity residential areas). Regarding the sensible heat flux, a general good agreement, for both areas, is obtained with a correlation factor of 0.7 and a NMSE of 4. A consistent overestimation is found, as well as higher values of RMSE; despite of that, the obtained values are in accordance with some of the studies conducted with this model (Ward et al., 2014, Järvi et al., 2014).

Overall, the UCM shows a better performance for both turbulent heat fluxes, for both areas. A consistent overestimation is obtained, with a MBE of around 3 W m^{-2} at the high intensity residential area. At the low residential area, a MBE of 7 and 0.4 W m^{-2} is obtained for the sensible and latent heat flux. Compared with the LSM and SUEWS, UCM shows the lowest RMSE, with values of 53 W m^{-2} [high intensity residential area] and 45 W m-2 [low intensity residential area] for the sensible heat flux; for the latent heat flux a RMSE of 35 and 50 W m^{-2} is obtained for the high and low intensity residential areas. The NMSE is closer to the ideal, for both areas, with values of around 4 for the sensible heat flux and around 2 for the latent heat flux. Similar to this study, previous studies with the UCM have also showed the same performance (e.g., Lee et al., 2011).

SUEWS and UCM simulations reproduce well the changes in the energy partitioning according to the land cover characteristics; i.e. in the high intensity residential area the majority of the energy is partitioned to Q_H, related to high levels of built-up elements (roads, buildings, among others); while in the low intensity residential area the great share of energy goes to Q_E, related to higher fractions of vegetation cover. Despite both models have this capability, UCM model reproduces better the relation between the sensible and latent heat fluxes. For both areas, and since LSM minimize the effects of urban vegetation, a completely different energy partitioning is obtained, which does not represent the atmosphere-surface exchanges.

High intensity residential area (a) Low intensity residential area (b)

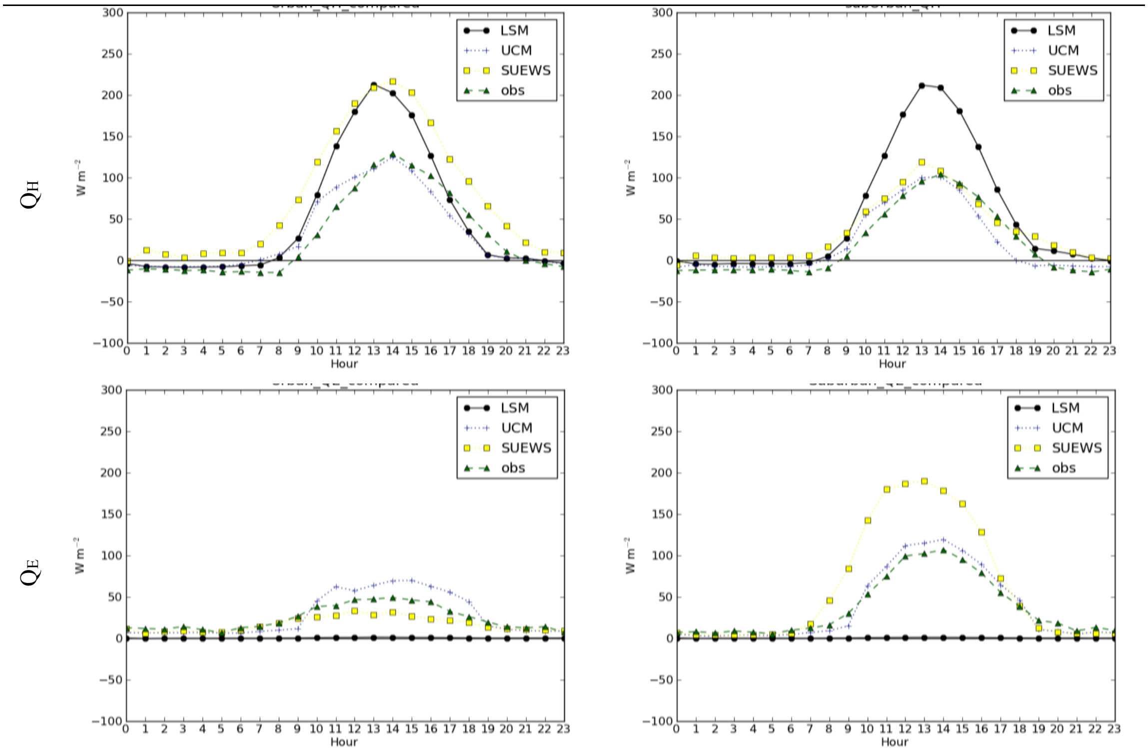

Figure 2. Modelled and measured five-months averaged energy balance at the high and low intensity residential areas. Q_E: latent heat flux and Q_H: sensible heat flux.

Meteorological variables

The 2-m air temperature and wind direction at 10-m for each urban surface parameterization (only for LSM and UCM), for the two study areas, were analysed to assess how the improvements in modelling surface energy balance components influence the accuracy of the meteorological variables simulation.

The UCM simulation compares better with the measurements than the LSM for both the residential areas, reproducing well the diurnal temperature profile, fact that is also shown by the statistic parameters. Both urban surface parameterizations show a correlation factor higher than 0.8; however, LSM overestimates the air temperature on both residential areas with a MBE of around 2°C in high intensity residential areas and 1°C in low intensity residential areas. For the commercial and industrial areas, when the diurnal temperature profile of UCM and LSM is compared, higher temperatures are simulated by LSM, which is in accordance with the data obtained for both residential areas. The model performance is slightly improved in UCM simulation, for both areas, in terms of a reduction of the RMSE and NMSE (0.01 for both residential areas in UCM). The statistical performance in near-surface wind speed shows some discrepancies between modelled results and observed data, for both UCM and LSM and for both study areas. These discrepancies are more notable in LSM, as is also shown by the statistics metrics. Both urban surface parameterizations overestimate the near-surface wind speed. At the high-density residential area, values of 0.95 and 0.19 m s^{-1} are found for LSM and UCM, respectively; at low-density residential area, bias is slight higher, with values of 1.5 and 1 m s^{-1}, respectively for LSM and UCM. This overestimation is mainly a result of an overestimation of nocturnal wind speeds (from later afternoon to early morning) in all simulations. At high intensity residential area, a correlation factor of 0.7 is found for both UCM and LSM; whereas, at low intensity residential area, a slight improvement is obtained, with an increase of the correlation factor from 0.65 (when LSM is used) to 0.7 (with UCM). Regarding the NMSE and RMSE, higher improvements are obtained at the low intensity residential area when the UCM is used, with a reduction of 38% of NMSE and a reduction of 0.7 m s^{-1} of RMSE. At the high intensity residential area, slight differences between LSM and UCM is obtained. Overall the UCM simulation compares better with the observations than the LSM for both the residential areas.

CONCLUSIONS

Due to the energy exchanges between the surface and the atmosphere, the obtained differences of the modelled turbulent energy partitioning, using different urban surface parameterizations, can explain the models performance in near-surface air temperatures. In turn, near surface temperature and wind speeds influence evaporation rates, thereby influencing the energy balance and the hydrological cycle. In addition, urban boundary layer flow characteristics occurs in response to exchange of momentum and energy with the urban surface, which is clearly distinct from natural surfaces in form and material characteristics. These linkages, encompassing the overall discussed results, demonstrate the relevance of the appropriated model physics definition, as well as the considered surface parameters, for an accurate simulation of the urban microclimate.

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